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Condition assessment of different historic bridges using Non Destructive Techniques (NDT) with FTIR analysis in Izmir after the Samos Island earthquake

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Abstract

The study aimed to contribute to condition assessments of historic bridges in Izmir, Turkey and the estimation of their predictable functional lifetime after the Samos earthquake. This document is a summary of the study into the reliability of Non-Destructive Techniques (NDT) for testing the state of different historic bridges impacted by the October 30, 2020 Earthquake. Besides providing data on material characteristics, NDT can help identify hidden bridge structure defects, such as cavities and moisture. This study also used FTIR (Fourier Transform Infrared Spectroscopy) spectral data analysis in conjunction with NDT as a multidisciplinary evaluation technique and demonstrates the value of this approach in the field. This study is of special relevance to bridge engineers.

Keywords: Historic bridges, Samos earthquake, GPR, Thermal imaging, NDT, FTIR spectroscopy

Introduction

Historic bridges are vital signs of any culture's history, so it is critical to protect them from pressures such as flooding, freeze/thaw phases, dynamic loads, and general aging. Numerous bridges are open to the public, which benefits the authorities responsible for them, both financially and in terms of their standing in the community. As well as the natural processes mentioned above, the vibrations caused by live loads cause damage, such as cracks, which can weaken and eventually destroy the structure. Some structural deterioration occurs below the surface, and visual examination alone cannot provide a sufficiently thorough assessment of a structure's condition. Therefore, NDTs are essential [1, 2].

Maintaining a culture's structural legacy requires a program of bridge assessment and monitoring to achieve continuous maintenance. Although there is no fixed standard for assessing bridge health, monitoring should be multidisciplinary, with the appropriate experts and dedicated technology [3, 4]. In order to extract detailed information about the present condition of the historic bridge, a multidisciplinary documentation is undertaken in this study, merging geometric documentation information and products with historical, architectural, and masonry material data.

While there are strict criteria for modern bridge constructions, historic bridge construction methods and materials varied widely, according to the era in which the work was completed. Different construction materials included bricks, stones, adobe, or mortar, with varying block sizes and building styles.

In addition to safeguarding these ancient bridges from numerous threats to their structural integrity, it is also critical to assess seismic risk in locations like Turkey. Performing a reliable bridge risk assessment presents many difficulties, requiring qualitative and quantitative methodologies to ensure appropriate

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maintenance judgments [5]. Qualitative data can be collected through inspection of degradation, faults and through relevant literature reviews. However, quantitative data collection requires much more complex methods carried out by specialists, which makes the process costly in terms of time and money, and is thus suitable in a restricted number of circumstances, and only after other approaches have failed to yield the essential evidence [6].

Recording the condition of preservation of historic bridges requires, systematic NDT acquisition and integrated treatment of multisource scientific data. The importance of interdisciplinary inspection approaches is frequently cited in the literature, particularly in circumstances when constructed material of exceptional cultural value is deteriorating or posing significant dangers. Similarly, NDT monitoring technologies have been identified as a key aspect in preserving historic structures which are experiencing severe deterioration or are currently at risk. As a result, active and passive NDT, as well as suitable signal processing technologies, are frequently employed as interdisciplinary data sources for inspection and monitoring applications [7–9].

Various NDTs are available, including sonic/ultrasonic, electromagnetic, electrical, and infrared thermography. Each of these can provide highly specific information. Previously, most of these procedures were laboratory-based, but advances have reduced the cost of non-laboratory NDTs, notably GPR (Ground Penetrating Radar) and infrared thermography, making them more feasible [2, 10, 11].

In particular, infrared thermography has expanded from civil engineering to sectors such as medicine, publishing, and the detection and analysis of hidden mineshafts. NDTs are commonly used in civil engineering to evaluate concrete and reveal degradation and abnormalities inside structures. Other contact-based NDT techniques can be used to further enhance models created by remote approaches by permitting a higher level of subsurface examination for a more accurate outcome [3].

When combined with more traditional means of evaluation, such as visual examination, these techniques can produce credible assessments to guide decision-making. However, the most effective approach may involve a combination of two material assessment NDTs because this can produce high quality data with reduced measurement noise for individual diagnostics. This paper discusses visual examination, GPR, and infrared thermography. The presence of water and, to a lesser degree, porosity, reduces the accuracy of the GPR system. Although the effectiveness of ultrasound varies in the presence of moisture and density, it is nevertheless an effective measure of the modulus of elasticity [12, 13].

FTIR can be used to measure the infrared spectrum of absorption or emission of solids, liquids, or gases. An FTIR spectrometer captures high-spectral-resolution information over a large spectral range simultaneously. FTIR spectroscopy of probe molecules can be used to evaluate surface locations in catalysts. Because the spectra for each adsorbate is unique, and highly dependent on the type of surface bonding to the local environment, FTIR spectroscopy is a suitable and effective method. Selection of the most appropriate probe molecule is thus strategic: some probes may adsorb on specific locations, which can then be identified and measured from the absorption strength [15, 16].

Although these alternative evaluation methodologies are more expensive, their use may be justified by greater measurement reliability. Accordingly, this study examines the effectiveness of NDTs to test a multi-disciplinary approach to evaluating the structural condition of historic bridges.

Infrared thermography is a low or medium cost evaluation NDT for tracking temperature over time. Although straightforward to use for a qualified operator, its reliability may vary depending on the environmental circumstances. In addition, it can only provide information about the material surface, since infrared radiation does not penetrate very deeply. GPR's deeper penetration, on the other hand, allows for better sub-surface data gathering [11, 13]. As previously noted, using these two approaches in conjunction provides a wider range of data for comparison and validation.

Because historic constructions are frequently prone to serious problems, such as cracks and voids, it is critical to gather as much information as possible. This can be accomplished by integrating two complementary NDTs in the evaluation procedure. Historic bridges are also unlikely to have many surviving structural documents, making traditional inspection procedures ineffective due to a lack of information on, for example, the location of internal supports.

Wide-ranging and consistent structural assessments of historic bridges are possible using the inter-disciplinary approach outlined above. This can provide a complete report on which to base structural maintenance decisions and detect hidden defects, such as cavities, delamination, cracks, and moisture ingress.

Historic bridges and visual inspection

As previously noted, visual examination remains a useful method for assessing the status of structures. It is cost-effective for quickly identifying visible faults, such fractures, moisture infiltration, and delamination, but lacks detail, and must be combined with additional inspection techniques for a more comprehensive assessment. In this study, many extensive visual inspections were conducted on the case study bridges, as reported in the results section. Historic bridges were impacted by the Samos island Earthquake on October 30, 2020. The selected bridges are at five different locations in Izmir, a city with a long history. The bridges, located variously to the north, south, east and west of İzmir, are different ages and have been exposed to different climatic conditions (Fig. 1).

Visual examination is generally only the first stage of an extensive condition audit as it can be followed by a more in-depth investigation if judged essential. A thorough assessment approach involves the collection of both qualitative and quantitative information through in-situ testing, laboratory checks, and mathematical modelling. These methods are expensive, but time-saving.

Historic case study bridge 1

The first case study bridge, called Uc Kemer Bridge (Fig. 2) and built in the Roman period, is located in the Bergama district, İzmir province, specifically across the Selinus Brook in the city. The largest arch is 10 m high; the width is 9.60 m; the bastion is 4.50 m wide and 56.40 m long. FTIR analysis was used to pinpoint the origins of its rock and stone formations.

The visual inspection showed that, following a flood, the bridge's saturated fill had expanded due to freezing conditions, causing further cracking in the arch barrels and spandrel walls. The stream bed at the piers had also been scoured (Fig. 3).

