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Remote Sensing Monitoring and Assessment of Silk Road in Turkey: Integrating Drone Systems with GPR and RM

Türkiye'de İpek Yolu Uzaktan Algılama İzleme ve Değerlendirme: Drone Sistemlerinin GPR ve RM ile Entegrasyonu

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Abstract

Maintaining a country's heritage requires the implementation of appropriate methods, which enable the condition assessment of historic infrastructure with preferably zero damages/interventions and minimum post-inspections. A vast expanse of intricate land- and sea-route networks is known as the Silk Roads. They were crucial in bringing Eastern and Western cultures together. Additionally, it has been noted that major cities in Western Anatolia, such as Baghdad or Izmir, have been able to establish links because to their advantageous position. Non-Destructive Techniques (NDT) can meet such criteria, while they are also time and cost-efficient. This paper recommends the combined use of several techniques to maximize information range and accuracy. More specifically, High Definition and Infrared Thermography (IRT) drone systems to assess sub-surface state and detect external heritage defects, and Ground Penetrating Radar (GPR) and Resistivity Measurement (RM) for detecting internal defects. By accumulating suitable data from heritage structures along the Silk Road in Turkey, this study presents a comprehensive approach that can accurately identify surficial and internal defects, in terms of their location and size.

Keywords: *Non-destructive techniques, Infrared thermography, Drones, Ground penetrating radar, Resistivity measurement, Historic heritage*

Özet

Bir ülkenin mirasının korunması, tercihen sıfır hasar/müdahale ve minimum son denetimlerle tarihi altyapının durum değerlendirmesine olanak sağlayan uygun yöntemlerin uygulanmasını gerektirir. Karmaşık kara ve deniz yolu ağlarının geniş bir alanı İpek Yolları olarak bilinir. Doğu ve Batı kültürlerini bir araya getirmede çok önemlidirler. Ayrıca Batı Anadolu'daki Bağdat veya İzmir gibi büyük şehirlerin avantajlı konumları nedeniyle bağlantı kurabildikleri kaydedilmiştir. Tahribatsız Teknikler (NDT) bu kriterleri karşılayabilirken aynı zamanda zaman ve maliyet açısından verimlidir. Bu makale, bilgi aralığını ve doğruluğunu en üst düzeye çıkarmak için çeşitli tekniklerin bir arada kullanılmasını önermektedir. Daha spesifik olarak, yüzey altı durumunu değerlendirmek ve dış miras kusurlarını tespit etmek için Yüksek Çözünürlüklü ve Kızılötesi Termografi (IRT) drone sistemleri ve dahili kusurları tespit etmek için Yere Nüfuz Eden El Radarı (GPR) ve Direnç Ölçümü (RM) kullanılmıştır. Bu çalışma, Türkiye'de İpek Yolu üzerinde uygun verileri toplayarak, yer ve büyüklük açısından yüzeysel ve iç kusurları doğru bir şekilde tanımlayabilen kapsamlı bir yaklaşım sunmaktadır.

Anahtar kelimeler: *Tahribatsız teknikler, Kızılötesi termografi, Dronlar, Yer radarı, Direnç ölçümü, Tarihi miras*

1. Introduction

Main ancient roads, such as the Silk Road, used basic cultural and geographical principles to connect important economic and strategic centres. The routes were carefully chosen to ensure quick, secure and easy movement, even under difficult geomorphological conditions. Ancient roads connecting major centres usually ran through valleys, alongside rivers, across mountain passes, along wide mountain ridges or open plains. Geomorphological, climatic, and environmental factors played a significant role in deciding these routes so that they remained open year-round, while minimizing threats and losses to humans. These historic roads provided safe and comfort facilities, as well as alternative routes wherever needed. In earlier periods of history, smaller scale links connected societies and cultures, but later, additional routes were developed to create vast networks, across continents, such as the Silk Road, the Persian King's Way, Hadrian's Road and the ancient American Indian paths (Dell et al., 2014).

The silk trade originated in Central Asia and the Middle East in the 2nd century and continued into the 18th century. Significant demand developed from state dignitaries and wealthy people in Europe and Asia for silk from China. Silk products were used in large quantities, especially by the Sasanids, Arabs, Byzantines, Selcuks, Ottomans and many European states (Yıldırım and Oban, 2011). The Silk Road, which developed out of economic necessity to meet this demand, is the oldest and longest road network in history. It retained its importance from the 2nd century to the 1800s, playing a crucial role in connecting East and West, and North and South (Figure 1). Its geographies encompassed three distinct ethnicities as well as different civilizations, cultures, political bodies, nations, languages and religions. For centuries, the road was the scene of inter-state disputes and wars, but despite this, it also had a role in creating a sense of unity and common understanding (Özgün, 2008; Oban, 2006).

