

1 UAV Photogrammetry, Infrared Thermography and GPR for 2 Enhancing Structural and Material Degradation Evaluation of the 3 Roman Masonry Bridge of Ponte Lucano in Italy

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11 Abstract

12 This paper presents a case study regarding the cooperative use of non-destructive
13 contactless diagnostic investigations as a tool to aid and assist the degradation
14 evaluation of an iconic Roman masonry bridge: Ponte Lucano in Tivoli, Italy.
15 Specifically, unmanned aerial photogrammetric surveys are considered to
16 perform detailed visual inspections and obtain a geometrical 3D model; infrared
17 thermography analyses are carried out to characterize the thermal surface map of
18 the structure detecting anomalies related to material degradation, such as the
19 presence of humidity; ground penetrating radar investigations are performed to
20 improve knowledge of the bridge subsurface structure. The results of the analyses
21 demonstrate that the integration of mentioned diagnostic tools provides
22 information regarding the degradation state of the stones and its causes, as well as
23 regarding the evolution of the structure from its construction up to the present
24 configurations.

25 **Keywords:** Infrared Thermography; Ground Penetrating Radar; Historic
26 Structures; Material Degradation; Stone Masonry.

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1. Introduction

Historic masonry bridges make up a considerable portion of the historical monumental assets of Italy and of the Mediterranean basin area (see Figure 1) and, still today, play a significant role as a road connection network for both vehicles and pedestrian. However, due to their extensive use and ageing over the centuries, many bridges experience several problems, related to end use changes, development and transformation of the traffic loads to be sustained, development of the safety requirements prescribed by technical standards of different countries, as well as damages and material degradations caused by human and/or environmental actions. Hence, their maintenance is a relevant issue, which involves restoration and structural consolidation activities that should be carried out with a twofold purpose: the structural maintenance for their functionality and the preservation of their historical value.

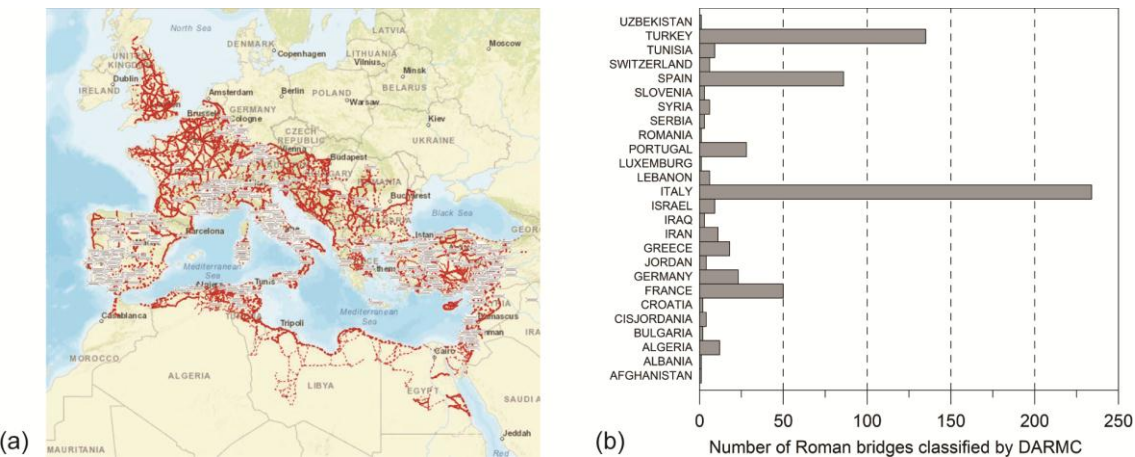


Figure 1. Maps of the Roman bridges classified in the DARMC website [1] (a) and analysis of their location in the Mediterranean basin area (b).

Several scientific contributions related to historical constructions, and more in detail to masonry bridges, are available in literature and propose advanced techniques aimed at analysing their structural performance ([2],[3],[5],[6],[7],[8],[9],[10]) and material degradation assessment ([11],[12],[13],[14]) to achieve suitable consolidation

techniques to comply with the historical value of the construction ([15],[16]). The interpretation of damages and material degradation for numerical modelling is still an open issue due to the complex interaction between geometrical irregularities and uncertainties in material properties, which generally affect the structural behaviour. In this regards, some contributions can be found in literature which consider such effects on geometrical ([17],[18],[19]) or material side ([20],[21]), often through probabilistic approaches and the use of surrogate models.

As a further contribution to the existing literature, this paper presents the analysis activities carried out on Ponte Lucano in Tivoli, Italy. This is a Roman bridge, located along the Aniene river, the largest tributary of the Tiber river, and can be considered as an emblematic iconic structure in synthetizing the needs of structural consolidation and monument conservation. Beside its historical importance, Ponte Lucano has also a significant social value as a symbol of the current state of degradation of the entire archaeological site to which it belongs together with the Mausoleum of Plautii. Therefore, societal interest has grown in recent years demanding for an in depth requalification of the site. Moreover, it should be noted that in the area of Tivoli there are two cultural heritage sites protected by the UNESCO and one by the Italian Environment Fund (FAI): Villa Adriana (built between 118 and 138 A.C., located 1.5 km away from the flood prone area of the Aniene river), Villa d'Este (one of the symbols of the Italian Renaissance, it is a remarkable complex stretching over 4 hectares and only 600 m away from the Aniene river) and Villa Gregoariana (consisting of woods, trails, waterfalls, caves and vegetation that stretches at the foot of the ancient acropolis). In this sense, Ponte Lucano and the Mausoleum of Plautii, situated directly at the Aniene river, are characterized by a major flooding risk, which represents today one of the most significant environmental hazard affecting the area.

The investigation surveys on Ponte Lucano were carried out by means of fully non-destructive techniques, such as Unmanned Aerial Vehicle (UAV) 3D photogrammetric, InfraRed Thermography (IRT) and Ground Penetrating Radar (GPR). Specifically, UAV 3D photogrammetry is considered to enhance the amount of information provided by visual inspections, which represent the gold standard method to evaluate the maintenance condition of a manmade structure. In addition, being the bridge affected by hydro-geological hazards due to Aniene river floods, IRT and GPR are considered as complementary technologies useful to obtain information about surface and subsurface structural features [23]. Infrared thermography and GPR work, indeed, synergistically: thermographic inspections give information on surface temperature, in some cases related to material texture and/or degradation ([24],[25],[26],[27]), while GPR investigates the subsurface structural composition allowing the imaging of material layers and of hidden anomalies or objects [28].

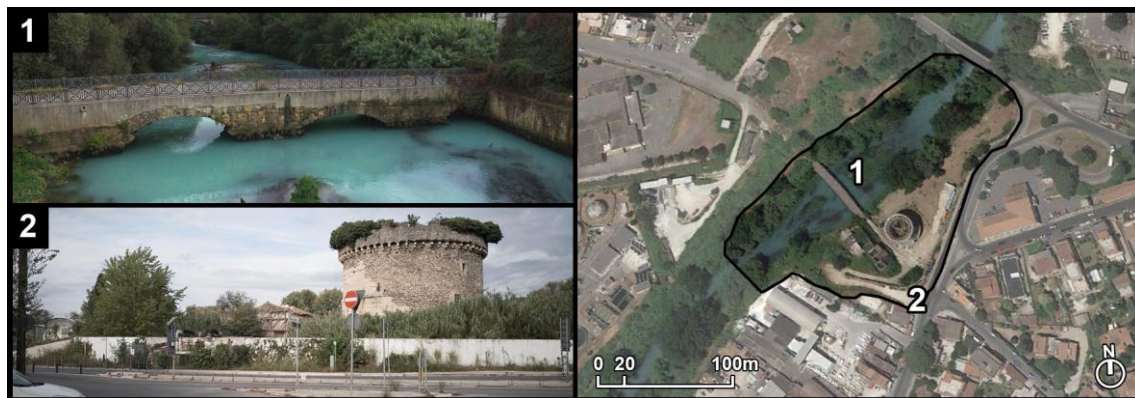
In this frame, it is worth pointing out that UAV photogrammetry, IRT and GPR are well-assessed technologies widespread employed in several applicative contexts ([28],[29],[30],[31],[32]). Regarding architectural heritage assets, they allow to investigate the state of conservation of ancient buildings from historical, archaeological, and structural points of view ([33],[34],[35],[36],[37],[38],[39],[40],[41],[42]). Moreover, specific contributions are focused on the application of such technologies on masonry bridges aimed at assessing their conservation state (without being exhaustive, the interested reader is invited to see the following papers, besides those previously mentioned: [43],[44],[45],[46],[47],[48],[49],[50],[51],[52]), also proposing, only in a few cases, data fusion approaches [53].

In the case study herein tackled, the cooperative use of UAV 3D photogrammetry, IRT and GPR provided useful information regarding the degradation

state of the Ponte Lucano materials and its causes, as well as regarding the structural evolution of the bridge from its construction up to the present configurations. More in detail, UAV 3D photogrammetry allowed a detailed digital mapping of the bridge, covering also those parts difficult to be reached by a human operator, and revealed precious information such as chromatic properties and size characteristics of the entire bridge surface. IRT results corroborated the hypothesis that the present degradation condition of Ponte Lucano is mainly a result of the water retention within its materials. GPR images provided information about the inner material stratification of the bridge and allowed the localization of two buried arch structures, allegedly located in the northern bank and at the Plautii Mausoleum, whose presence confirms the historical-bibliographical hypothesis regarding the construction phases of the bridge.