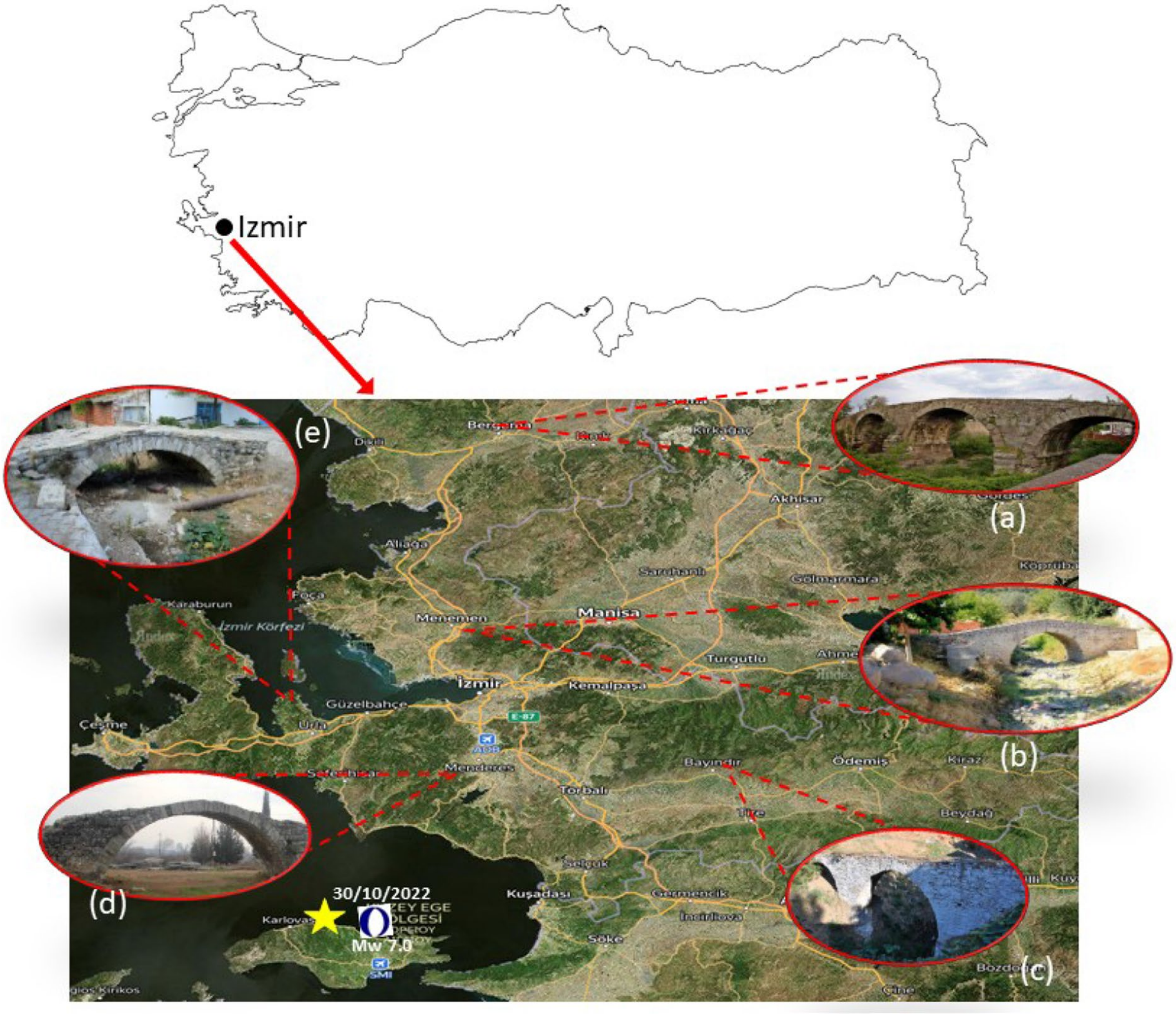


Fig. 1 Case Study Bridge lacations **a** Uc Kemer Bridge, **b** Ignedere Bridge, **c** Yahudi Deresi Bridge, **d** Sarıkemer Stone Bridge, **e** Ozbek Village Bridge

Fig. 2 Front View of Uc Kemer Bridge

Fig. 3 Side and Back View of Uc Kemer Bridge

Historic case study bridge 2

The second case study bridge, called Ignedere Bridge (Fig. 4) and built in the Ottoman period, is located at the center of Ignedere Village in Menemen district, Izmir Province. It consist of a single span of cut stone on Ignedere River, from which the village takes its name. The bridge has recently been renovated and is in good condition.

The single span stone arch structure is 16 m long and 2.4 m wide, with a circular arch of 4.92 m radius. The bridge is made of large, rough, local stones that have been shaped. The surfaces of the front of the bridge

Fig. 4 Recent View of the Ignedere Bridge

arch were constructed using rubble wall masonry techniques.

Visual examination showed that the bridge had suffered mortar discharges in the rubble stone wall and loss of stones, leading to stone fractures. The pebbles, which were pressed into the rubble masonry, had become exposed, leading to ruptures in places (Fig. 5).

Historic case study bridge 3

The third case study bridge, called Yahudi Deresi Bridge, built in the Byzantine period at an unknown date, is located in Bayindir, Izmir. It was built over a creek for the purpose of transportation (Fig. 6).

The stone arch structure has a single lane and is 16 m long, and 2.4 m wide with two span (Fig. 7). The

Fig. 5 Previous View of Ignedere Bridge before restoration

Fig. 6 Front View of Yahudi Deresi Bridge

Fig. 7 Back View of Yahudi Deresi Bridge

visual inspection showed that, Yahudi Deresi Bridge is an excellent example of a historic structure that still performs its original purpose, since it forms part of the village's pedestrian road network.

Historic case study bridge 4

The fourth case study bridge, called Sarıkemer Stone Bridge, crosses Saricay creek, 800 m south of the center of Menderes district in Izmir, although it is no longer functional (Fig. 8).

The bridge was built in the Byzantine period and the visual inspection revealed an attractive-looking structure of cut stone with a single span, 24 m long, and 8.8 m wide. Its characteristic yellow arch is represented on the flag of the Menderes district (Fig. 9).

Fig. 8 Front View of Sarıkemer Stone Bridge

Historic case study bridge 5

The fifth case study bridge is called Ozbek Village Bridge which has a single-span, and is 8 m long, and 2.4 m wide. Located in Ozbek village, Urla district, Izmir, its construction date is unknown. (Fig. 10).

Summary of the case study bridge

The five case study bridges were each examined internally and externally. All were made of masonry, either brick or stone, bound by mortar. Various defects were identified, including deterioration, water seepage, cover delamination, and large regions of cracking. The damage caused by delamination required repairs to bridge abutments and piers. In particular, the piers were in such bad condition that a separate safety evaluation was required before beginning restoration work. The decks and the surface of all bridges were in poor condition and in need of repair. There were also potholes and fretting. Each bridge's core was substantially higher than the rest of the structure.

Methodology

The preservation of historical bridges necessitates great sensitivity in applying intervention techniques, which in turn requires precise evidence regarding the bridge's condition. In this study, each case study bridge was inspected via visual examination, material analysis, GPR testing, and thermal imaging. The findings using each method were then compared to precisely evaluate each bridge's structural condition.

A historic bridge's condition must be determined, especially if it has been damaged by a natural disaster, and even more so if the problem already existed; ideally, there should be complete information of the bridge's condition before any disaster. This enables a risk assessment and the implementation of an appropriate maintenance plan. The bridge should be evaluated as soon as possible after any disaster to determine its safety status. The assessment of pre-event and post-event safety conditions require different approaches; the first assesses potential danger, whereas the second assesses actual damage. The findings from the latter examination can then be used to decide on any necessary repairs.

