

Monitoring and averting secondary collapse mechanisms in already ruined historic bridges by means of metric values obtained from archival photographs and the geometric analysis of the intrados

Auscultación y prevención de mecanismos secundarios de colapso en puentes históricos en ruinas mediante el uso de valores métricos obtenidos de fotografías de archivo y el análisis geométrico del intradós

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ABSTRACT

This text describes a methodology for the geometric monitoring of abandoned bridges. In order to define the actual state and to monitor the evolution over time it is proposed the use of digital elevation models of the intrados and archival photographs. On the one hand, the digital elevation models might jointly notice the presence of a varied range of conditions in a simple way; therefore, no prior knowledge regarding the active dynamics of the bridge is necessary and, thus, it is a valuable option for preliminary studies, in which only scarce information on this regard is available. On the other hand, the usefulness of stock photographs is analyzed too, in particular, showing the evolution of the case study through the comparison of images taken 50 and 30 years ago.

Keywords: *geometric monitoring; bridge; intrados; photogrammetry*

RESUMEN

El presente texto describe una metodología de control geométrico adaptada a puentes abandonados. Para el establecimiento del estado actual y monitorización de las dinámicas se propone, por un lado, el uso de modelos digitales de elevaciones del intradós del arco ya que este producto permite reflejar de manera conjunta la presencia de un variado elenco de afecciones de una manera sencilla. Por consiguiente, no resulta necesario disponer de un conocimiento previo detallado sobre los mecanismos activos en el puente, resultando una opción apropiada para estudios iniciales en los que la información a este respecto es escasa. Por otro lado, se analiza el valor de las fotografías antiguas para trazar procesos que se desarrollan durante periodos largos de tiempo, en concreto, se muestra como ejemplo la evolución a través de la comparación con fotografías de hace 50 y 30 años.

Palabras clave: *auscultación; puente; intradós; fotogrametría*

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1. INTRODUCTION

Bridges are essential for transport and economy; hence, strict regulations are in force for their periodic inspection so as to ensure their proper functioning—see, for instance, for the Spanish case, the specifications published by the Ministry of Public Works and Transport (1), (2).

Bridges that are no longer in use as communication routes but maintain their cultural and landscape values are a case apart (3). Often, these structures lack of any kind of maintenance and some constructive parts (such as parapets, running surface, arches...) are missing; moreover, the remains usually are located in out of use paths and, consequently, they are hardly accessible. Nevertheless, the fact of already being in ruins does not imply that their situation cannot get worse over time and that new collapse mechanisms occur and continue until the complete disappearance of the element, at the same time that they pose security risks for visitors. Another non-negligible circumstance is that many of these bridges are protected by legal provisions so cultural administrations have to take steps in order to preserve them.

In this text, the case of the Mantible bridge over a bend of the Ebro river in Spain, between the municipalities of Laguardia (Basque Country) and Logroño (La Rioja) is presented. This bridge was declared a National Monument (Royal Decree 430/1983) and, at present, retains two of the seven arches that originally had (figure 1), arches that will be numbered as 1 and 3 in right to left direction, upstream.



Figure 1. Upstream view of the remains of the bridge from a picture taken with a drone in 2017. The arch in the front corresponds to number 3 and the one at the back is numbered as 1.

The construction might date back to the 2nd century B.C. (4), although, this point is controversial and some authors prefer to place the erection during the Middle Ages (5). In origin, it should have been a 160 metres long structure with voussoir arches of variable span from 7 to 30 metres (6) and, it seems that, by the 9th century, it was already in ruins (7). However, the sources do not provide information to assess how much of the building remained at each time until the middle of the nineteenth century, when a description informed that only the two arches that exist nowadays were standing (8).

Prior to this work, no information was available concerning the active mechanisms affecting the stability of the Mantible bridge, for this reason, a precise photogrammetric recording was done in 2017 (9). In the following sections, the generated 3D model will be used for comparison with a new set of measurements taken two years later with the aim of detecting active dynamics. Moreover, the model will be also compared with 50 and 30 years old stock photographs so as to monitor long-term and accumulative effects.