2. The Ponte Lucano in Tivoli: historical framework and the hydro-geological issue

Ponte Lucano belongs to an important archaeological site comprising the bridge itself and the Mausoleum of Plautii, which was built by the diumviro M. Plautius Lucanus between the 2nd and the 1st Century B.C. The bridge was constructed over the Aniene river and served the road from Tivoli to Rome until the middle of 20th Century. It is 70-80 m long and has a width in plan of about 7.5 m. The Mausoleum of Plautii rests on the east side of the bridge and today, together with all the archaeological complex, results in an advanced state of degradation. Currently, Ponte Lucano is used as a pedestrian bridge connecting the two banks of the Aniene river (Figure 2). The Aniene river is a left tributary of the Tiber. With a length of 99 km it drains a catchment of 1414 km², 683 of which are located upstream of the falls of Tivoli. Firstly, flowing in a narrow valley, it is augmented by new sources between Agosta and Roviano. After the valley, it changes direction, becomes wider and passes several waterfalls upstream of Tivoli.



129

130 Figure 2. Urban setting of the archaeological site and detail images of Ponte Lucano (1) and the
 131 Mausoleum of Plautii (2).

132

133 Throughout the centuries, Ponte Lucano has undergone several restoration and/or
 134 consolidation interventions, as well as reconstruction processes after local collapses
 135 mainly occurred after flood events of Aniene river. Thanks to archival documents, four
 136 main phases can be identified, that affected the structural configuration of the bridge.

137 Phase I (80 B.C. - 540 A.C.) characterized the original aspect of the
 138 archaeological site composed by Ponte Lucano and Mausoleum of Plautii, as
 139 hypothesized by the archaeologist and architect Luigi Canina, with a five-arches bridge
 140 composed by a regular masonry texture connecting the two banks of the river (Figure
 141 3(a)). The following centuries (Phase II, 540 - 1798) were distinguished by several
 142 events, which significantly changed the aspect of the bridge and of the surrounding area.
 143 Among them, particularly noteworthy are: the destruction by Totila of the first arch near
 144 the mausoleum during the Goths invasion in 544 a.c.; Aniene devastating floods
 145 (documented in 716, 1534, 1564, 1589, 1671 and 1740); the fortification of the area
 146 with the construction of a gate tower on the north-west side of the bridge in the years
 147 1180-1189 and of a defense building near the mausoleum at the beginning of the 17th
 148 Century; other reconstruction works carried out from the 14th to 17th Century. In this

period, some drawings illustrate the bridge with three main arches between the mausoleum and the gate tower and another lower arch beyond the gate tower (Figure 3(b)). In Phase III (1798 - 1950) Ponte Lucano is represented with other two little arches in the bank opposite to the mausoleum constructed after the redesign of the river banks started in 1822 (Figure 3(c)). In 1839 other restoration works were carried out on the banks and in the plastering of the parapets till the travertine claddings. In a later time, in the second half of the 19th Century, other works were made with the aim of expanding the roadway to enable also the railway traffic on the bridge, which stopped in 1932. In the second half of the 20th Century (Phase IV, 1950 - 1979), Ponte Lucano showed the four main arches out of the banks, with wooden balustrades at the roadway level (later substituted with steel elements) anchored on the external walls of the bridge, in a progressive state of degradation (Figure 3(d)). After a disastrous flood of Aniene river in 1978 the second arch was damaged and the bridge closed to the traffic. The last restoration and consolidation works began in 1990, characterized by an extensive use of reinforced concrete to create a continuous beam along the bridge, comprising the external walls above the masonry arches and the parapets; moreover, micropiles were drilled and then injected to strengthen the foundations of the arches abutments.

In Figure 4 two historical illustrations depict the structural configuration of Ponte Lucano during Phase II (Figure 4 (a)) and Phase III (Figure 4 (b)), in which the two little arches constructed for the bridge extension on the West side (and closed later during other works) are visible.

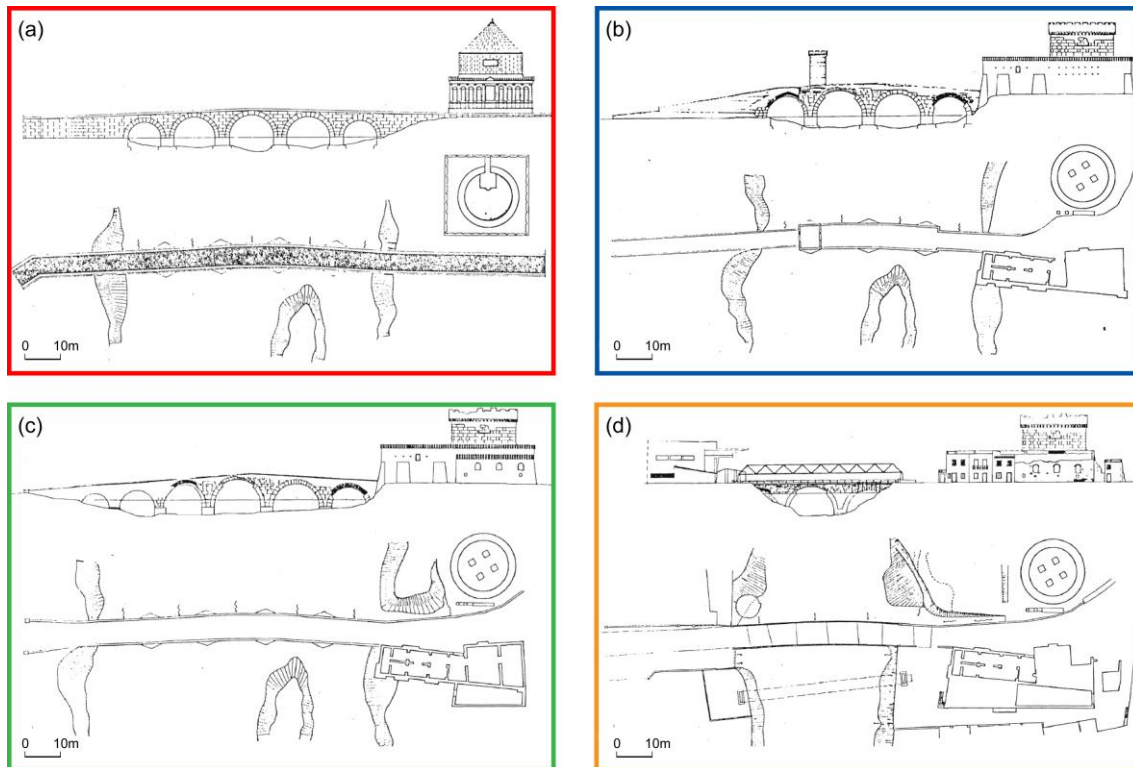


Figure 3. Illustrations of different phases characterizing the structural evolution of Ponte Lucano extracted by archival documents related to a restoration and consolidation design of 1980 [54]: (a) Phase I (80 B.C. - 540 A.C.); (b) Phase II (540 - 1798); (c) Phase III (1798 - 1950); (d) Phase IV (1950 - 1979).



Figure 4. Illustration of different phases characterizing the structural evolution of Ponte Lucano: (a) Phase II: drawing by Daniël Schellinks (1627-1701); (b) Phase III: images of about 1865 attributed to Altobelli & Molins.

As already introduced, today the main problems of the site are related to flood events of the Aniene river. In the period range of 1914-2001, 23 events that caused damages and evacuations were registered. The present configuration of the segment

between Aniene and Ponte Lucano has been determined by the protective hydraulic interventions that ended in 2004, that put the Monumental Mausoleum of Plautii behind a concrete wall of 4 m height (Figure 2), essentially limiting its use and fruition. This work was also ineffective from a hydraulic point of view. As of today, streets and roads have undergone many inundations (see Figure 5) showing that the problem is far from being solved. The intervention invasively affected the existing landscape, disfiguring and obstructing the sight of the archeological ruins. The wall on the left bank traces a new river course, which blocks the inflow towards the riverbed and hence the mausoleum is constantly exposed to the raising waters of the Aniene river. The situation has yet made worse by the flood waves that year by year become stronger due to both the lack of bank maintenance, which caused the shutdown of 3 out of the 5 Roman bridge arches, and the debris carried by the upstream tributaries. Building dams did not solve the problem of floods in the area and as a supplementary intervention water-scooping devices were installed that absorb water from the street and spill it towards the monument and the river itself.



Figure 5. Image of the flood occurred on May 21st 2008.

The Italian hydro-geological management plan (Piano d'Assetto Idrogeologico – PAI) established a risk map of the area based on the Varnes equation the flood risk (R) defined as a function of hazard (H probability of occurrence of the event), the exposition value (E) of the structures located in the site involved and the vulnerability index (V) of the concerning area

$$R = H \times V \times E \quad (1)$$

The values of E and V in Equation (1) must take into account the tangible and intangible values. Tangible values describe monetary damage through direct (physical) water contact or indirect contact with flood water. Damages to the structure and mobile assets of living and industrial buildings are called direct values while indirect values consider production losses, market disturbances and loss of time. The intangible values, as human health and life, environment and cultural heritages, cannot be expressed monetarily, but are physically exposed to harm in case of a flood (direct water contact). Four degrees of sensitivity are used for the evaluation of risk: 1. Very high, 2. High, 3. Medium, 4. Low. The study area has a value equal to Very high (Figure 6).