FTIR spectroscopy analysis

Because FTIR spectral data collection is complex, fundamental variations inside samples may go undetected, hence feature extraction is critical (Fig. 11).

The results become more interpretable once the vast number of variables collected from the IR spectral data is reduced multivariate statistical analysis (Fig. 12). In this study, this was achieved by a combination of unverified and verified procedures [14, 15].

A material examination of the bridges was conducted, using both individual laboratory and field analysis techniques, to determine the impacts of ordinary occurrences, such as snow, rain, heat variations, and air

Fig. 9 **a** Side View of the Sarıkemer Stone Bridge, **b** View of the bridge pier

contamination. One of the techniques used was the determination of the presence of water-soluble salts, such as nitrate, nitrite, sulphate, phosphate, carbonate, and chloride, and their pH levels. This analysis was particularly important given the types of materials found in historical bridges, such as stone, earth, ceramic, and mortar [16].

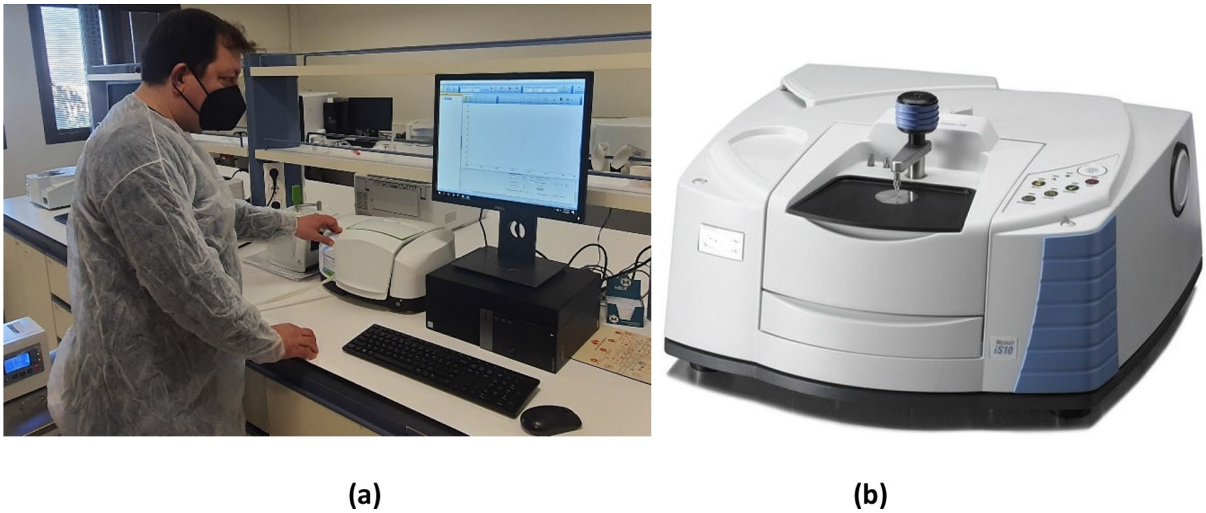
GPR survey

GPR is a well-known and widely used NDT for assessing structural health. Electromagnetic pulses are sent into the structure from a source antenna and reflected back to a receiving antenna. The information stored in the pulses is then analyzed to find any hidden traits. GPR can detect hidden fractures, material layers, delamination, leakage, and settlement.

In this study, the primary goal was to detect concealed fractures or moisture penetration. The survey was conducted with a TR HF model (a 2 GHz antenna), and USRADAR GPR (4 GHz antenna) (see Fig. 13a). To prepare for the GPR survey, straight longitudinal and transverse survey were painted on the surface with a temporary shade, ensuring that the entire area was covered and the data could be referenced to fixed positions (see Fig. 13b).

The transportable and manoeuvrable GPR device used for this study can capture high-grade, densely surveyed information, suitable for generating

Fig. 10 View of Ozbek Village Bridge



(a) (b)

Fig. 11 **a** FTIR Spectrometer in use, **b** FTIR Spectrometer

high-quality tomography and 3D data. IDS GRED data examination software was used to create a 2D tomography of the subsurface layers and a 3D image of the surveyed capacity. By integrating the longitudinal and transversal data, a single tomographic map of the structure was constructed.

Fig. 12 Examples of the investigated historic bridge samples

Thermal imaging procedure

Thermal imaging assessment relies on absorption by and emission of infrared radiation from the substance being evaluated. This can be detected using a thermal imaging camera. Infrared radiation refers to changes in sources due to heating and cooling processes induced by variations in the surrounding air temperature. The emitted radiation's wavelength ranges from 0.75 to 10 microns. These can be grouped into spectrum bands covering both visible light and microwaves [11, 18]. The amount of radiation released is proportional to the sample size. A thermal camera captures the emissions and presents them as a coloured image. This can show that, for example, that a region of delamination between corroding reinforcing

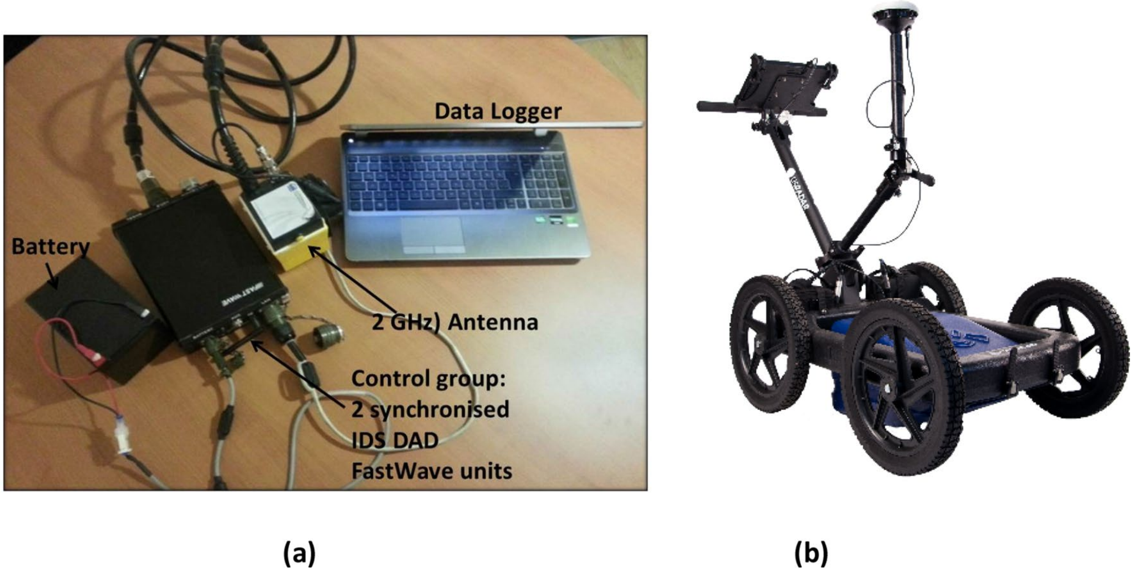


Fig. 13 **a** TR HF GPR Antenna, **b** USRADAR GPR Antenna

bars and the surrounding concrete is more susceptible to temperature variations because of its lower mass and larger surface area. The thermal imaging camera can use these response variations to determine the position of individual features. This kind of examination is appropriate for measuring extremes of temperature since it can detect temperature differences as small as 0.08 °C. However, wind, direct sunlight, and rain during testing can make the results less reliable.