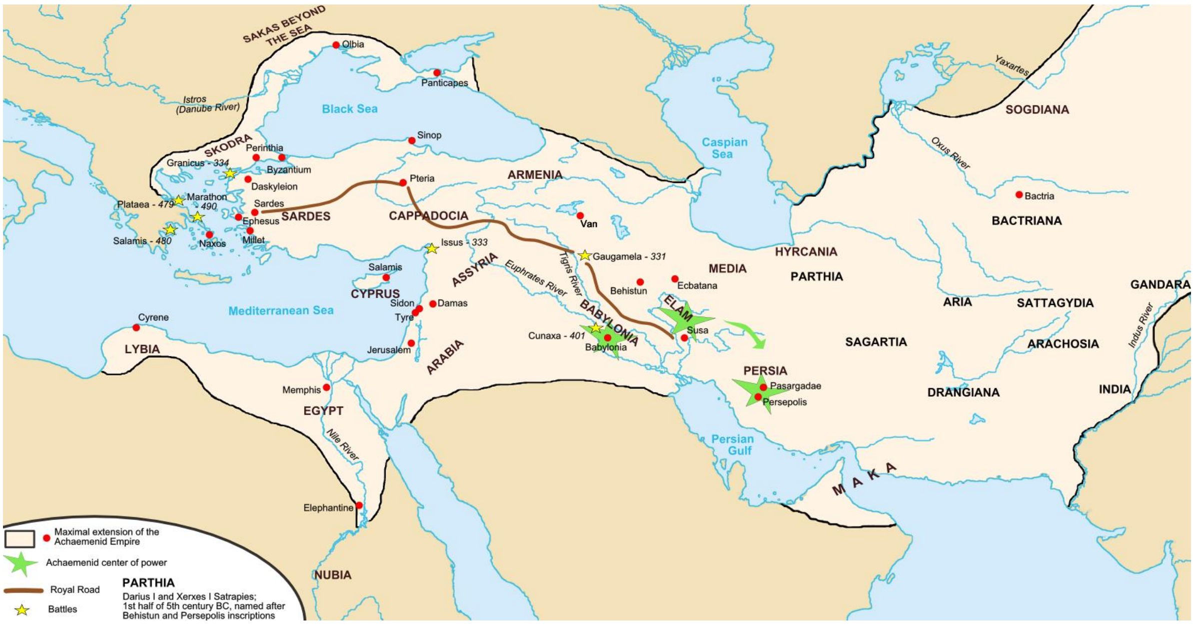

Figure 1. Routes of the silk road (Özgün, 2008)

Izmir, on Turkey's Aegean coast, played an important role in the Silk Road as an international trade centre and important port after the 1620s. For example, the French historian Paul Masson mentions the arrival of Persian silk in Izmir in 1621. Persia was the main source of silk production and export to the Middle East during the 17th century. By the end of the Ottoman-Persian war of 1615-18, Izmir had already become a major rival of the city of Aleppo, which was then the centre for trading Persian silk with English merchants (Fodde, 2006).

Road maintenance is a critical factor in transportation networks. It is important to identify and repair both exterior and internal structural faults and damage, both of which can cause network failure and transportation disruption. Once a transportation project has been implemented, faults should be minimized throughout its life-cycle. Nowadays, various methods are used to detect such faults, each suited to specific pathology types. Major faults are usually observable from visual inspection, while in situ measurements provide information about their three-dimensional extents and severity. Internal faults, however, are less directly detectable, and may require techniques such as drilling cores from the infrastructure's interior in order to assess its integrity (Fodde, 2006).

This paper presents a new method that eliminates the need for core drilling to assess the condition of the heritage Silk Road, by integrating Ground Penetrating Radar (GPR) and high definition Camera Resistivity Measurement (RM) with an Infrared Thermography (IRT) drone system. The Non-Destructive Techniques (NDT) methods, GPR and RM, are used to detect internal layer defects such as faded cracks, buried holes and settlement problems. GPR is one of the most frequently-used NDT for routine sub-surface inspections due to its capacity to provide high-quality radar signal images from the interior of structural members.

IRT is an NDT for measuring object temperature based on the radiation in the infrared band (8-14 mm). Using thermodynamics and heat transmission, this thermographic approach is able to identify irregularities on and/or below the surface (Kilic, 2017). It is based on detecting changes in thermophysical properties and/or thermal reactions in the zones of the damaged areas, such as interior and exterior fractures, as well as air cavities, whose reaction to thermal is different from non-damaged areas. The surface emissivity of objects has a major effect on the thermographic results (Ahmadi et al., 2020). The emissivity of the target is influenced by both the construction materials and the surface texture; for instance, roughness, rusting, cracks and cavities. This in turn affects the temperature recorded by the camera. For this reason, different methods have been used according to particular applications: heritage structures (Ibarra-Castanedo et al., 2017), bridges (Janků et al., 2019), road surfaces (Khalifa et al., 2018), asphalt pavements (Han et al., 2020), etc).