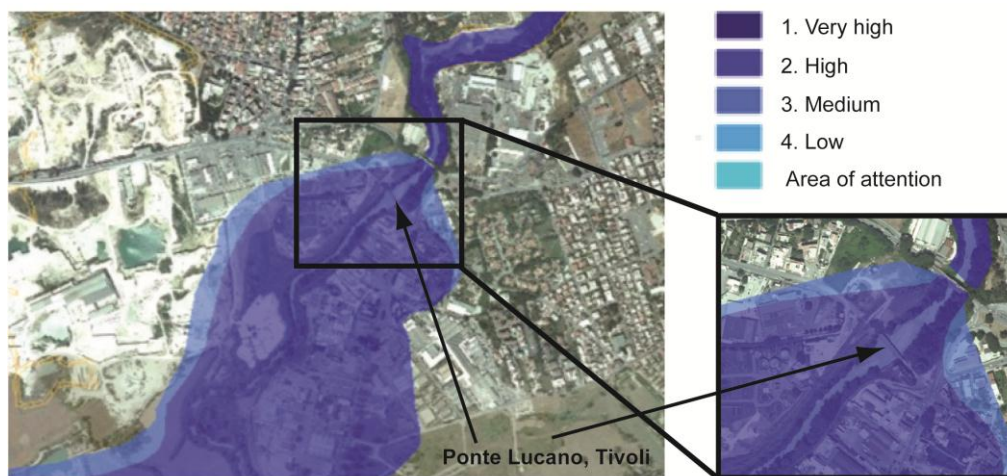


Figure 6. Flood risk map of the area around the Aniene river near Tivoli defined by the Italian hydro-geological management plan, with a specific focus on the area of Ponte Lucano.

3. Multi-Sensing Approach

In order to perform a systematic analysis providing information useful to evaluate the current state of Ponte Lucano, a survey protocol based on the use of different sensing technologies was adopted. This protocol was designed by taking into account the specific hazards affecting the structural integrity of the bridge as well as the needs of gathering data about previous modification/restoration actions, and it involves technologies capable of providing information about surface and subsurface features of the structure under test. Accordingly, three different techniques providing complementary information were considered. Specifically, UAV based photogrammetry was considered to perform visual inspections, IRT was adopted to investigate the thermal behaviour of the different elements of the bridge and GPR was taken into account to reveal buried objects, such as iron reinforcement bars and earth submerged arches.

A brief description of each one of the employed techniques, summarizing the working principle and the adopted data processing, follows.

3.1 UAV based photogrammetry

Aerial photogrammetry is a system of observing and acquiring spatial data through the use of a remotely piloted drone, which can be generally equipped by a digital camera and other sensors, such as lidar camera or spectrometers. The direct results obtained by photogrammetric procedure are the spatial placement of the pixels derived by the analyzed images. Then, the fundamental result consists of the well-known points cloud, represented in the 3D space by a series of X,Y,Z coordinates. As explained in several documents available in literature (e.g. [55]), the structure from motion technique requires the making of multiple shots by different points of view and directions, in order to localize each observed point. With respect to the standard photogrammetry, working

with UAV based photogrammetry, further parameters must be considered, as the shutter speed of the drone camera, the number of photos per second and the flight speed. These parameters must be defined on the basis of the percentage of desired overlap or the space between two shots. The scale definition depends on the Ground Sample Distance (GSD), which represents the distance between the center of two consecutive pixels or, alternatively, the amount of the observed structure included in one pixel. After the definition of GSD, the second phase of the aerial photogrammetric survey is the definition of a polygonal lattice that is synchronized by a remote device to the drone. In order to achieve a correct georeferenciation of the processed points, the position of each frame is generally improved by the positioning of physical markers on the structure that are localized through a Global Position System (GPS) station. The GPS coordinates of each marker are used as reference points in the processing of all the images. In this work the software Agisoft Photoscan was used.

The results of the graphic processing is a point cloud, that can be meshed and texturized using the same images previously processed, so that a 3D model characterized by the same dimensions, positioning in the georeferenced space and colors of the actual structure is obtained. The 3D model allows to gain several information, as well as geometrical, material and degradation surveys. The geometrical data are directly related to the points coordinates and, through further elaborations, accurate drawings (e.g. plan, elevations and sections) can be obtained also in the case of irregular structures. Concerning the constituent materials, significant advantages are observed in the case of inaccessible structures, where direct visual inspections are not allowed. Finally, since the 3D model presents a texturized mesh with an actual distribution of colors, the use of image tools, even available in the more classical image processing software, allows us to obtain a detailed map of material degradation,

especially when different colors with own specific thresholds can be simply associated to the observed degradations.

3.2 Infrared Thermography

Infrared thermography is a well-known fully non-destructive testing method, which detects infrared energy emitted from bodies, converts it to temperature, and displays a map of the surface temperature distribution [56]. Concerning the applications on degraded materials, if no heating is applied, differences in thermal distributions can be associated to the presence of anomalies in the composition of the materials, which are in some cases related to pathologies of materials and structures ([25],[57],[58]). Being the analysis strictly related to the temperatures of the bodies and the heat flux through them, it is generally recommended, in the cases of civil structures and infrastructures, to carry out the investigation in different environmental conditions, with or without direct solar radiation and in different times of the day. Differences in surface temperature, may also be useful to reveal the presence of buried voids and lacunas that are not visible through optical inspections.

3.3 Ground Penetrating Radar

GPR is an active sensing technology that exploits microwaves capability of penetrating non-metallic materials to perform non-invasive surveys devoted to detect and localize hidden targets, such as subsurface material interfaces and localized objects. Similar to any conventional radar, a transmitting (*Tx*) antenna radiates an electromagnetic signal into the probed medium, and when the radar wave impinges on a target (i.e., an electromagnetic perturbation occurring into the probed medium), part of the energy is reflected/backscattered and captured by the receiving (*Rx*) antenna with a time delay with respect to the transmitted signal. The output of a GPR survey is an image, referred

to as radargram, which provides a coded representation of the investigated scenario, wherein localized objects appear as hyperbola whereas material interfaces as constant reflections of the signal along the scanning line [28]. Moreover, the radargram is affected by undesired components, such as the signal due to the direct coupling between the T_x and R_x antennas, the measurement noise and the clutter, which may affect its informative content. Therefore, in order to improve targets visibility and, thus, the radargram interpretability, filtering procedures devoted to reducing the effects of the undesired signals are commonly used [28].

The raw data collected at Ponte Lucano were processed by means of the following procedures, listed according to the order in which they are applied:

- DeWOW: subtraction of the mean as computed for each one of the collected time-dependent waveforms;
- Zero timing: setting of the actual starting time, t_0 , of the observation time window;
- Time gating: selection of the portion of the observation time window where the target response is expected; this procedure allows us to erase the direct antenna coupling and clutter signals occurring outside the time windows portion of interest.
- Linear Gain: compensation of the effects due to the geometrical spreading and the electromagnetic losses acting on the microwave signal propagation into the probed medium; this operation is useful to emphasize the response of deeper targets and to make it comparable with that of shallower ones.
- Band pass filter: low and high frequency components of the signal are filtered out; specifically, only the portion of the signal spectrum that is not lower than 3 dB of its maximum value is taken into account.

4. Testing results

4.1 UAV photogrammetry based analysis

The geometrical survey of Ponte Lucano was carried out by means the most modern techniques of 3D photomodelling and UAV based inspection, which have been characterized by a continuous growing interest during the last years in application to historical structures. The UAV inspection was performed using a DJI Phantom 3 Standard whit 1/2.3'' CMOS Sensor and 20 mm (35 mm format equivalent) f 2/8 lens. Four flights were planned in order to exploit as much as possible the better diffused light conditions for each side. For the North front and the deck of the bridge a morning time slot was chosen, while the afternoon time slot was chosen for the South front. The shots were made on the nadir direction for the deck and on the orthogonal direction to both North and South fronts. Moreover, another series of shots with inclined direction with respect to the horizontal were taken along the development of the bridge in order to superimpose the markers placed on the deck. The 3D photogrammetry procedures allowed to obtain a dense points cloud and thus a 3D model of the bridge, from which orthophoto-plan images on the horizontal direction of the two fronts and the deck plan were extracted (Figure 7). The geometrical survey and the orthophoto-plans obtained by the points cloud were the bases for the analysis of the constituent materials and of their degradation state, respectively. In order to simplify the following descriptions, the arches have been numbered from I to IV starting from the West abutment.

In Figure 8 a manual classification map of the main materials is illustrated, in which the sequence of the restoration and/or reconstruction processes described in Section 2 can be identified. Starting from the East side, Arch IV consists of several materials: on the North front there is an arch made of travertine scales, while on the South front the arch was covered with a mixture of travertine filler and epoxy during the

last restoration works. Arch III, made of travertine squared blocks, seems to be the one belonging to the original construction.

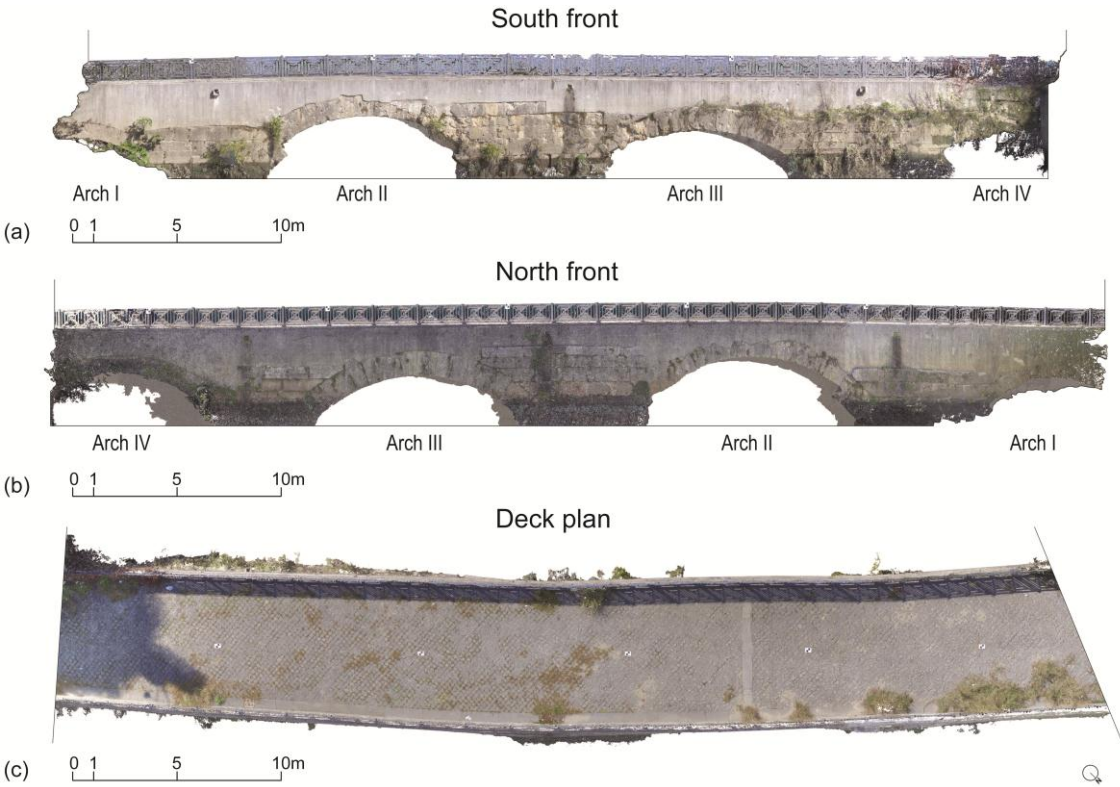


Figure 7. 3D modelling of Ponte Lucano obtained by photogrammetry technique: view of the South front (a), the North front (b) and the deck (c).