All in all, this paper develops a methodology for the geometric monitoring of a building structure which tries to take advantage of the way that several foreseeable changes will modify some especially sensitive parts, such as the intrados of a bridge. Although the case study presented here is for a derelict historic stone bridge, there is no reason for which it cannot be applied to other kind of buildings of any other material, both operational or no longer used.

2. OBJECTIVES

The main objective consists of presenting a methodology for assessing the current state of an abandoned structure, as well as being able to track its evolution in the past and foresee its future behaviour, all this based on changes in its geometry. This knowledge will provide useful information for planning actions aimed at the preservation of the building and its safe use by visitors.

The first challenge to cope with is that the techniques we can turn to for tracking the geometric evolution retrospectively are different from the ones suited for the active monitoring nowadays so, actually, two separate stages will be used for detecting past and current changes and, later on, the results will be pulled together in order to draw joint conclusions.

Beginning with the monitoring of the ongoing situation, as the dynamic of the structure is unknown, the methodology to be used needs to be sufficiently general to detect different kinds of active processes, not only those that seem more or less evident but also the unanticipated ones. Besides, the abandoned state of the area (which might imply: difficult access, construction possibly unstable, significant parts covered with debris and vegetation and so on) makes advisable the employ of simple and contactless techniques that can give results even with incomplete sets of data. With that in mind, in this text, the resort to dense digital elevation models of the intradoses is evaluated. These 3D models can be easily generated by photogrammetric techniques or by laser scanning and allow reflecting mechanisms that are affecting not only the arch itself but also other parts of the bridge that are connected to it. In addition, this approach does not require physical contact with the walls, nor the attachment of measuring devices.

On the other hand, the evolution in past years will be tracked by means of old photographs. Because of that, local administrations and authors who have previously written about the monument were contacted with a view to gather pictures from different times. As a result, some pictures taken in 1970 and 1990, which were suitable for the geometric analysis through their perspective (by reconstructing the position of the vanishing points), were selected.

3. MATERIALS AND METHODS

Techniques for geometric documentation applied to bridges and other engineering elements are continually evolving and, thus, providing room to new products which, step by step, are improving the resolution and accuracy of the representations, at the same time that the costs (equipment, time and money) are progressively more affordable. So, for example, up to the decade of the nineties, the most precise representation was obtained by means of stereoscopic photogrammetry and the individual 3D drawing of every component of the structure (stone blocks, ground line...), some illustrative examples can be seen in (10) and (11). From year 2000 on, total stations theodolites added the possibility of measuring distances without prism, which allowed the geometric recording of the boundaries and points to define the surfaces directly on-site -e.g. (12), (13)-, this data was imported in a CAD system where the three-dimensional model was generated. During those same years, digital photographs started to be used, which gave rise to incipient texturized virtual models.

In recent times, the techniques for massive data recording have permitted generating very detailed and accurate 3D models. In particular, and focusing only in bridges, successful results have been obtained during the last years both by means of laser scanners (14), (15), (16), (17) and convergent photogrammetry (18). Both approaches generate dense point clouds (even with resolutions under one centimetre) that can be used directly as final outcome or being the base for the generation of models of surfaces (meshes); additionally, other techniques such as Ground Penetrating Radar (GPR) may be added to give information about the inner part of the structures (19), (20).

However, other aspects must be considered too. Firstly, 3D models have to be complete, which requires coverage from as many points of view as necessary so as to fully record every single part of the structure. On this regard, UAV systems (drones) have proved to be very interesting tools for acquiring data with versatility (21). Secondly, point clouds and meshes are able to generate semi-automatically a wide range of outcomes (orthoimages, cross-sections, etc.); nevertheless, other attainable products will require more processing, such as the segmentation and parameterization that

is necessary in order to generate entities for BIM (Building Information Modelling) systems or for structural analyses (22), (23). In any case, it should be indicated that traditional products such as the line drawing of the individual stone blocks are still demanded by many users.