Results

FTIR spectroscopy analysis

Before conducting the FTIR spectroscopy analysis, the rough surface layer of each ceramic fragment was smoothed, and subsequently cleaned with alcohol before scraping a 1 mg sample.

The IR spectra revealed the presence of varying levels of calcite (ca. 1230 cm−1) and quartz (685, 676 and 627 cm−1) in every sample. Some samples also had gypsum (ca. 3320, 3504, 1214, 1116, 667, and 622 cm^{-1}) or considerable volumes of calcite. In several samples, the FTIR spectra differed for the interior and exterior sides. Figure 14 shows the FTIR spectra of the pieces with high levels of calcite, gypsum, and differences between outside and insides. The first graphs of each bridge displayed in more detail under the Fig. 14a–e.

Studies of historic bridges generally report equal quantities of plant- and mineral-tempered stone samples in all samples [14], but in the present study, the upper levels had far fewer mineral-tempered stone samples. The usage of organic temper is indicated by the cavities in the cross divisions, as seen in the Fig. 14. The coarse calcite granules may have been added to the clay raw material in the mineral materials [15]. These granules could be either ordinary, such as carbonate sand, or purposefully derived from the stone samples, by fracturing carbonate rocks or calcite veins, depending on the use of the stone samples [14–16].

GPR survey

Due to the complimentary connection between resolution and depth, the TR HF model (2 GHz antenna) and USRADAR GPR (4 GHz antenna) were reasonable compromises for use in each historic case study, given the complex geometry of the bridges due to their specific features. For this approach to be used effectively, the goal of the surveys should be established to determine the appropriate antenna option. The analysed radargrams yielded qualitative results and revealed important details regarding the masonry makeup and structure. The quantitative data gained from these radargrams, namely the various trace amplitudes, was later utilized to characterize the panels. This made it possible to identify diverse strata, discontinuities, and the size of the researched ancient constructions, as well as some masonry traits. These historical case studies demonstrate the value of this method in deciphering the data produced by GPR surveys and analyzing radargrams.

The center cross-section of the radargram shown in Fig. 15 was obtained from the GPR scan at the case study bridges. The radargram clearly shows the old bridge arches and material modifications. The interpretation is

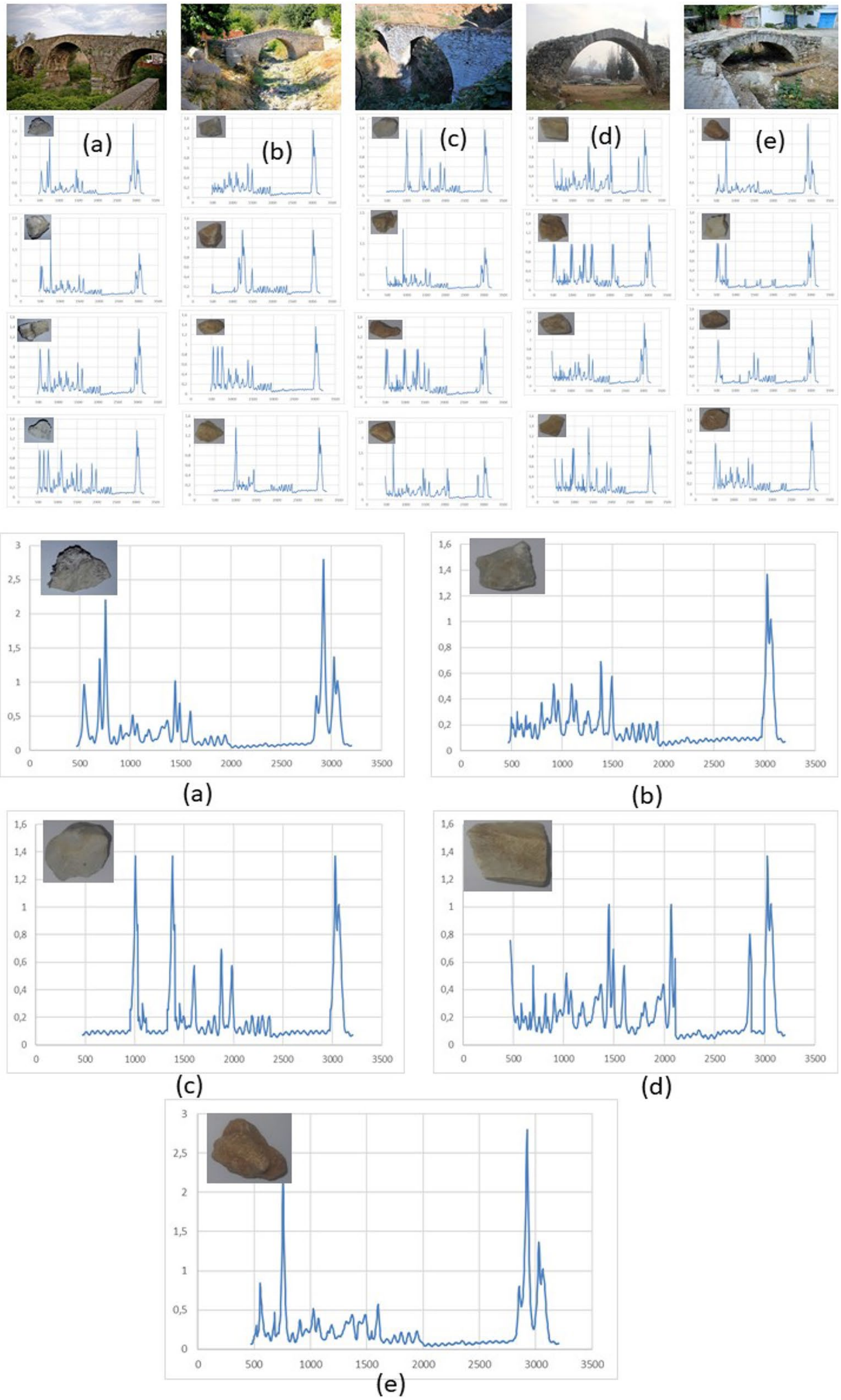
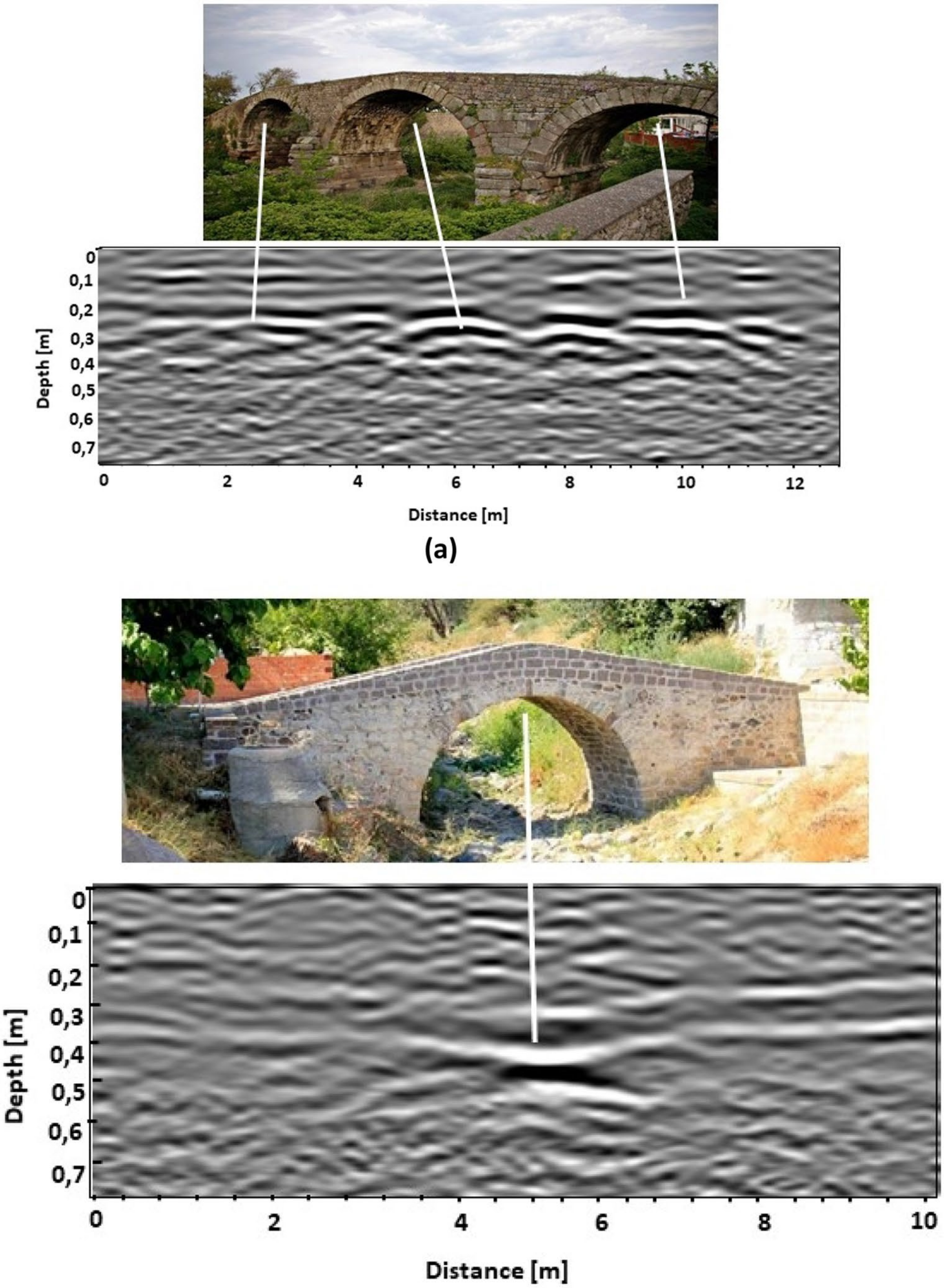