2. Materials and Methods

2.1 Background of the survey area

The part of Silk Road in Turkey was chosen as the case study due to its geographical location. As a bridge between East and West, Anatolia was one of the route's most important segments. By the Middle Ages, the Silk Road extended along various routes from Central Asia through Anatolia, Thrace and Europe. Europe was also accessible through the Anatolian Aegean ports of Ephesus and Miletus, the Black Sea ports of Trabzon and Sinop, and the Mediterranean ports of Alanya and Antalya (Özgün, 2008). During the 18th century, Phocea, situated on the Aegean coast northwest of Izmir, began to challenge Bursa as an Anatolian silk trade hub. To avoid Bursa's silk taxes, both Far-Eastern and Persian merchants from both Persia and the Far East started sending their silk via Phocea, and later, Izmir (Oban, 2006).

Due to its location, and the presence of European merchant colonies and consulates in the second half of the 18th century, Izmir became an important silk market, particularly for European merchants. Izmir thus began to compete with Aleppo and Sayda (Sidon) for the silk trade with Europe. Consequently, the route to Izmir from Erzurum via Tokat became the most widely used Anatolian caravan route during the 18th century, due to the demand for both domestic and transit silk from Persia. Warehouses in Izmir, Istanbul and Bursa also purchased silk, with Bursa silk being exported to European ports by merchants of various nationalities residing in Anatolia's large commercial centres, especially Izmir (Oban, 2006).

2.2 Visual inspection

Visual inspection remains an important method to assess the status of heritage structures. It is cost-effective and produces direct data for visible faults, including cracks, moisture absorption, and delamination. However, because of its low level of detail and accuracy, a more thorough assessment requires more elaborate inspection methods. Experienced investigators performed several such systematic visual inspections for the examined case study, as reported in Section 3. Typically, visual inspection is the initial stage of a full condition assessment, followed by in-depth analysis, if deemed necessary. A complete evaluation involves the costly and time-consuming compilation of both qualitative and quantitative data from in-situ measurement, laboratory testing, and numerical modelling.

2.3 Ground-Penetrating Radar

Ground-Penetrating Radar (GPR) is a well-established and widely-used NDT for evaluating heritage structures. A transmitter antenna sends electromagnetic pulses that are reflected back to a receiver antenna. The stored records are analysed in the sequence to identify unexpected characteristics. Thus, GPR can provide data for hidden defects, material layers, settlements, etc. The GPR inspection used in this study aimed to reveal the hidden features in the Silk Road infrastructure. The survey was conducted with a USRADAR GPR over model on 30 March 2019. Like other imaging technologies, the triple bandwidth offers a superior range and resolution (Figure 2a). In preparation for the GPR examination, straight longitudinal and transverse lines were marked with temporary paint on the ground to ensure that the entire examined area was fully covered and all the necessary data were collected, as shown in Figure 2b.

(a) (b)

Figure 2. (a) USRADAR GPRover antenna (https://usradar.com/), (b) GPR survey of the silk road

The employed USRADAR GPRover tool can collect high-quality, densely-sampled data, from which high-quality tomography and 3D data can be generated. In this study, GRED data analysis software was used to generate the 2D underground layer tomography and a 3D image of the surveyed volume. A tomographic map can be created by combining the longitudinal and transversal data.

2.4 Resistivity Measurement

Resistivity was measured by a Wenner series of electrodes, most of which were mounted in small holes drilled in gaps in the Silk Road to ensure good contact. Resistivity was determined by passing an AC current through the two external electrodes and measuring the tension between the two internal electrodes (potential difference). To improve its precision, this method was repeated several times in various locations (Cavalcanti et al., 2018; Diallo et al., 2019).

The following data processing steps were applied (using Res2D-INV data processing software) to the data collected by the Multi-Electrode ERT system. Figure 3 shows the resistivity colour scale and mean resistivity (MR) values used for imaging, while Figure 4 shows the equipment used in the electrical resistivity tests to effectively assess the condition of a heritage item.