Arch II, in fact, even if constituted by travertine squared blocks, presents large blocks at the impost of the arch, what suggests that in a certain period of the past the arch was rebuilt to increase the span. Arch I has a singular aspect, being composed by several arches also with different shapes that have been constructed throughout the centuries. The external arches that are visible today date back to the restoration works of the 19th Century and are made of brick masonry. The external walls of the piers are made of big travertine blocks and, finally, the continuous strip of reinforced concrete material is placed above the arches and the piers along all the bridge.

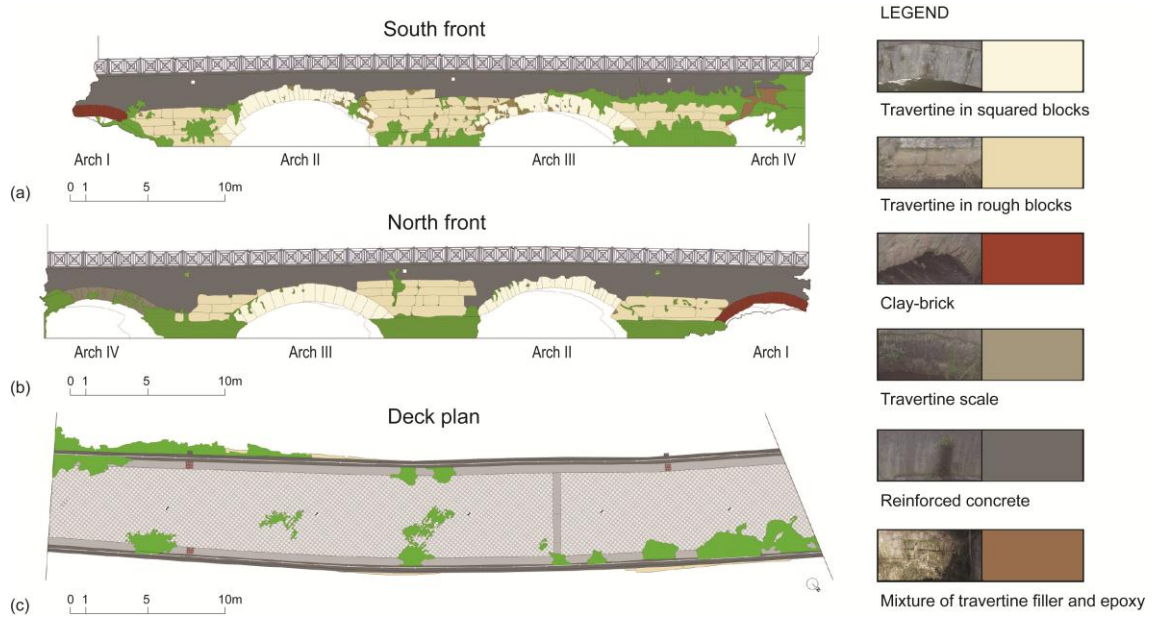


Figure 8. Map of the constituent materials observed on the South front (a), the North front (b) and the deck (c) of Ponte Lucano.

The significant heterogeneity of the constituent materials determines, as a consequence, a variety of degradations affecting them. In order to carry out a classification of the material degradations consistent with the scientific literature, the analysis was referred to the ICOMOS glossary on stone deterioration patterns, which actually represents «an important tool for scientific discussion on decay phenomena and processes» and «an excellent basis for tutorials on stone deterioration» [59]. In Figure 9 a map of the main degradations observed on the structure, obtained through an automatic color mapping procedure as explained in Section 3.1, is illustrated. As far as it concerns “Discoloration and Deposit” category, both black crusts and superficial deposits are visible on the travertine stones, together with material losses related to both the impact of materials during flood events and internal stresses which could have been generated by different causes, namely thermal stresses, increase of active loads and more. The concrete material on the other hand is mainly affected by a dark patina related to the water percolation from the deck level and, consequently, by a biological

patina, which is more widespread on the North front. On the other hand, the South front, too longer exposed to the sunlight, is characterized by a significant presence of vegetation that would require constant maintenance activities.

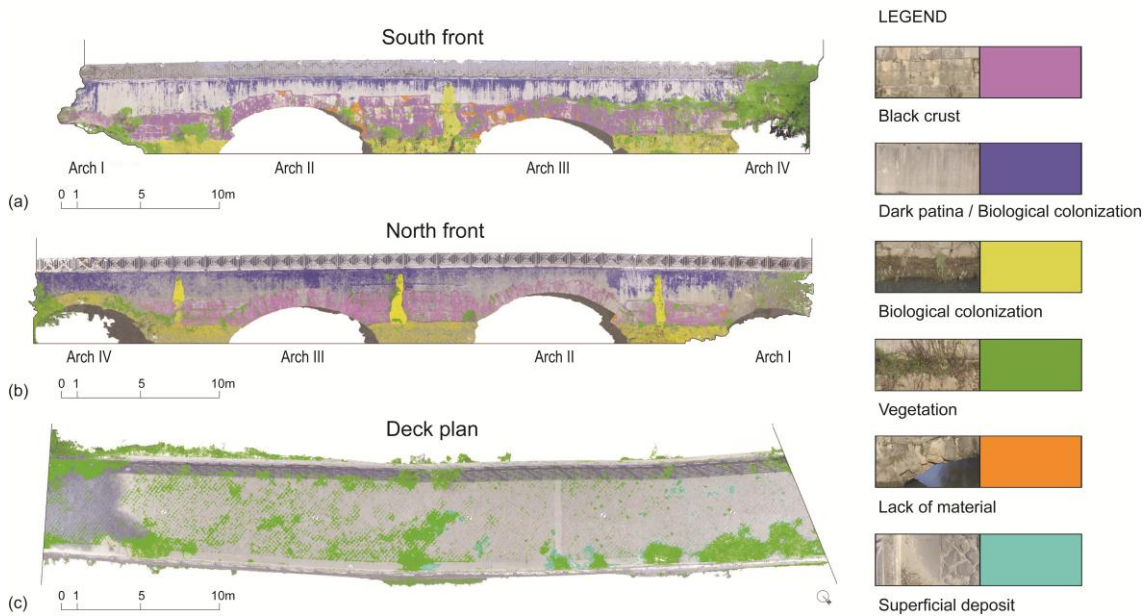


Figure 9. Map of material degradations observed on the South front (a), the North front (b) and the deck (c) of Ponte Lucano.

The black crusts can produce, over time, serious injuries or rifts caused by the sulphatation of limestone elements or a bad surface thermal distribution. Moreover, the high concentration of humidity in the air and the poor quality of the water of the Aniene river have favored the deposition of dust amplifying the black crusts. Equally, the dark patina of the concrete material has increased the risk of thermal inhomogeneity which can generate, with the concentration of humidity during the day, surface cracks or detachments of material. In addition to the above, the presence of small vegetation, grown between the joints of natural stones, has amplified the risk of splits. The mutual interaction of the material degradation can cause through the years significant problems on the overall stability, especially when the bearing structural parts are particularly

involved. For example, the continuous loss of the material in the vaulted structures changes the load path on the piers, which could lead to different settlements other than to the collapse of the vaults.

4.2 Thermographic investigations

Thermographic investigations allowed to better understand the previously described state of degradation of Ponte Lucano, especially in regards to the presence of humidity. The test campaigns were carried out in two days of January 2019 at different times, by using an infrared camera model Testo 885-2 (resolution of 320x240, thermal sensitivity <30 mK at 30°C). The first inspection was made on January 26th at 11.30 a.m. in sunny weather condition and with an ambient temperature of 13°C; the latter on January 29th at 05.00 p.m. with similar environmental conditions, but without solar radiation, with an ambient temperature of 9°C. Heavy rainfalls occurred during the days between the two testing campaigns. In both campaigns the South and the North front of the bridge were analyzed as a whole, while more detailed images were shot to Arch I and Arch IV, more precisely from the North side and the South side, respectively, as depicted in Figure 10. As already observed in Section 4.1, the South side of the bridge is affected by a more advanced state of degradation, in particular of black crust, lack of material, vegetation and biological patina diffused both on the masonry and on concrete surfaces (Figure 11(a)).



Figure 10. Location of the cones of vision used in thermographic investigations.