Fig. 14 FTIR Spectra of the samples

depicted in Fig. 15a–e. Following a more individualized processing step for each profile, spots in the data with strong reflectors were manually identified as coarse fill materials inside the bridge.

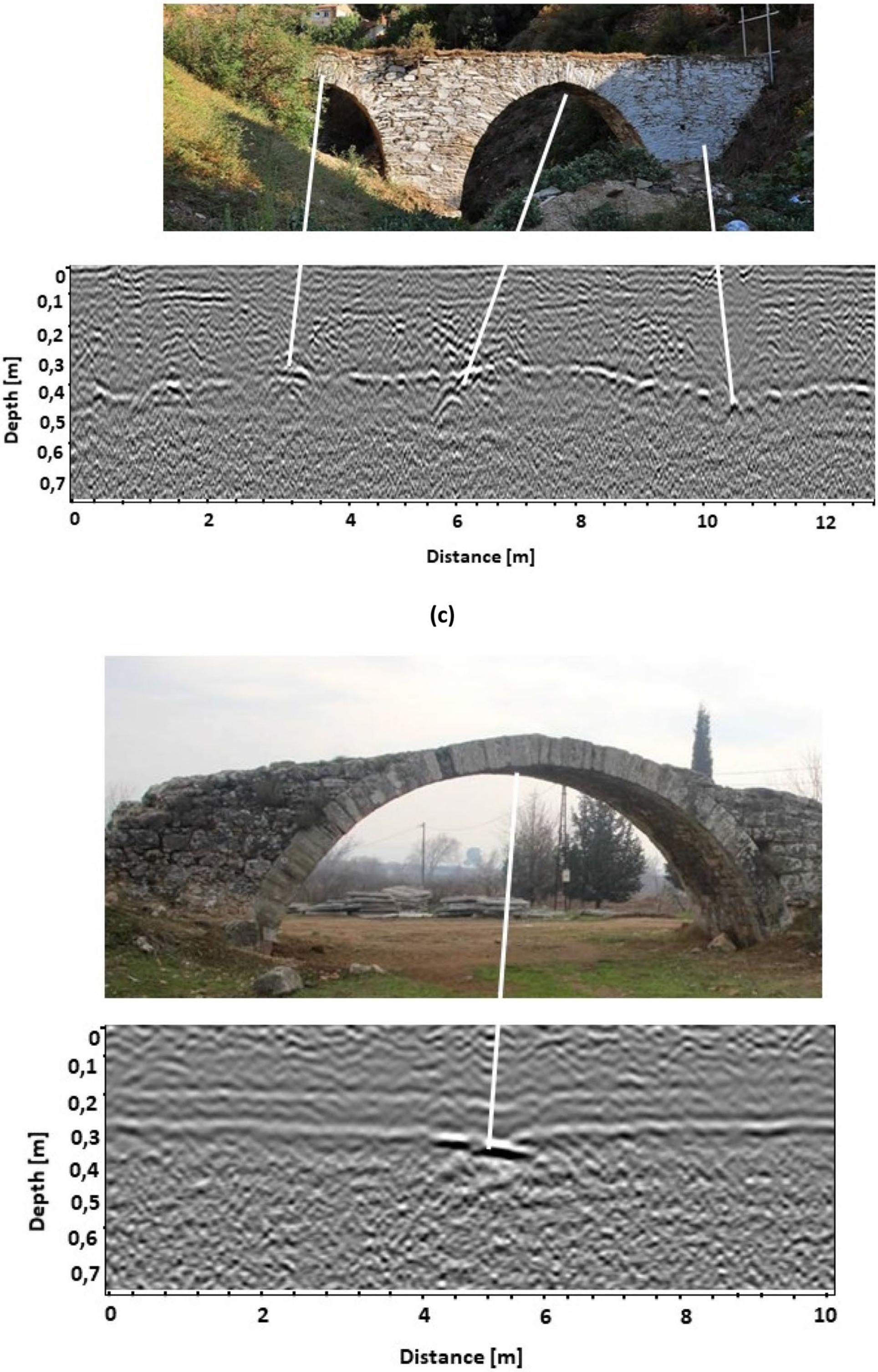
The GPR receiving antenna collected several radar rebounds, which may have restricted and obscured abnormality signals, as can be seen in the GPR radargram shown in Fig. 15. The layers and locations showing potential damage by moisture entry are clearly marked.