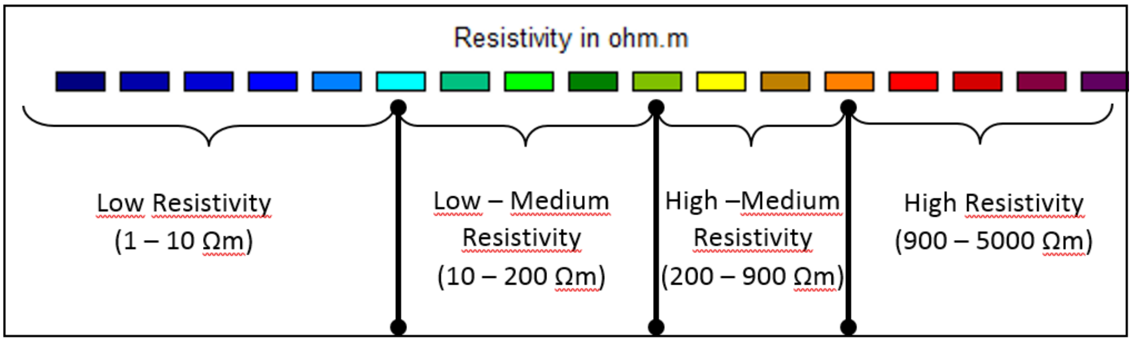

Figure 3. Resistivity colour scale and mean resistivity (Ωm) values used in imaging (Diallo et al., 2019)

Figure 4. Ambergeo brand, Mangusta TMG 255 E model multi-electrode (48 electrode capacity) resistivity tomography device

GPR and RM are rapid inspection methods based on the transmission of electromagnetic waves. The radar wave sent from the antenna passes through the medium, and is transferred when the receiving antennae detects an interface of different dielectric constants. Increasing the difference in the dielectric properties of the signal increases the probability of detecting targets, which can improve the resolution and accuracy of the method. Numerous studies have applied GPR and RM to various engineering and architectural applications (Cavalcanti et al., 2018; Diallo et al., 2019). These procedures have been effective in identifying and evaluating heritage structures, such as roads and pavements (Bai and Sinfield, 2020; Ortega-Ramírez et al., 2020; Asadi et al., 2020), bridges (Kilic and Unluturk, 2016), and tunnels (Kilic and Eren, 2018). GPR has also been applied for finding hidden targets (Kilic, 2017), moisture inspection (Shapovalov et al., 2020; Kilic, 2015), rebar corrosion assessment (Jazayeri et al., 2019), and locating sub-surface faults, such as cracks, voids, and delamination (Kilic and Eren, 2018; Johnston et al., 2018).

2.5 High-Definition Infrared Thermography Camera Drone System

A thermal imaging system measures the analysed material's absorption and emission of infrared radiation. Infrared radiation indicates variations occurring in objects due to natural heating and cooling caused by air temperature variation. The released radiation can be separated into bands, including detectable light and microwaves, with a wavelength between 0.75 and 10 microns (Fabbri and Costanzo, 2020; Meola et al., 2017). The amount of radiation depends on the sample size. Emissions are detected by a thermal imaging camera and reproduced as a colour image. In the case of corroded reinforcement bars and surrounding concrete, the delaminated area becomes more sensitive to temperature changes due to its reduced mass and increased surface area. Such differences in sensitivity allow the thermal imaging camera to determine the position of defects. Matrice 210 - Zenmuse XT2 inspection system, shown in Figure 5, is ideal for temperature extremes, as it can detect temperature differences as small as 0.08 °C. It should be noted that wind, direct sunlight, and rain can decrease the accuracy of this technique.

(a) (b)

Figure 5. (a) High-definition thermal camera drone system (Dslrpros, 2021), (b) Drone survey of the silk road

3. Results

Regarding the history of a site, the design, materials, and construction technology used are as important as buildings, structures and landscapes themselves. In some historical settings, the design and development represent a utilitarian and vernacular use, while others represent a passion for a particular architecture, intricate theories relating to landscape and scenery, or the application of advances in civil engineering. The developed visual evaluation of the Silk Road consisted of external inspections, integrated with a high-definition drone camera to assess condition of the heritage. There were reports of several defects requiring extensive routine maintenance due to weather, temperature and use. Surfaces erosion and degradation is caused surface water, rain and ice. In addition, vegetation growth obscures what is often an indistinct line across the countryside. Figure 6 presents photos from the visual inspection.

Figure 6. Silk road visual inspection results

Figure 7 depicts the central cross-section of the radar signal from the Ground-Penetrating Radar (GPR) survey of the study area. The centre cross-section of the radargram shown in Figure 7 was obtained from the GPR scan in the case study road.