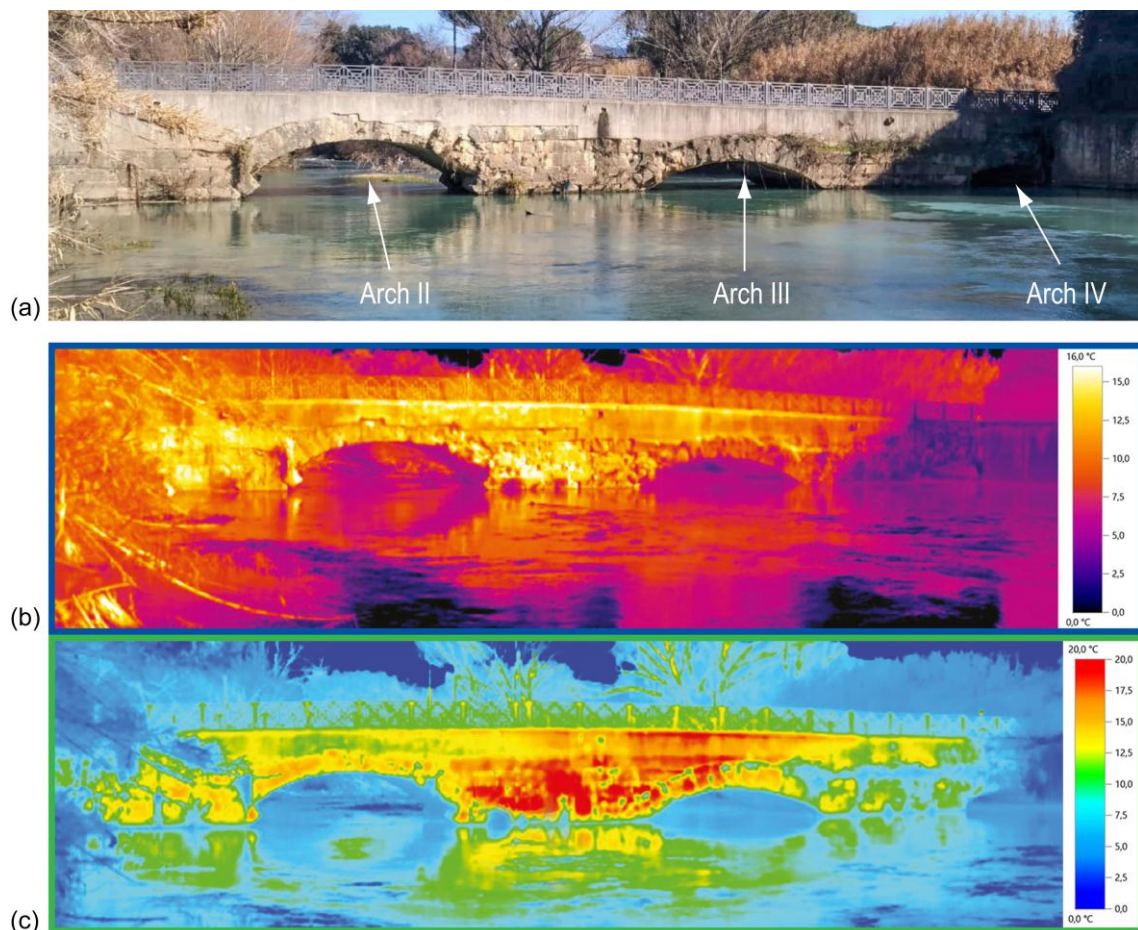


Figure 11. (a) Image of the South front of Ponte Lucano. (b) Thermal image with solar radiation (11.30 a.m. of January 26th). (c) Thermal image in absence of solar radiation (05.00 p.m. of January 29th).

Figure 11(b) shows the thermal image of the South side of the bridge in the morning with direct solar radiation (first campaign). The irregular temperature map is also evident in the concrete surface above the masonry arches, highlighting the zone of the bridge that is mostly affected by humidity retention. In the masonries, the irregularities in temperature ($\pm 5^{\circ}\text{C}$) can be observed in correspondence to the black crusts and lacks of material, in which the gradient of thermal stresses can exacerbate material degradation in relation to the presence of humidity due to freeze/thaw cycles. Moreover, the presence of vegetation can induce significant thermal stresses on the masonry, which are more emphasized in the case of dry vegetation with respect to the alive vegetation, owing to passive heat reduction properties that smooth the differences in temperature. On the other hand, the alive vegetation can lead to the increase of mechanical stresses induced by the roots developed in the joints between the mortar blocks and in the lacks of material. Figure 11(c) depicts the temperature map in absence of solar radiation (second campaign) and after rainy days. The pier between Arch III and Arch IV exhibits a lower temperature, probably due to a more significant presence of water inside the structure and a lower exposure to sunlight with respect to the central pier. The irregularities in temperature (of about $\pm 3^{\circ}\text{C}$) are locally present in Arch III, which results the most degraded one, and on the longitudinal development of the concrete wall, revealing the parts of the bridge where the water flows may be prevented. More detailed images obtained from Position 2 (Figure 10) of the South front of the bridge (Figure 12(a)) and of Arch IV on the East abutment (Figure 12(b)), shot during the first and the second campaign, respectively, highlight the aspects described above. The main aspect worthy of note is that Arch IV on the right is constantly in the shade, due to the presence of the nearby structural bank, which is higher than the arch, preventing the direct solar radiation during the whole day. The surface temperature is

not homogeneous both in the morning and in the afternoon, with clearer gradients in the material of the two central arches and in the pier between them, due to a more prolonged exposure to sunlight of the left arch. Moreover, the presence of a drainage duct in the adjacent corner between the embankment and the first arch on the right amplifies the thermal heterogeneity on the area.

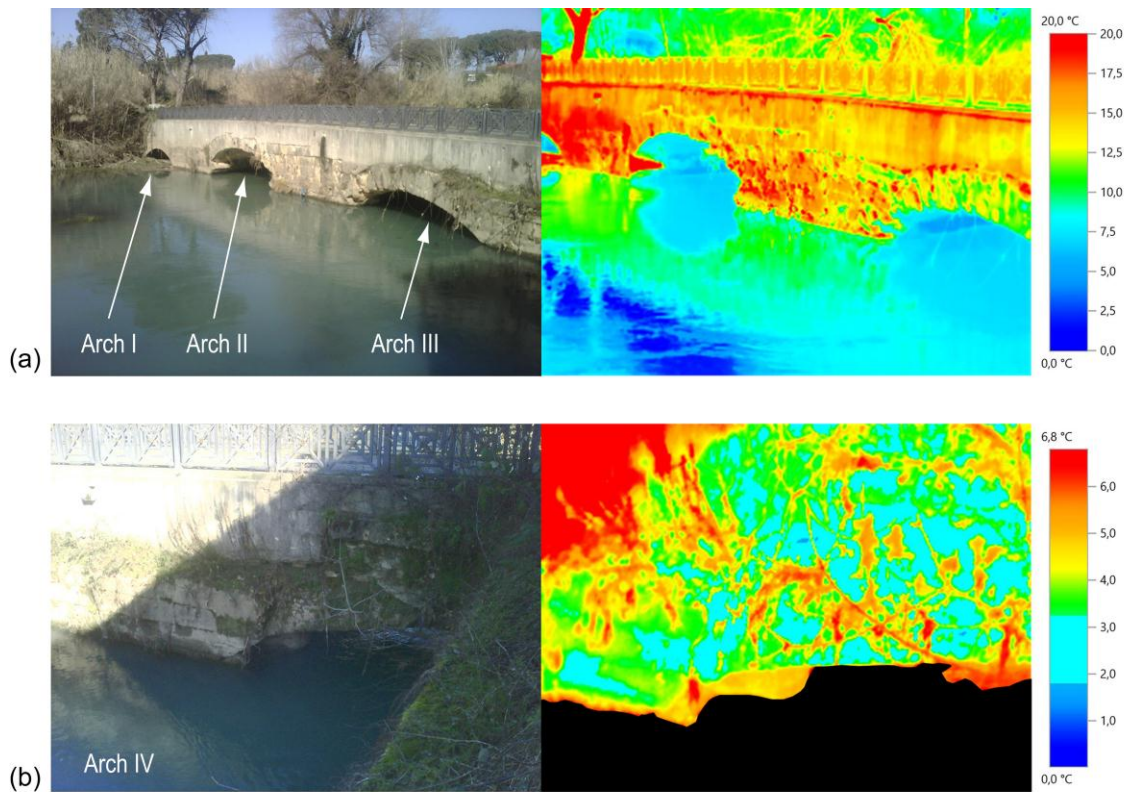


Figure 12. (a) Photographic and thermal image of the South front of Ponte Lucano shot from the Position 2. (b) Photographic and thermal image detail of the arch near the East abutment of the bridge.

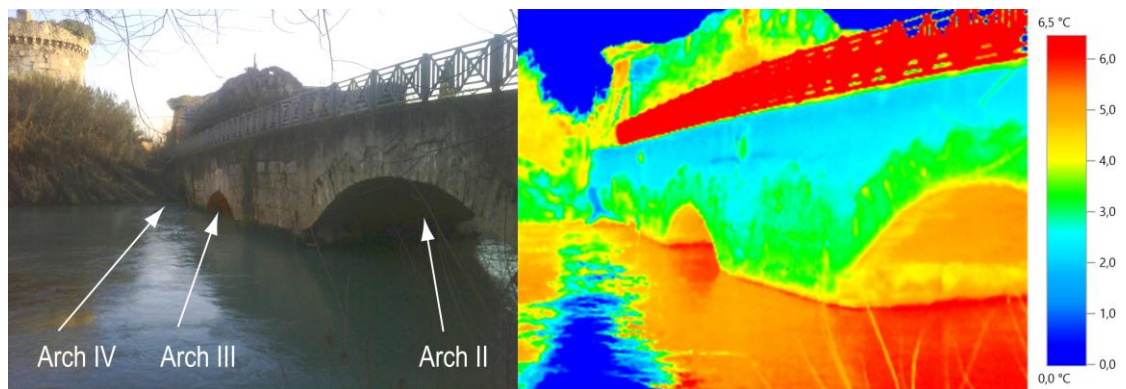


Figure 13. Photographic and thermal image of the North front of Ponte Lucano shot from the Position 4.