(a)

(b)

Fig. 15 Processed GPR Radargram Data and Possible Interpretations **a** Case Study 1, **b** Case Study 2, **c** Case Study 3, **d** Case Study 4, **e** Case Study 5



(c)

(d)

Fig. 15 continued

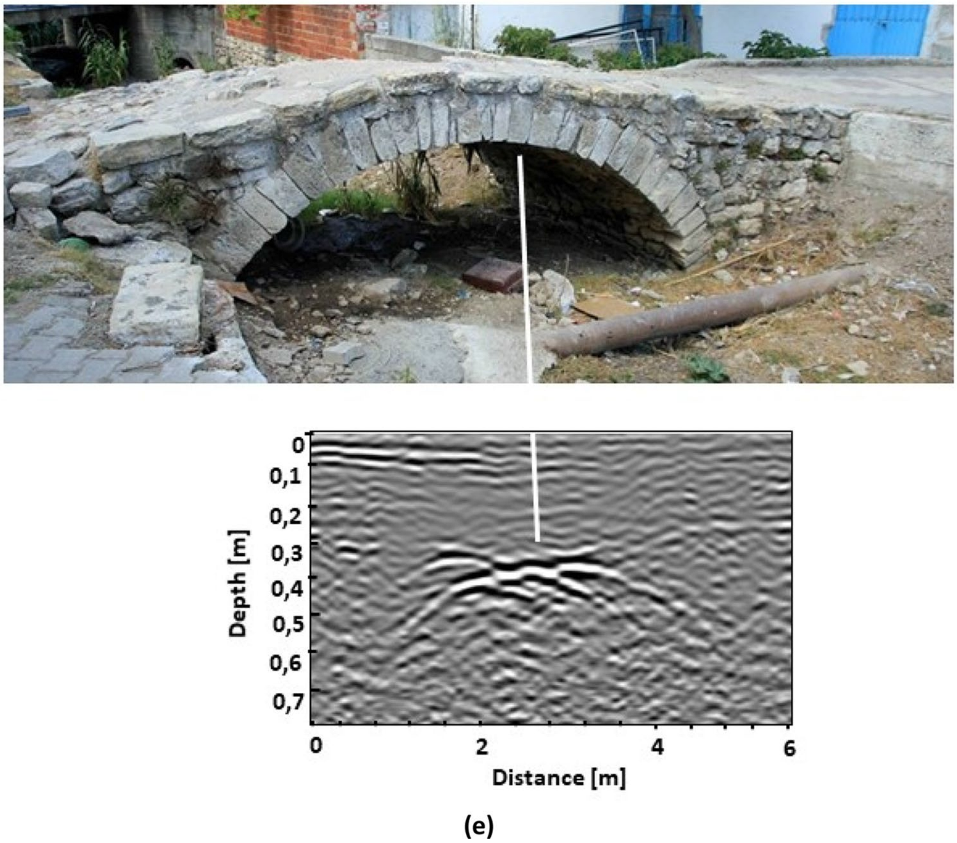


Fig. 15 continued

The facade masonry and the ashlar facing had distinct structural traits while the analyzed piece of the facade had inner and outer stone faces concealing a rubble core. The irregularities detected in the ashlar facing of the case study bridges were probably caused by cracks, voids, or defective mortar.

Thermal imaging

The thermal imaging examination revealed concrete degradation, cover delamination, water seepage, and large fractures. The thermal camera was employed in the historical case study, where the observed ambient temperature was 18 °C and the ambient moisture content was around 48%. The use of this technology showed and corroborated the location of cracks, delamination, and faults that were discovered during the visual inspection (see Fig. 16). The delamination found here represents a case of natural IR active thermography, which is associated with daily temperature variations and the establishment of varied temperature gradients between delaminated and non-delaminated regions (Fig. 16).

In addition, delamination and objectivities of the mural were discovered. The presence of stored heat (see Fig. 16) indicated that sections within the fractures in this location had become separated, necessitating rapid repair work to prevent further degradation and potentially permanent damage.

Discussion

Turkey is situated in a seismically active zone with frequent tremors and occasionally severe earthquakes. The $Mw = 6.9$ earthquake on Samos island struck offshore, causing considerable damage in Izmir, which is around 75 km from the epicenter. Given the short distance between the impacted region and the epicenter, the city center of Izmir suffered an unanticipated level of damage. However, an investigation of the old bridges revealed no earthquake-related damage. Following the earthquake, the historic bridges were considered safe for usage. Consequently, ancient bridges that survived the earthquake were considered viable without the need for emergency intervention.

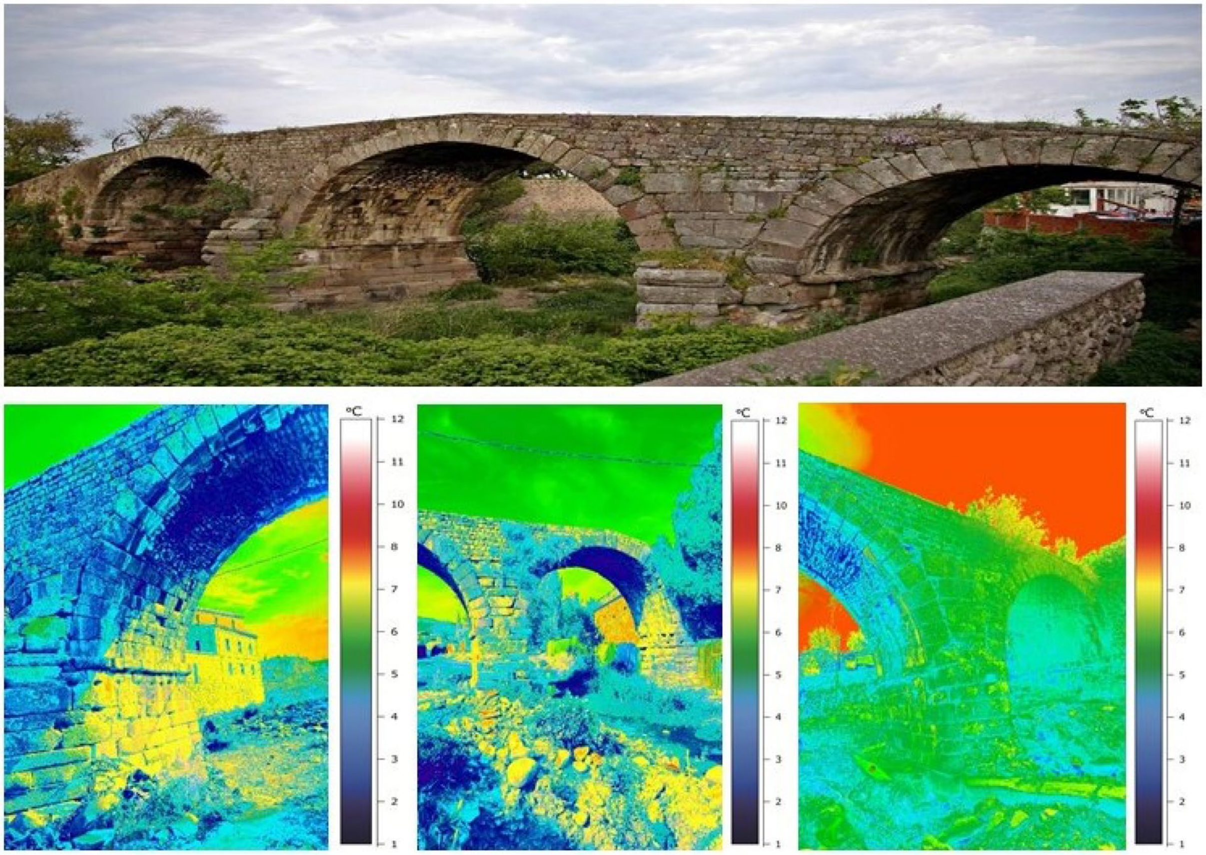
The visual evaluation provides a quick assessment of the ancient bridge's condition from the outside. If any damage, such as cracking or delamination, is discovered, it is recommended that the state of the bridge be further investigated using GPR and Thermal camera technology. The radargrams (Fig. 15) generated by processing the GPR data illustrate the usefulness of two different manufacturers' GPR antennas in giving vital structural information, however they are unable to provide details such as grain size and quality. Thermal imaging (Fig. 16) is a low-cost, rapid method of detecting surface and interior abnormalities. However, environmental conditions such as wind, intense sunshine, and rain can seriously affect the accuracy of this technology.

This study examined a number of historic bridges that are currently in use. Because of the lack of plans or other paperwork for these bridges, structural assessments were conducted to determine their current status. These showed that the majority of the bridge sections need urgent repair. The findings were arrived at by integrating data from three inspection methods: visual inspection, GPR, and infrared thermography in conjunction with FTIR spectral data analysis. In combination, these provided a detailed picture of the bridges' current status, which can guide decisions about essential remedial work [16–18].