Concerning the structural behaviour of masonry arches and vaults, different techniques are in use, such as finite element method - FEM (24), (25); discrete elements method - DEM (26) or thrust lines (27). In particular, for our case study, Heyman's theory on the limit conditions for the stability of arches in terms of the width of the voussoirs (28), (29), (30) will be of paramount importance since arch 1 shows a clear pattern of hinges, similar to the ones predicted by this theory. Nevertheless, it should be noted that methods for structural analysis usually assume that the elements are in good enough conditions to transfer loads. This premise may not be quite certain for the Mantible bridge, in particular for the aforementioned arch 1, because the visible cracks suggest that the pillar beside the river might be broken inside (31) and, in addition, some of the central stones of the arch felt down, compromising the continuity between the constructive elements.

Apart from the "static" study of the structure from its geometry (and, additionally, also thanks to the information about mass, strengths, etc.) in a particular moment, it is also interesting being able to study the evolution over time, for this purpose, it is necessary to compare sources of information from different epochs (32).

Differences between epochs can be established through methods based on the monitoring of specific points (for instance, targets placed on strategic parts of the structure), profiles or complete surfaces (33). The approach followed in this work analyses surfaces but it is limited to the intrados. This choice does not imply a renunciation to monitor the bridge in its entirety since—as it has fruitfully studied in many kinds of structures (34), (35), (36), (37)—there is a strong link between what can be seen in the arch and the changes in the elements that, such as the pillars, are connected to it.

Moreover, instead of studying directly the changes in the geometry of the intrados in 3D, the differences will be measured regarding a reference surface, more specifically, a cylinder

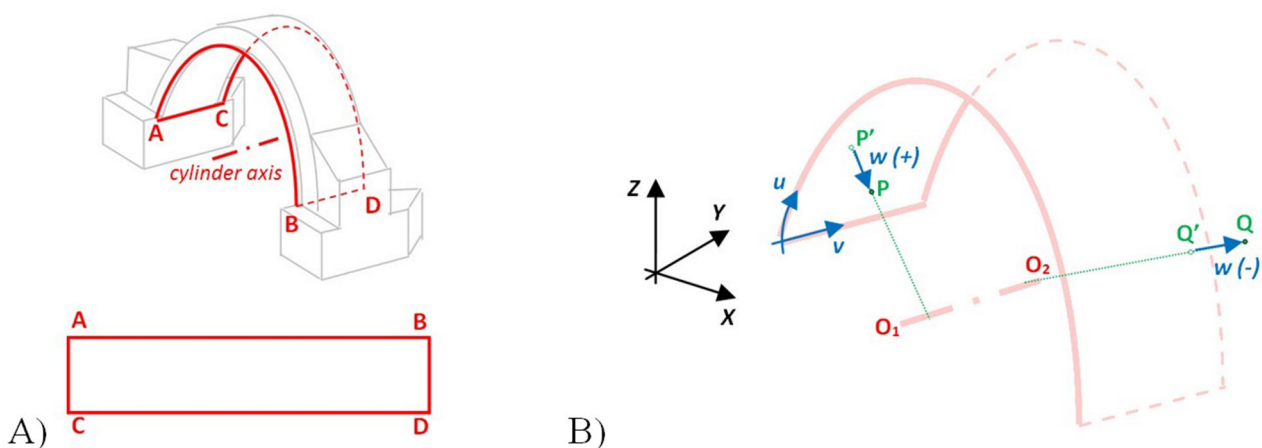


Figure 2. (A, left) the geometry of the intrados will be computed by means of the difference to a reference cylinder that will be represented in a 2D developed view. (B, right) three-dimensional Cartesian system of coordinates (x, y, z) and relative system to the cylinder (u, v, w).

that will be subsequently developed. In this manner, both the state in any specific moment and the comparison between occasions can be represented in a simple 2D plan view, furthermore, the information about the state and the changes will be represented only in the third coordinate (distance to the cylinder), for instance, by means of contours lines. The resort to reference surfaces is common in many types of structures such as tunnels, dams or refrigeration towers, by the use of, according to the case, not only cylinders but also spheres, paraboloids, cones, etc. (38), (39), (40).