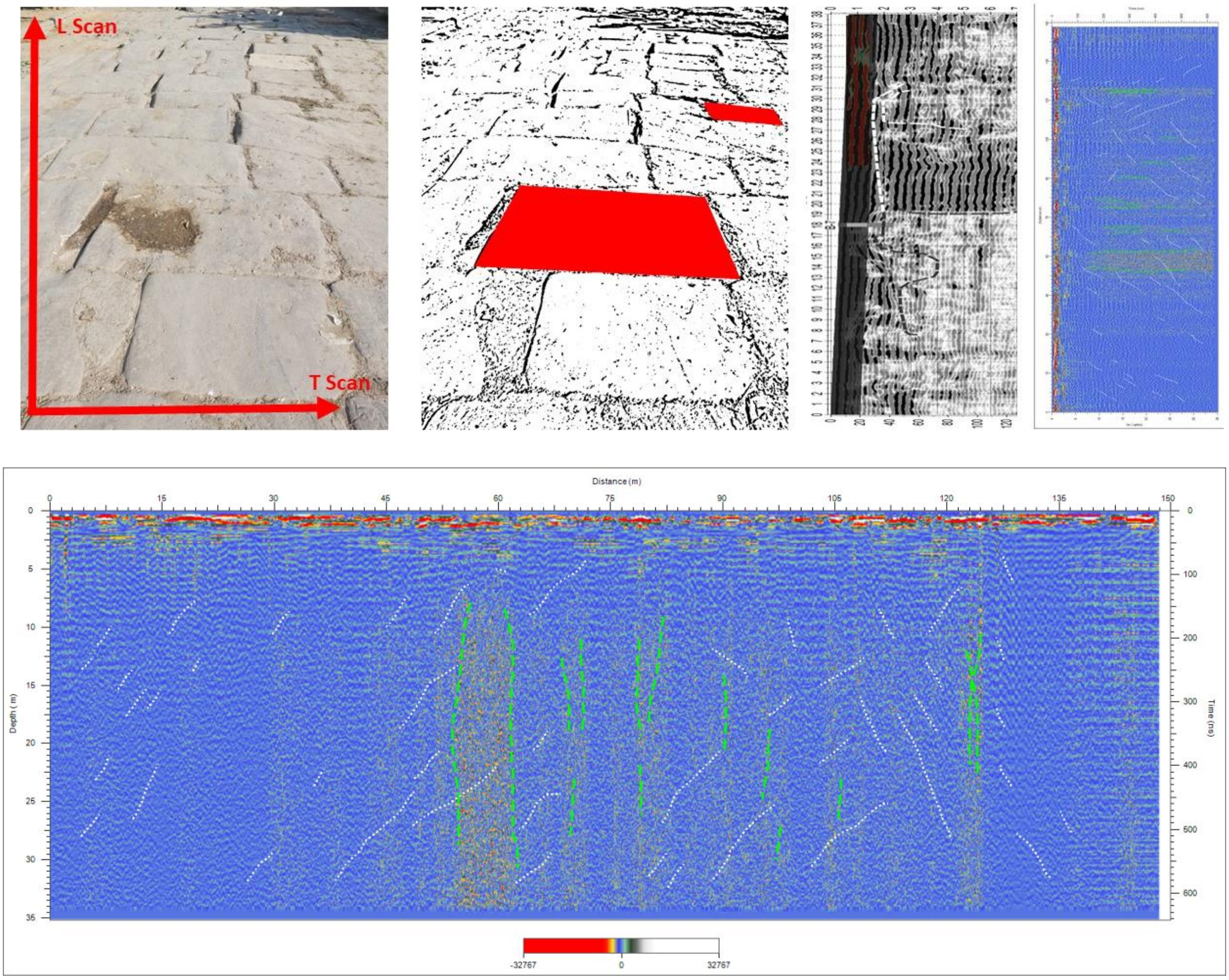

Figure 7. Processed GPR data and interpretation

Figure 8 presents the GPR radargram. Most radar echoes were recorded by the receiving antenna, causing possible interference to hidden anomaly signals. And also in Figure 8 the radargram clearly shows modifications to the historic road material.