The findings indicate the importance of taking a multidisciplinary approach to such surveys, particularly in the case of old bridges with little or no structural documentation. Although the range of approaches available inevitably increases the complexity of such analyses, the technique used in this study demonstrates that such issues can be resolved. The outcome is a combination of NDTs that avoids the need for additional examinations [1, 2, 6].

This approach is not suited for other bridge types such as steel bridges, and thus, the research focused on the assessment of the condition of historic bridges. However, by adapting this system and adding new NDT for specific bridge types, it has potential for adaption to other bridge types. This integrated method reduces uncertainty by pinpointing NDTs that can complement one another, allowing for a full assessment of the bridge's state without the need for extra testing unless found absolutely necessary.

The initial visual assessment of these old bridges revealed, in a cost-effective and straightforward manner, fractures and moisture intrusion across a large percentage of the spans. Following this, two evaluation techniques, GPR and infrared thermography, were used to



(a)

Fig. 16 Position of the moisture, and delamination **a** Case Study 1, **b** Case Study 2, **c** Case Study 3, **d** Case Study 4, **e** Case Study 5

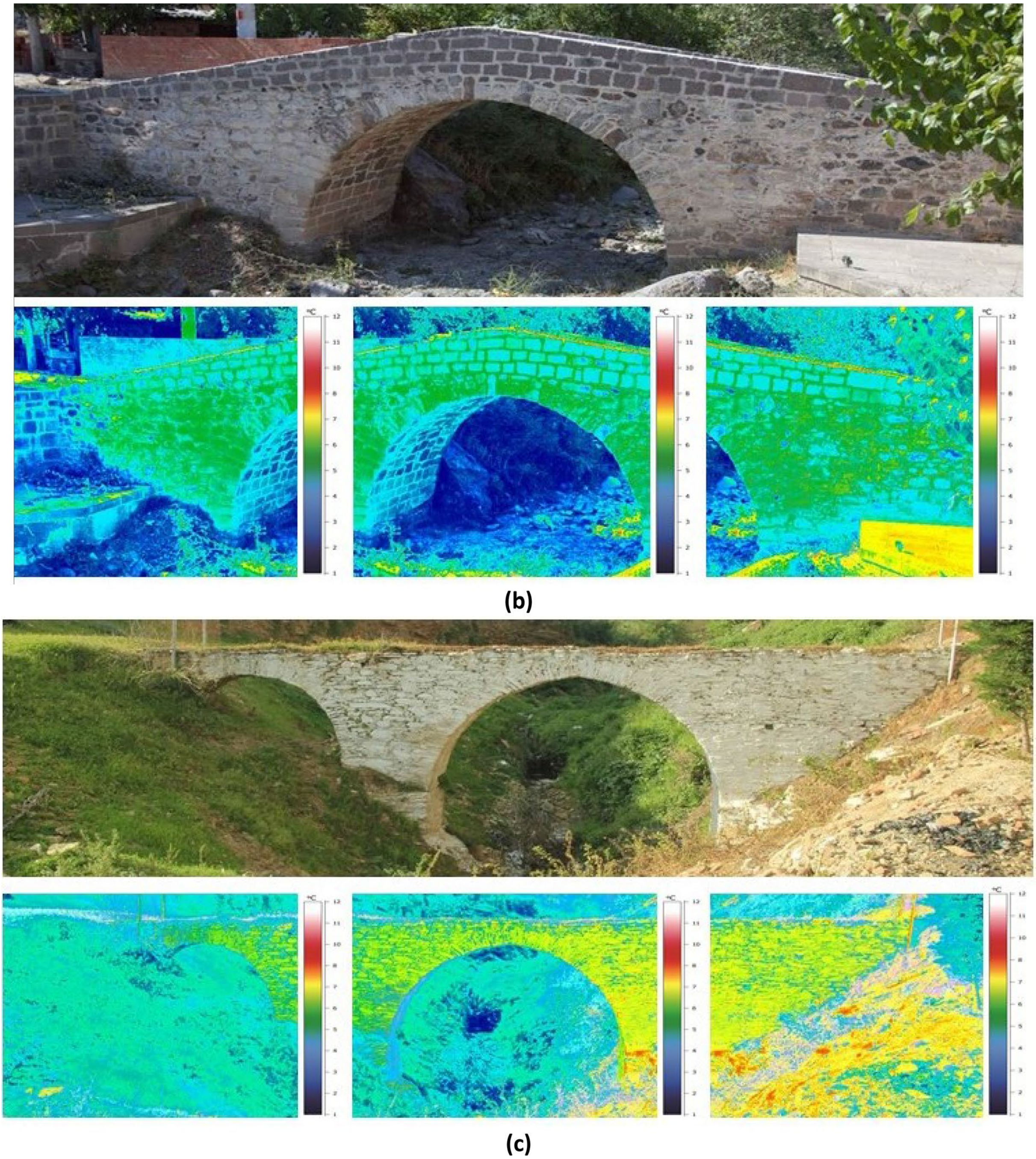
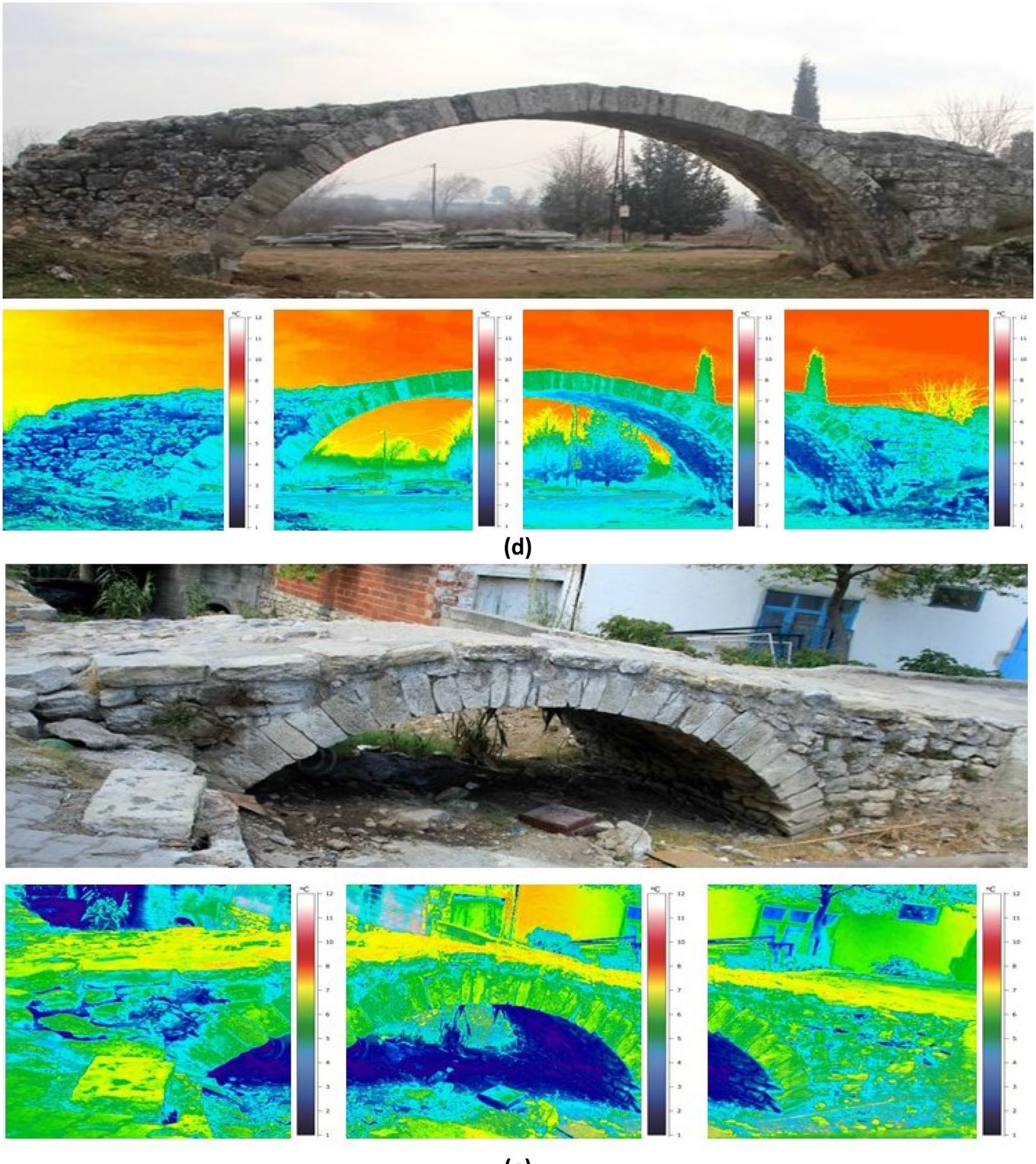