The expressions to transform the original (x, y, z) Cartesian coordinates of the point cloud to the coordinates (u, v, w) relative to the reference cylinder are reported below. Starting by the scheme (figure 2a) in which the reference cylinder is represented in red together with the outline of the arch, this cylinder has a radius (R) and can be developed in a 2D plan view as it is showed in the rectangle (A, B, C, D) beneath.

The initial geometric information of the intrados is taken from the point cloud, as can be the points indicated by the letters “P” and “Q” (figure 2b), densely distributed all over the bottom surface of the arch. The original system is the 3D Cartesian (x, y, z) and the transformed one has two coordinates (u, v) on the surface of the cylinder and the third one (w) is the distance in the direction of the radius, as sign criterion it will be taken as positive the values inwards and negatives outwards.

The transformation to be done is described next. Firstly, two points in the axis of the cylinder are defined (“O1” and “O2”), these points show the limit for the development of the cylinder. In our case, we will take “O1” by the downriver front and “O2” by the upriver one. The corresponding azimuth of this axis can be computed by the expression:

$$[1] \theta_{O1}^{O2} = \text{atan} \left(\frac{x_{O2} - x_{O1}}{y_{O2} - y_{O1}} \right) + C$$

Being “C” a constant dependent on the quadrant where the azimuth lays, which has values of: 0 (first quadrant, azimuths between 0 to $\pi/4$), π (second or third quadrant, azimuths between $\pi/4$ and $3\pi/4$) and 2π (fourth quadrant, azimuths between $3\pi/4$ and 2π).

Coordinates (u, v, w) of point “P” can be obtained from the Cartesian ones (x_p, y_p, z_p) by the following steps. Firstly, the increments from “O1” are computed:

$$\begin{aligned} \Delta x &= x_p - x_{O1} \\ [2] \Delta y &= y_p - y_{O1} \\ \Delta z &= z_p - z_{O1} \end{aligned}$$

Next, the angle in the XY plane between the line O1-P and the cylinder axis is computed, by the subtraction of both azimuths.

$$[3] \alpha = \theta_{O1}^P - \theta_{O1}^{O2}$$

Moreover, the distance between “O1” and “P” on the horizontal plane XY is obtained through:

$$[4] d_{O1}^P = \sqrt{\Delta x^2 + \Delta y^2}$$

Finally, the transformed coordinates (u, v, w) are then found by the following expressions:

$$\begin{aligned} u &= R \left[\text{atan} \left(\frac{d_{O1}^P \sin(\alpha)}{\Delta z} \right) + \frac{\pi}{2} \right] \\ [5] v &= d_{O1}^P \cos(\alpha) \\ w &= R - \sqrt{(d_{O1}^P \sin(\alpha))^2 + \Delta z^2} \end{aligned}$$

The procedure for the generation of the developed view consists of computing, for each point of the cloud with original (x, y, z) coordinates, its transformed (u, v, w) coordinates. In addition, it is appropriate to define an output resolution (res) for the images (e.g. 1 cm), value that will be used to discretize the variables (u, v) in such a way that both of them will be expressed in rows and columns in the final image (or in form of a grid):

$$\begin{aligned} [6] \text{column} &= \frac{u}{\text{res}} \\ \text{row} &= \frac{v}{\text{res}} \end{aligned}$$

The normal situation when going along the file with the point cloud is that every square (row, column) contains many points. From those, it is necessary to keep with a