Figure 13 shows the thermal image of the North side of the bridge, as shot in the morning (first campaign), that remains in the shade almost all day long. The temperature map is more homogeneous in the constituent materials, mainly the travertine stones and the concrete, besides the steel balustrade. The concrete surface appears to be colder than the other materials (of about 2-3°C), mainly for its lower thermal conductivity, but also for the presence of a widespread biological patina, which particularly affects the porous surfaces. Other cold parts are visible in correspondence to the black crusts and in the areas where biological patina cover the stones. As already observed in the previous Section, the North front of the bridge appears to be less degraded with respect to the South front in terms of lacks of materials and presence of vegetation, confirming that the continuous exposure to solar radiation favors the growth of vegetation, while a strong presence of humidity combined with freeze/thaw cycles creates quite unfavorable conditions for material conservation. In Figure 14 a detailed image of the brick masonry Arch I, near the West abutment, highlights the presence of local damages, both on the concrete wall and on the brick masonry arch, probably due to the hits of large woody debris occurred during flooding events.

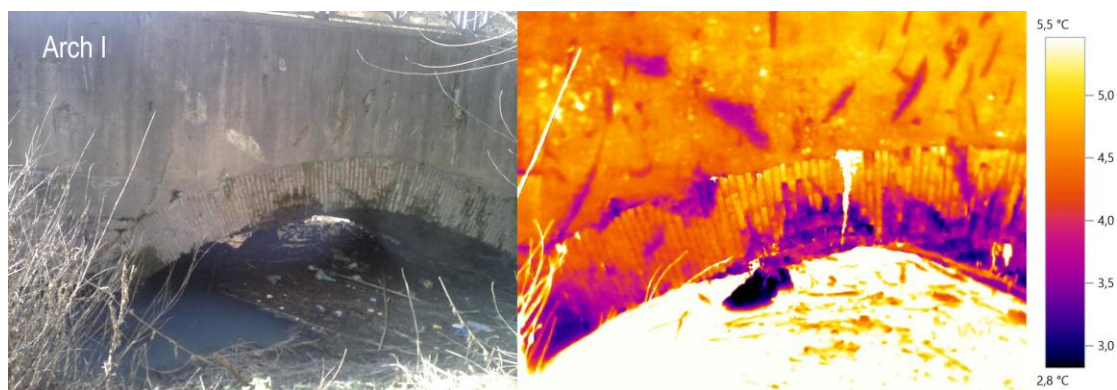


Figure 14. Photographic and thermal image detail of the brick masonry Arch I, near the West abutment of the bridge, shot from the Position 3.

4.3 GPR surveys

The GPR survey was carried out by using the time domain, IDS manufactured, TH DUAL-F HI-Mode GPR system equipped with a single fold, shielded, dual frequency antenna, whose nominal central frequencies are 200 MHz and 600 MHz. Data were gathered along the entire path of the bridge, whose length is about 110 m, by considering a proper spatial offset, dx , among the measurement points along the trace and a certain observation time window, Δt . Specifically, these quantities were $dx = 0.0352$ m and $\Delta t = 256$ ns for data at 200 MHz and $dx = 0.0176$ m and $\Delta t = 128$ ns for data at 600 MHz. Both the data sets were elaborated by means of the same processing chain as described in Section 3.3. The processing parameters are summarized in Table 1 where t_0 is the zero time, t_{tg1} and t_{tg2} denote the portion of the time windows selected by the time gating and f_{min} and f_{max} are the minimum and maximum frequencies of the selected signal spectrum.

Table 1: GPR data processing parameters

	t_0	t_{tg1}	t_{tg2}	f_{min}	f_{max}
200 MHz	15 ns	16 ns	116 ns	140 MHz	370 MHz
600 MHz	9 ns	9 ns	108 ns	250 MHz	650 MHz

Figure 15 (a) shows a plan view of the GPR trace, where P1 and P2 denote the limits of Ponte Lucano as it appears nowadays, i.e. after the last restoration actions; the pointer B indicates a visible leucite or basalt stone block; a1 and a2 identify the west and east sides of an extended buried anomaly, which can be observed into the filtered radargrams at 200 MHz and 600 MHz, shown in Figures 15(b) and 15(c), respectively. Let us note that the vertical axis provides the depth instead of the time and the time-

depth conversion was computed by assuming an average relative permittivity equal to 9. Such a value was fixed according to the reference relative permittivity values given in literature for the materials of the bridge, which is mainly made of concrete, travertine and clay bricks [28].

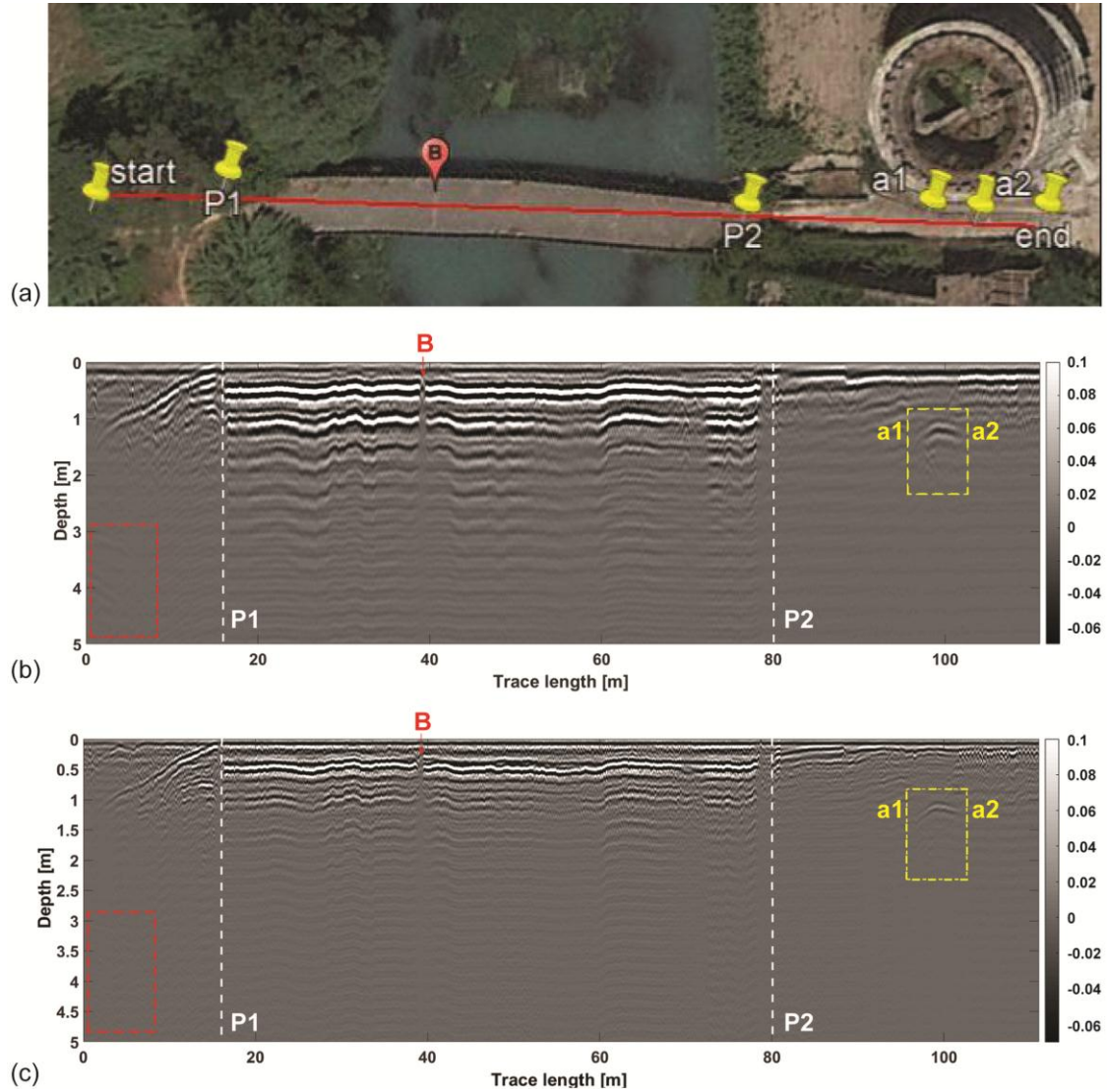


Figure 15. GPR survey: (a) Plan of the GPR inspection with indication of the strating and the end points of the trace covering the entire bridge; (b) 200 MHz filtered radargram; (c) 600 MHz filtered radargram. In the figures, P1 and P2 denote the limits of Ponte Lucano as it appears nowadays, the pointer B indicates a leucite or basalt stone block, while a1 and a2 identify the west and east sides of an extended buried anomaly, visible in both the filtered radargrams.

As it can be observed from Figure 15 the filtered radargrams at 200 MHz and 600 MHz provide comparable images wherein several subsurface features appears, of course

with a different spatial resolution. The only significant difference is the deep reflections denoted by the red box, which do not appear clearly into the 600 MHz filtered radargram and are due to geological settlements.

The vertical white dashed lines appearing in Figure 15 identify three main regions of the investigated area. In particular, the middle region, from $x = 16$ m to $x = 80$ m, corresponds to the bridge part with the three visible arches over the river, while the other regions, i.e. for $x < 16$ m and $x > 80$ m, correspond to the West and East access regions to the bridge. The middle region and the East access of the bridge were restored in the early 90s. The yellow box denotes an extended object located in correspondence of the Mausoleum of Plautii.