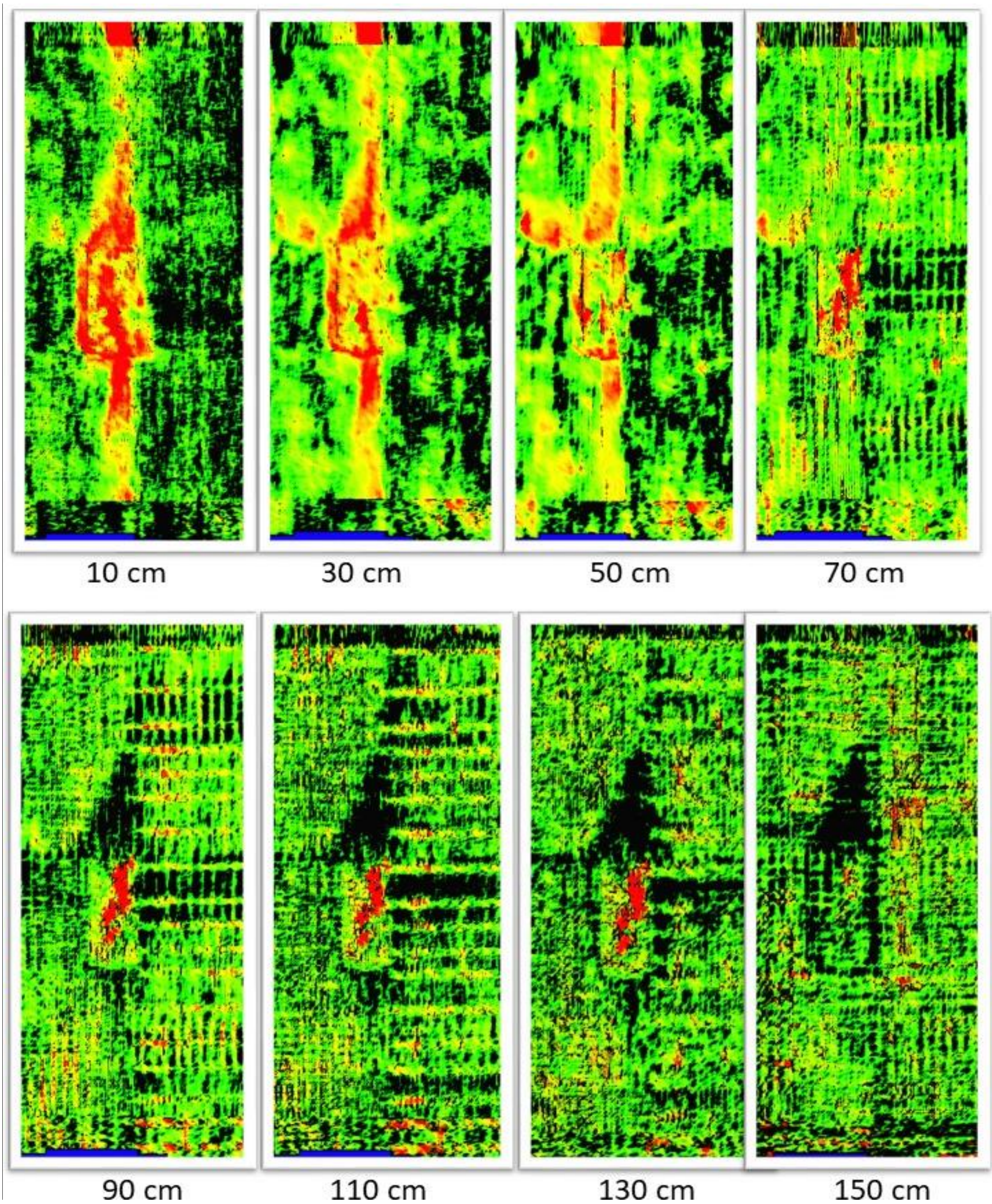

Figure 8. GPR 2D data slices, depth of each slice from left to right, and top to bottom: 10, 30, 50, 70, 90, 110, 130, and 150 cm

All data recorded in the analysis were carefully examined and processed. The colour scale was measured in two sections, based on the Colour Scale used in the Resistivity Measurement (RM) views. These colours represent resistivity values, and Figure 9 illustrates the obtained resistivity measurement results.