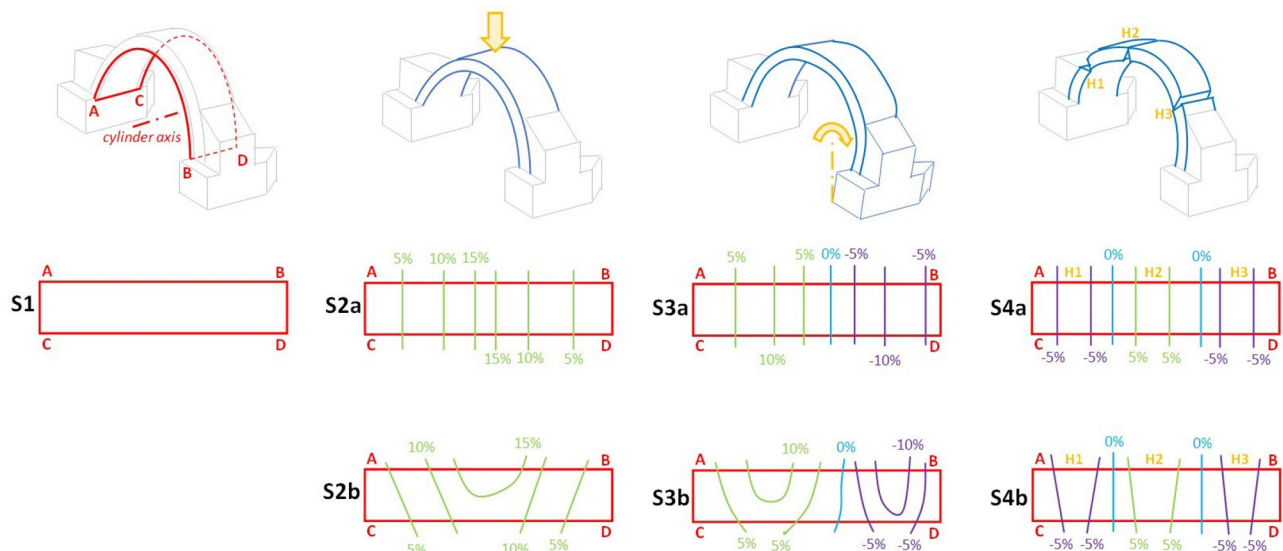


Figure 3. Representation over the development of the intrados of some model cases regarding deformation patterns.

single value that can be the average, although a simpler value that gives good results is selecting the highest (w) value. As final result, an array of rows and columns with values of (w) for each square will be obtained. If the size of the squares (resolution) has been well selected, no empty areas will appear, otherwise, it is possible to turn to interpolation algorithms for filling the gaps.

At the same time that the point cloud is analyzed with the aim of obtaining the (w) values for each cell, we can also store the chromatic channels (RGB values) of the same point from which the (w) has been selected and generate a photographic representation of the developed intrados.

After that, from the digital elevation model, a set of contour lines are obtained. For the interval between the lines it is preferable to resort to values relative to the radius of the reference cylinder (in percentage). This way, the lines can be interpreted independently of the dimensions of the arch.

If the resolution and accuracy of the digital elevation model allow it, contour lines can be used to depict very detailed surface deterioration processes such as cracks, losses of mortar, holes or protruding stones. Nevertheless, for a first general view of the structural state of the whole arch, it may be preferable to begin with a reduced set of contour lines with smoothed profiles; therefore, some processing/redrawing has to be done from the original set of contour lines extracted from the elevation model, i.e. simplifying noisy paths, removing small chunks, etc. In the case study that is developed in the next sections this processing was performed manually.

The pattern of contour lines gives information about the geometrical state of the bridge. The following scheme (figure 3) illustrates some of the possibilities. In particular, the situation “S1” shows an arch perfectly semi-circular in which no contour level will be represented, in “S2” it is depicted a pattern of lines that can be expected in a lowered arch (being “S2a” a situation in which the magnitude of the deformation is similar in both fronts of the arch—downriver and upriver—and “S2b” a case in which one of the sides has a bigger deformation). The situation in “S3” shows the leaning of one of the pillars causing deformation of the arch, but still without a

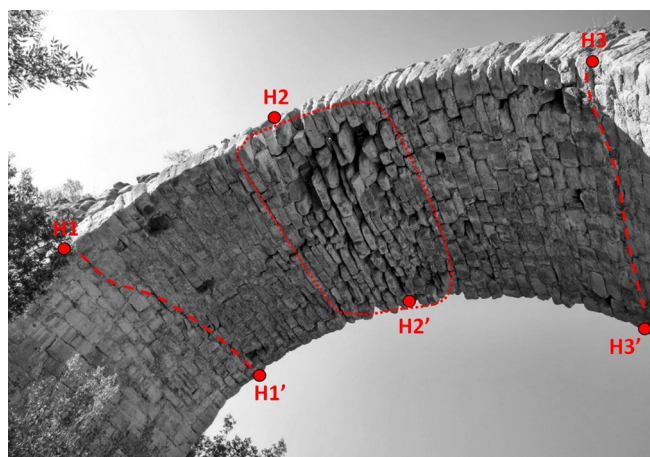


Figure 4. Photograph of the intrados of arch 1, taken in 2017. The “hinges mechanism” that is evident in front elevations (points “H”) can also be noticed in the intrados by means of cracks, leaning changes and loss of voussoirs.