Fig. 16 continued


(d)

(e)

Fig. 16 continued

examine these degradation regions to obtain precise interior data about the exact type of faults and their extent, as well as the bridge's general structural health. While NDTs are normally employed in isolation, this study highlights the need to combine techniques to obtain the maximum possible range of data. Bridge degradation rates, expressed as a percentage decline in condition rating each year, were calculated using previously reported condition rating and age curves. Depending on the state or nation, the condition ratings were generally reflected by a seven-or nine-point grading system. In a comparable seven-point grade system, bridge degradation rates

Table 1 Case Study Bridge inspection Condition rating form (Adopted form [19])

Case Study 1					
Deck		**Support**		**Approach fill**	
Deformation	8	Main damage	6	Settlement and Slump	6
Cracks	9	Support bed	5	Erosion on road platform	5
Masonry Disintegration	8	Loss of elements	2	Erosion in fill	6
Holes and cavities	7	Deformation	5	Overall grade	5.67
Water leakage	8			**Stabilization**	
Overall grade	8.00	Overall grade	4.50	Settlement and Slump	6
				Erosion	5
				Scour in bed level	5
				Overall grade	5.33
Abutment		**Beams**		**Piers**	
Deformation	7	Deformation	8	Deformation	7
Cracks	6	Cracks	9	Cracks	6
Masonry Disintegration	6	Masonry Disintegration	8	Masonry Disintegration	6
Holes and cavities	8	Holes and cavities	6	Holes and cavities	8
Water leakage	5	Water leakage	8	Water leakage	5
Water and debris abrasion	6	Water and debris abrasion	6	Water and debris abrasion	6
Scour in foundation	4	Scour in foundation	4	Scour in foundation	4
Overall grade	6.00	Overall grade	7.00	Overall grade	6.00

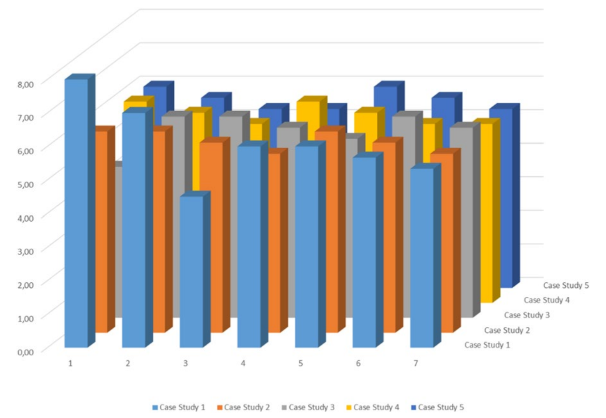


Fig. 17 Case Study Bridge inspection Condition rating graph

typically varied from 0.01 to 0.1 for relatively new bridges and 0.1 to 0.7 for structures over 40 years old.

Table 1 and Fig. 17 exhibit the author's suggested bridge inspection rating card. In a view of concerns over the decay of historic bridge components, and how long the structure can survive without them, several coefficients are applied to identify the components most in need of attention. The inspection-grading card provides condition ratings of bridge components at various levels, as well as an overall bridge grade. Table 1 and Fig. 17 indicate the subgroup circumstances that are considered from visual examination, GPR radargrams, thermal imaging, and FTIR data for each of the components [19–21].

The inspection-grading card provides explanations for the underlying various levels of historic condition rates using FTIR spectral data analysis in conjunction with GPR and Thermal Camera results.

This study demonstrates that the adopted strategy is adequate for evaluating historic bridges (Fig. 17). However, it is less suitable for steel or reinforced concrete bridges. Nonetheless, thermal imaging is applicable regardless of bridge layers. These methods can be tailored to select the most appropriate NDTs for a specific bridge [19, 21–26].

Conclusions

Cracks discovered in certain antique bridges were not attributable to any significant action. The majority of the fractures were pre-existing, and were formed by rainfall, which was the consequence of a long-term chemical reaction in the bridge materials. The earthquake produced no further expansion of the fissures. The most crucial aspect of the Izmir earthquake were increased ground vibrations on soft ground more than 70 kms from the epicentre. The characteristics of the Izmir earthquake were investigated in this article, which included field damage assessments of old bridges and an investigation of ground vibrations with an emphasis on site impacts.

This study investigated five historic bridges in Turkey that are still in use. These specific cases were chosen because of the lack of information about their structures. A detailed technical test was provided by visual inspection, GPR, and infrared thermography with FTIR.

The initial visual assessment revealed considerable cracking and other flaws. The GPR investigation provided further information about fissures, moisture, and recognized soil layers in additional regions. By combining GPR with intrusive testing, it was possible to identify the regions of most concern regarding water intrusion. Finally, infrared thermography was used to detect degradation regions from a distance, such as severe sub-surface cracking and detached parts in the mural areas. This rapid feedback enabled real-time decision-making.

Fortunately, no historic masonry structures in Izmir fell during the October 30th earthquake. However, several structures were severely damaged. Given the present level of earthquake frequency, it is possible to conclude that the damaged structures are unlikely meet the existing seismic regulation's safety requirements. As a result, the earthquake can be seen as a warning, a call to action regarding the weakest structures. This lesson from the earthquake should be taken seriously, and these structures should be upgraded to ensure their future safety.

To the author's best knowledge, this study is the first of its kind. It therefore makes a significant contribution to knowledge in the field. In particular, it demonstrated how an integrated strategy employing a selected set of NDTs for evaluation can provide consistent information about apparent and concealed flaws impacting the structural integrity of ancient bridges. In the absence of surviving documents pertaining to the original construction, this evaluation approach provides reliable information about hidden features, and thus, the most suitable approaches to maintenance. In the present study, this multidisciplinary methodology provided a comprehensive picture of the structural health and future requirements of five historic bridges, with great potential for use in comparable situations. The study thus adds to the body of knowledge and contributes to experts' operational information regarding bridge stability and durability.

Abbreviations

NDT: Non-Destructive Techniques; FTIR: Fourier Transform Infrared Spectroscopy; GPR: Ground Penetrating Radar.

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Author contributions

GK participated in the design of the study, carried out all the analyses and drafted the manuscript. The author read and approved the final manuscript.

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Availability of data and materials

Data available on request from the author.

Declarations

Competing interests

The authors state there is no conflict of interest.

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