Since the 600 MHz radargram allows a better spatial resolution, while assuring of reaching a depth of 2.5 m, i.e. the portion of the subsoil wherein the anomalies mainly occur, we focus the attention on it. In Figure 16(a)-(c) we show the above identified bridge portions separately by limiting the penetration depth at 2 m.

Figure 16(a) corresponds to the North side of the bridge and shows the presence of buried structures, which could be the structural elements of the ancient bridge covered by the deposit materials of the river banks. Specifically, two deck levels are visible. The flat one, highlighted by a white line, is detected in the entire radargram portion at a depth of about 0.1 m and represents the current level. The oblique one starts at $x = 2$ m with depth decreasing from 1.5 m to 0.1 m for increasing x values and corresponds to the old deck level of the bridge. Moreover, below the old deck level, several widespread scatterers appear, including a strong flat reflector extended from $x = 11$ m to $x = 15$ m at a depth of about 1 m. These deep electromagnetic anomalies could be related to ancient structural parts of Ponte Lucano not anymore visible as well as material deposits due to the restoration actions performed during the bridge history. In

particular, they could denote buried and filled arches as well as the pier between the buried arches and the pier at the beginning of the actual bridge portion. Such an interpretation is supported by the historical images of the bridge (e.g. see Figure 4(b)), which show that Ponte Lucano was made by two filled arches. The buried arches and piers are sketched in Figure 16(a) through dashed white lines.

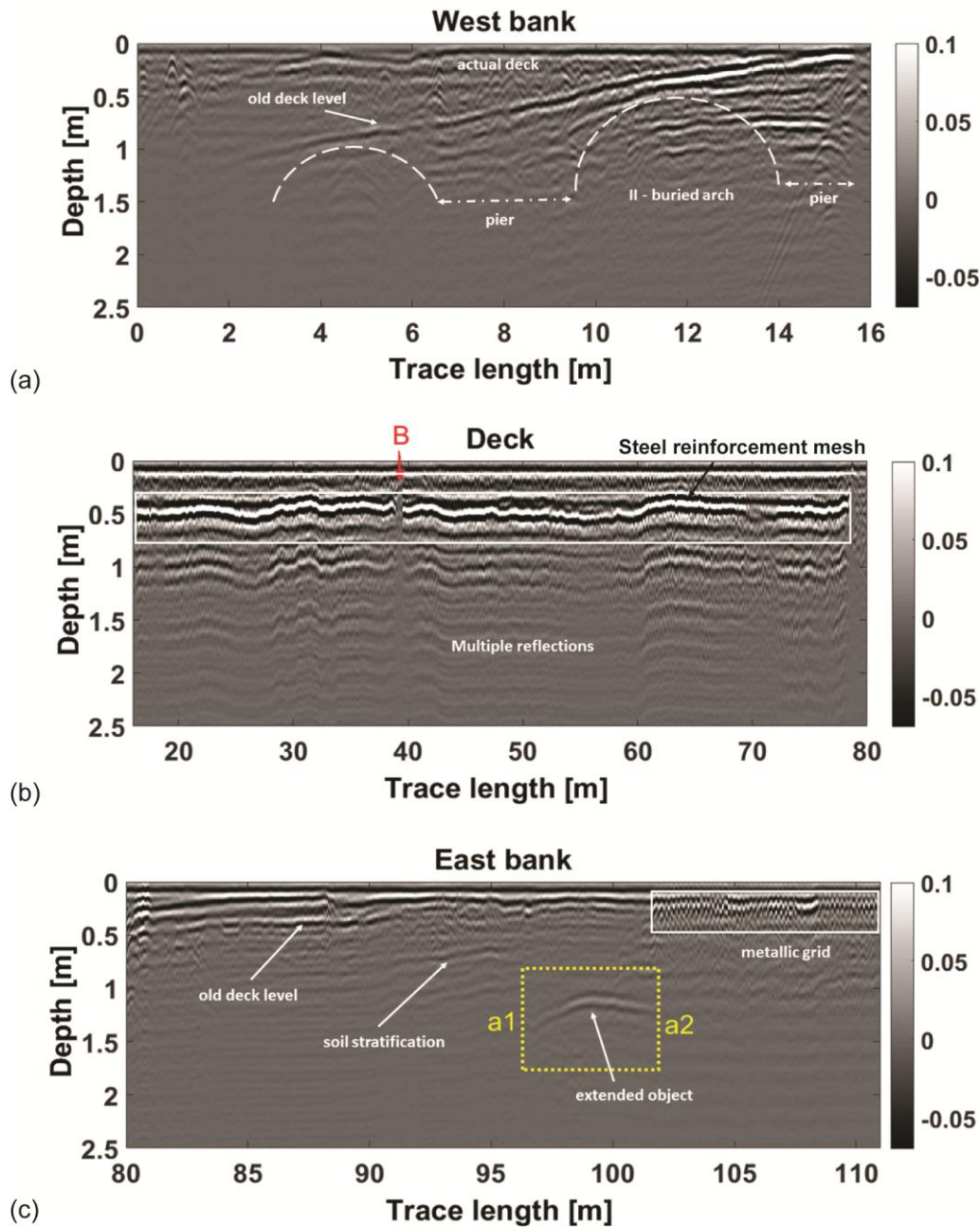


Figure 16. Portions of the 600 MHz filtered radargram: (a) West bank; (b) Actual deck; (c) East bank.

Figure 16(b) shows the radargram portion corresponding to the current out-of-banks bridge, allowing the localization of the deck level and the arrangement of the stone pavement, as well as of the concrete reinforcement structure, which appears at a depth of about 0.5 m. In addition, the strong discontinuity at $x = 39$ m corresponds to an absence of recorded signal due to the presence of a leucite or basalt stone block on the deck level, which is observable by means of a visual inspection and does not permit the propagation of the signal into the medium. On the other hand, the metallic reinforcement structure, positioned during the last restoration actions, generates multiple reflections and does not allow the detection of the bottom of the deck and the position of the arches. This happens also if the 200 MHz radargram is considered (see Figure 15(b)).

Figure 16(c) shows the radargram corresponding to the East side and in its first part, i.e. for x around 80 m, the abutment at the end of the bridge appears. Moreover, the old deck level of the bridge appears at x ranging from 82 m to 102 m at a depth of about 0.4 m, while the presence of a reinforcement metallic grid appears from $x = 102$ m up to the end of the radargram at a depth from 0.20 m to 0.50 m. Probably, this metallic grid was installed during a previous structural consolidation work devoted to facilitate heavy vehicle traffic. Going deeper and, in particular, in the middle of the investigated area at a depth equal to 1 m, two parallel interfaces are recognizable, which can be identified as a stratification of the soil. Finally, an interesting feature of this area is provided by the presence of a strong reflection from $x = 97$ m to $x = 102$ m and at a depth of 1.15 m, due to an extended object, which probably can be assumed to be an arch or underground passage, but actually no evidence was found in historical documents.

5. Discussion of the results

The combined use of UAV based visual inspections, thermographic investigations and GPR analysis allowed an improvement of the knowledge about the ongoing degradation state of Ponte Lucano.

In the following, some considerations made on the comparison between the results given by the tests show how a synergistic approach like to one adopted in this paper can allow achieving significant knowledge about the degradation state of an ancient structure. It is worth pointing out that IRT and GPR inspections revealed to be quite effective in allowing comparisons with aerial visual pics to perform a complete “clinical” picture of the structure.

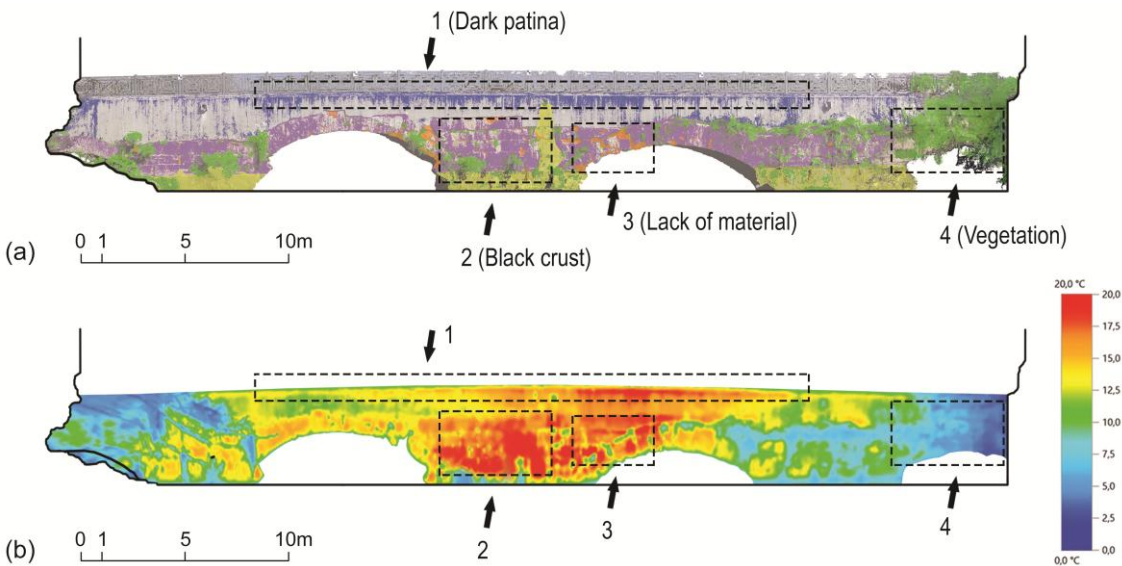


Figure 17. Comparison between material degradation map (a) obtained by UAV photogrammetric survey and thermographic inspection (b) on the South side of the bridge. For the map legend of material degradation refer to Figure 9(a).