clear system of hinges, which is the state illustrated by “S4”. As said before, the situations “a” correspond to cases with similar effect upstream and downstream, whereas, the cases denoted by the letter “b” characterize differences between both fronts. The contour level in cyan goes on the reference cylinder, green contours are below (“ w ” values positives) and magenta contours are above (“ w ” values negatives).

As stated above, the overall mechanism can be complemented by other changes such as block falls or cracking that will be also reflected in the contour lines (figure 4). Finally, as the contours are a concise representation of the geometry of the intrados, it is possible to overlap, in a single drawing, lines from different periods in such a way that the changes along time can be spotted.

Concerning the availability of multitemporal information, in a favourable scenario, it can be possible to even plan how and when monitoring data will be collected. However, although this might be attainable for current and future datasets, when it comes to recover information from the past, the usual situation is to have to settle for limited and heterogeneous data gathered over previous years. In this regard, flexible methods for obtaining metric values for non-specific sources gain importance and, in particular, the analysis of old photographs turns out to be a valuable option.

With large amounts of pictures, it is possible to resort to computer vision algorithms (such as Structure from Motion – SfM) for reconstructing virtually the elements three-dimensionally, as was done for Plaka bridge, in Greece, where more than 800 photographs previous to its collapse were employed (41). When only a scarce number of images are at disposal and, in addition, the set is diverse in dates and points of view, the work becomes harder and less automatic but the analytical expressions of the perspective geometry still can provide useful partial reconstructions (42).

For the case of the Mantible bridge the situation was still more unfavourable since we were looking for tracking a dynamic and, thus, the information for different years had to be considered separately. Consequently, we resorted to the dimensional reconstruction through vanishing points (43), a technique that allows working with individual images and that has proven to be useful for 3D reconstruction of heritage buildings from archival photographs (44).

The stock of photographs about the bridge consists of several pictures taken at the beginning of the decade of the seventies (provided by J.G. Moya) and the nineties (provided by B. Arrúe and J.M. González). Most of the images needed to be discarded since they showed either distant views or specific details and, therefore, they were not suitable for the reconstruction through perspective analysis. Indeed, appropriate pictures are the ones that clearly show two sets of perpendicular vanishing directions (figure 5). Undoubtedly, the terrain that surrounds the bridge, the vegetation and the river itself greatly condition the possible points of view. On the other hand, due to the fact that this is a graphical method, the ability to distinguish differences will be limited by the quality of the pictures (as well as for the correctness of the hypothesis that the elements selected in the picture are, in fact, perpendicular), therefore, only significant changes of, at least, decimetres will be determined with certainty.