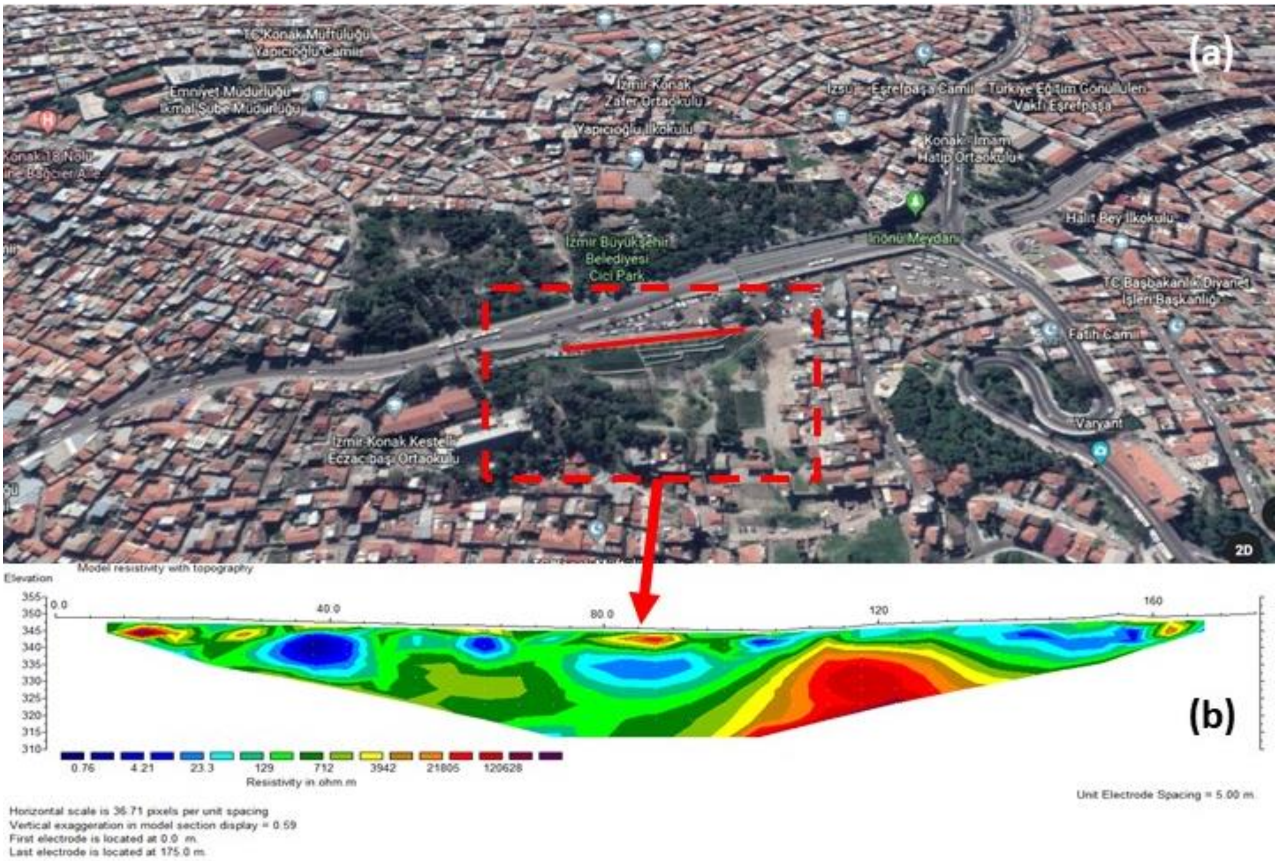

Figure 9. (a) Aerial view of Silk Road, (b) Resistivity Measurement (RM) results

These changes allow localisation of surface temperature variations. A map of internal irregularities in the material can thus be obtained by measuring surface temperatures to determine the heat flow. In this case study, this approach was used to demonstrate how IRT can provide information on the materials of a heritage item, its condition, its features, and its state of deterioration, which may not be apparent from visual inspection. The presence of stored heat (see Fig. 10) indicated that sections within the fractures in this location had become separated, necessitating rapid repair work to prevent further degradation and potentially permanent damage.