Figure 17 highlights interesting links between the color maps identifying the material degradation (Figure 17(a)) and the superficial temperature observed through thermography. Although no direct correlations can be established a priori between the phenomena causing the two color maps, the temperature scale can reveal in some cases

specific degradations, especially in the presence of humidity, to which correspond different levels of heat transfer through the materials, thus different levels of superficial temperature. For example, to the patina of the concrete wall upper side (enclosed in the window 1) corresponds a scale of temperature with no particular meaning in the degradation identification. On the other hand, the black crusts indicated in the window 2 are more evident, due to the chemical-physical characteristics of the external layers of the stones, which affect the heat transfer properties. This aspect is strengthened by the presence of areas with lack of materials, e.g. see window 3, where the absence of the black crusts determines a high gradient of temperature. Finally, in presence of vegetation and biological patina (window 4), directly related to humidity, lower levels of temperature can be observed.

Figure 18 summarizes the results of the combined investigations through the superposition of the filtered radargram at 600 MHz and the thermal images of the South side of the bridge. The alignment of the bridge profile was carried out through the analysis of the radar signal that clearly identifies the beginning and the end of the deck. In a first visual comparison between the radargram and the bridge profile multiple reflections appear in correspondence of the actual deck, i.e. about from $x = 16$ m to $x = 80$ m, which are due to the presence of the metallic reinforcement structure. This latter does not allow the signal propagation and thus the detection of the visible arches. On the other hand, the metallic reinforcement structure does not appear at a constant depth along the path ranging about from $x = 16$ m to $x = 80$ m, suggesting that where an increased depth is experienced the relative permittivity is higher than the adopted average value. This is coherent with an increased water content. Moreover a soft signal attenuation is observed over the middle arch, i.e. about from $x = 54$ m to $x = 60$ m, while a significant signal attenuation occurs over the first arch of the East side, i.e.

about from $x = 69$ m to $x = 72$ m. At the same time, the thermal analysis has highlighted that the East side of Ponte Lucano is in the shade all day long, resulting in high constant humidity levels, especially in the wet seasons. These last considerations induce to suppose that the signal attenuation observed in the East side of the bridge, corresponding to Arch IV, could be related to the high level of humidity affecting the backfill layers.

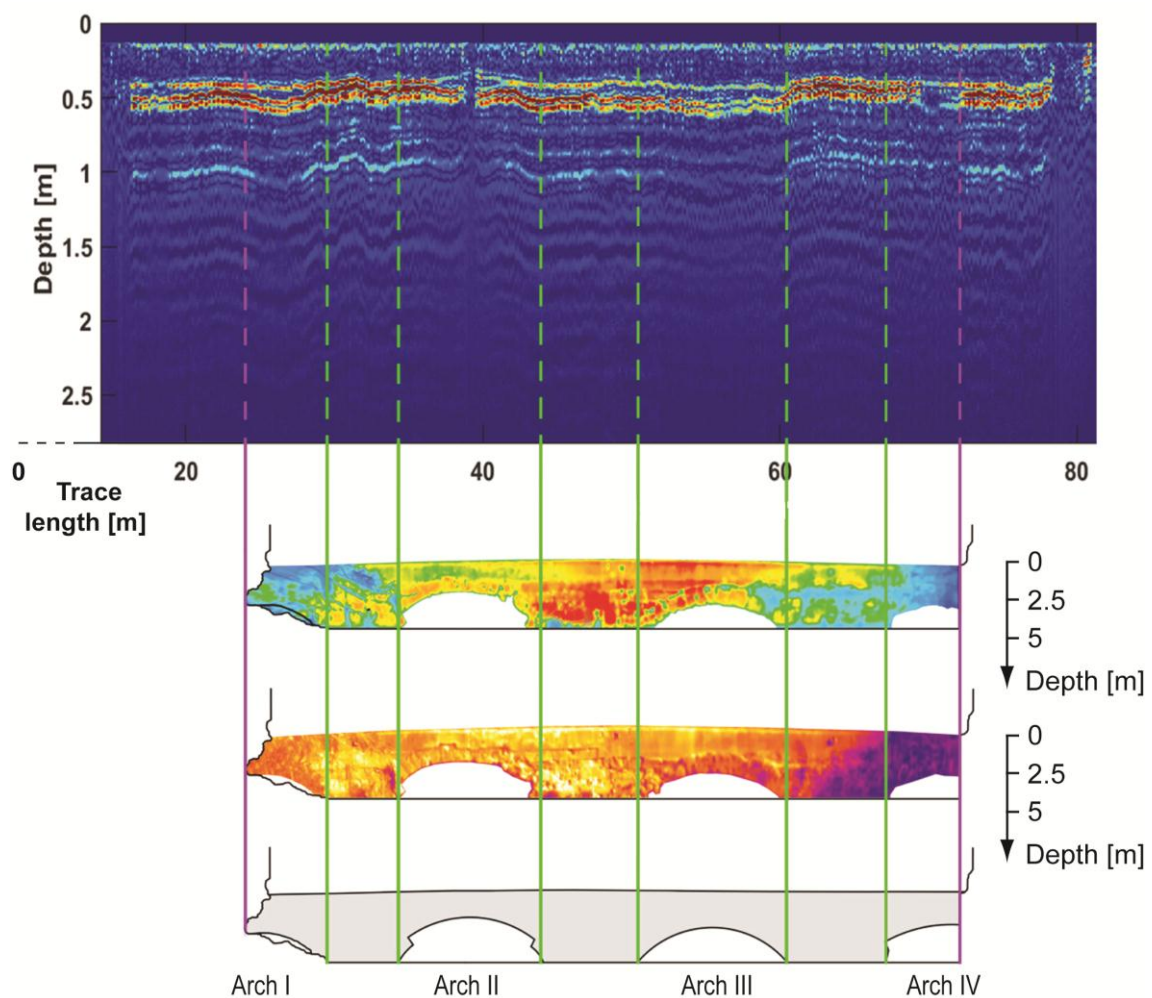


Figure 18. Comparison between GPR analysis and thermographic inspection.

An unexpected consequence of this condition characterizing this side of the bridge is an evident increase of the material degradation occurred in the period of inspection carried out by the Authors. In particular, after a significant rainfalls period, the external

cladding of the South front of masonry arch fell out (Figure 19). That material was applied during the last restoration works, but the environmental conditions were especially aggressive for its durability facilitating the ejection, probably after a progressive separation process due to the presence of humidity.

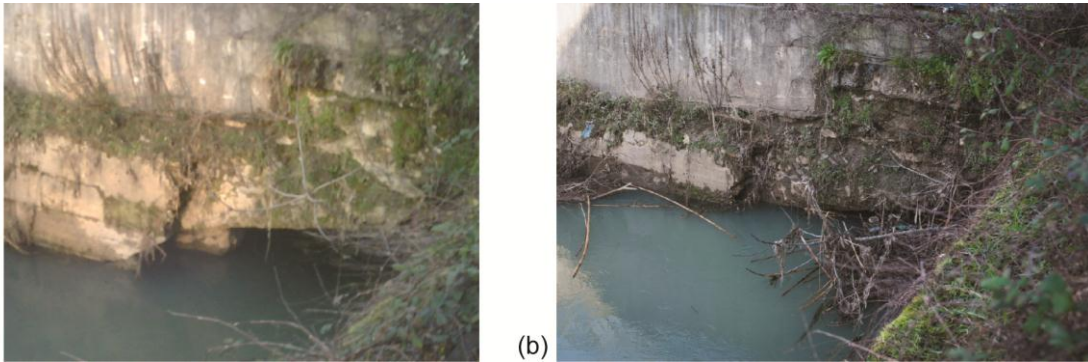


Figure 19. Increase of material degradation observed on the South front of Arch IV. The images illustrate the arch before (a) and after (b) a heavy rainfalls period.

6. Conclusions

This work has investigated the use of innovative methods for the analysis and diagnosis of historical masonry structures. An illustrative case study has been considered, consisting of the iconic Roman bridge of Ponte Lucano in Tivoli, Italy. Visual inspections via unmanned aerial photogrammetry, as well as thermographic and GPR analysis have been carried out in order to generate a “solid” link between the optical and qualitative analysis.

UAV 3D photogrammetric survey allowed us to easily reach almost every part of the structure and to obtain a detailed point cloud and thus orthophoto-plans providing metric and geometric digital representations of the bridge. Moreover, they revealed precious information regarding the structure under examination, including chromatic properties and size characteristics of the bridge. Such a detailed survey can be regarded

as an actual digital memory to be exploited for possible architectural – historical studies of the historic bridge, as well as to assist the design of future restoration interventions. This visual survey has guided the subsequent analysis of the construction materials, including a detailed degradation mapping of the wall texture through color masks.

The thermal camera, through the thermal irregularity of the surfaces, showed how the present degradation condition of the whole structure is mainly a result of the water retention within its materials. Besides, it allowed to conclude that the walls of the bridge are severely exposed to a strong thermal excursion, in particular during winter. This fact, in addition to the water retention, increases the cracking risk that might in turn produce more serious damages in time. Thermography was also able to point out the relation between the reinforced concrete element, built in 1990 as a restoring intervention, and the whole original structure. This relation ascertained the strong thermal impact of the reinforced concrete portion over the brick arches on the stones surfaces.

GPR analysis was the final step of the in-field investigation. It provided information about the internal structure of the bridge deck and its most humid parts as well as about the presence of buried objects, located at the two banks. In particular GPR results allowed to identify two arch structures allegedly located in the northern bank and in correspondence of the Plautii Mausoleum, thus confirming the historical-bibliographical hypothesis made regarding the construction phases of the bridge.

Overall, this work contributes to demonstrating that innovative contactless non-destructive diagnostic tools can work synergistically and provide precious information to aid structural evaluation and guide the design of restoration interventions on landmark historic masterpieces, in a context of preventive conservation of architectural heritage. The illustrated methodology can be extended to a large sample of bridges,

which have an important infrastructural function in connecting urban areas, beyond their historical and monumental value.

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