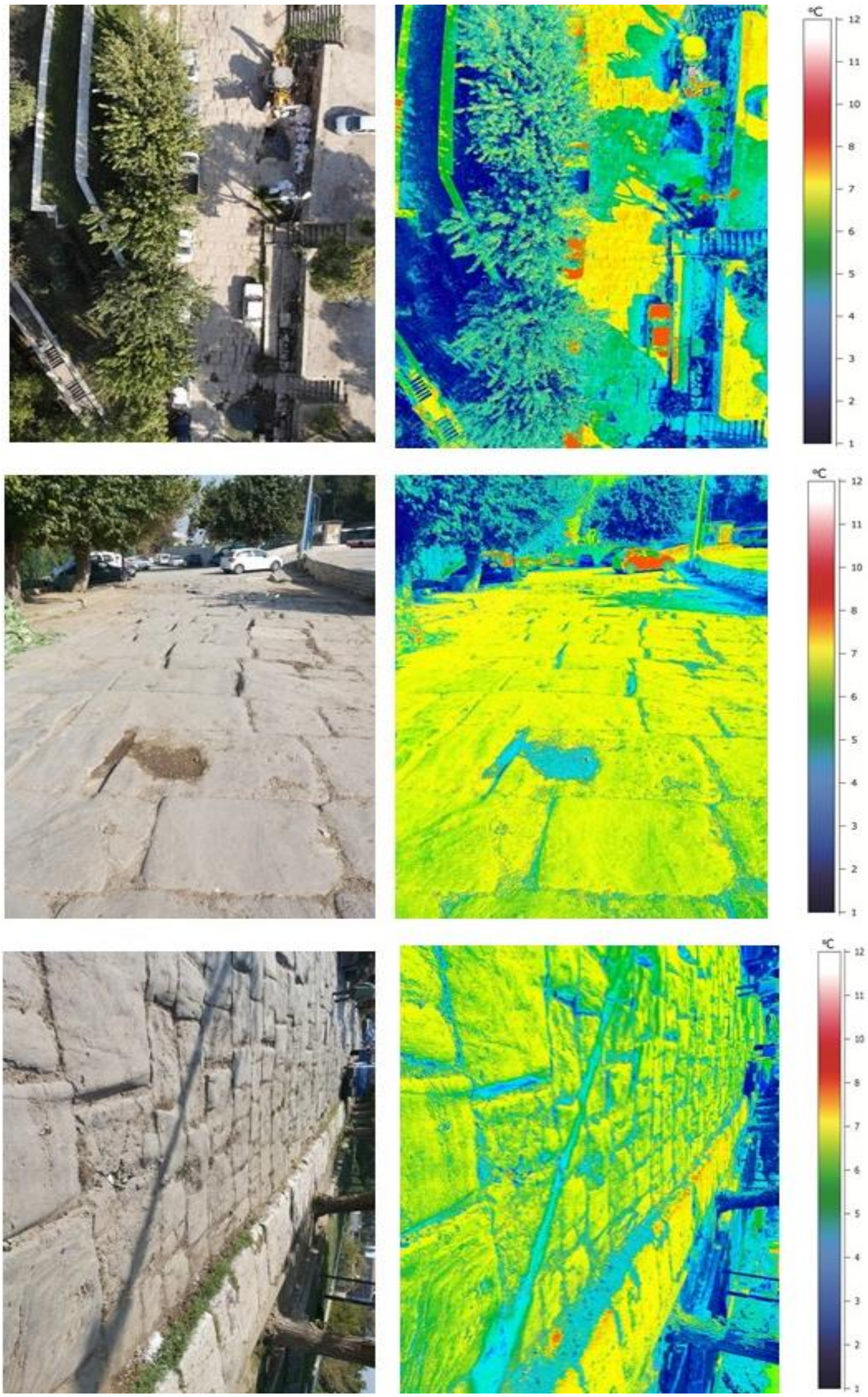

Figure 10. Thermal imaging procedure using drone system

4. Discussion

In view of the lack of existing plans or other documentation regarding the Silk Road in Turkey, a survey was conducted to evaluate its current state. This study demonstrated the urgent need for preservation work to be conducted on this important heritage. The assessment, performed by integrating measurements from three separate inspection methods: a visual survey, GPR with RM, and IRT, provided a more complete assessment of the examined heritage, which can guide decisions for determining protected zones (Capozzoli and Rizzo, 2017; Anchuela et al., 2018).

The findings demonstrate the importance of such surveys using this multidisciplinary methodology, especially for heritage items with little or no condition assessment available. While combining the broad range of employed methods created a challenge in term of complexity, the methodology adopted here demonstrates that such complexity is manageable. The outcome was the integration of NDT in a way which eliminates the need for additional examination, unless exceptionally specified (El-Qady et al., 2005; Carrière et al., 2013).

The initial visual inspection of the investigated potholes was conducted along a significant portion of the Silk Road. The combination of GPR, RM and IRT allowed the collection of detailed internal data on the exact nature and extent of the defects, and the overall condition of the examined heritage. Typically, single NDT procedures are used, but the current study clearly shows the benefits of integrating methods and the combined use of multiple techniques in maximizing data, both quantitatively and qualitatively (Sbartaï et al., 2007; Pellicer and Gibson, 2011; Fernandes et al., 2015; Zeybek and Biçici, 2020; Biçici and Zeybek, 2021; Zeybek and Biçici, 2021).

5. Conclusions

The main motivation for this study of the Silk Road was the lack of surviving heritage details. This study adopted a combined approach that integrated visual inspection with three contemporary techniques: GPR, RM and IRT. The initial visual inspection revealed major faults in different parts of the road, while GPR and RM provided more information about lower layers. Intrusive testing was also conducted, and the integration of two examination techniques allowed the identification of the most severely degraded area. This approach can provide immediate feedback to allow more efficient, real-time decision-making for retrofitting and maintenance.

This study makes a significant contribution by showing how a methodology combining a variety of NDT approaches can yield accurate data on both invisible and discreet faults affecting the status of a historical infrastructure, in this case, a section of the Silk Road in Turkey. Given the lack of documentation regarding the original road, this evaluation is important in enabling the collection of high precision data, including on hidden features, which can guide a conservation program. This interdisciplinary approach provides a full analysis of the road's current condition and its future requirements. In short, this study contributes to the available information for heritage preservation professionals.

Further research could focus on the following issues:

- While much work has been carried out in direct relation to historic roads and heritage with standard geometry to track dynamic effects and other damage, no extensive study has focused specifically on condition of historic roads.
- Inspecting and recording historic roads is essential for cultural heritage conservation and protection. Therefore, it is essential to record all such roads in national historic heritage databases and to incorporate them in a national Cultural Heritage Risk Management Plan.

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