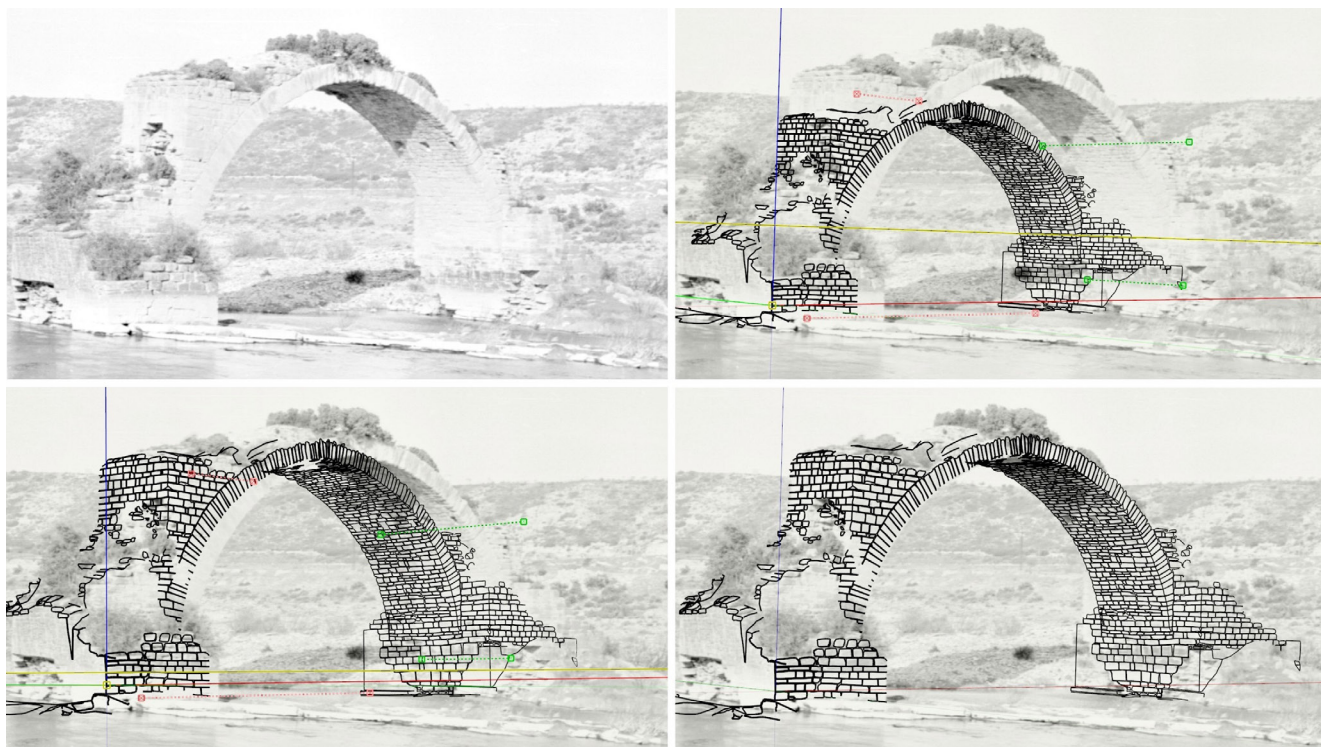


Figure 5. Sequence of the adjustment of the 3D line model of arch 3 generated in 2017 over a picture taken in 1970 by means of the location of the vanishing points (using the software SketchUp®). Upper left, photograph. Upper right, green lines define the vanishing point along the stream and red lines the perpendicular direction; in this picture, the position of the pillar at the river is fixed although the scale of the line model is not adjusted yet. Lower left, correcting the scale of the line model until it fits with the background picture. Lower right, final situation.

4. WORKS UNDERTAKEN

In 2017, the bridge was documented by means of convergent photogrammetry, combining pictures taken from the ground with a Canon EOS 5D Mark II camera of 20 megapixels with a 21 mm lens Zeiss Distagon T* 2.8/21 ZE and aerial photographs obtained with a drone Phantom 3 Professional equipped with a camera Sony EXMOR 1/2-3" of 12 megapixels. The images were processed with the software Agisoft Photoscan® (currently commercialized under the name of Metashape®) so as to generate three-dimensional surface models with photographic textures. Arches 1 and 3 were modeled separately since the river did not permit establishing a good continuous model only from the images; however, both models were oriented with control points, the coordinates of which were measured with a total station in a common coordinate system and, therefore, the resulting 3D models are in the same system and can be viewed and analyzed together. This very software was used to draw the boundaries of the blocks (the 3D line drawing that is shown in figure 5). The lines were drawn in 2D over the photographs and projected by the software onto the 3D model in order to generate 3D line entities. Likewise, from the three-dimensional model of surfaces, orthoimages of the upstream and downstream elevations, the sides of the pillars and the bottom views of the arches were obtained with a resolution of 5 mm.

The outcomes of the aforementioned work enabled to detect, represent and measure a series of damages such as cracks, leaning of the pillars, asymmetry of the arches and so on. Moreover, they provided a first quantitative estimation of the condition of the monument at that time. The most worrying results concern arch 1, indeed, the pillar near the river had a

leaning outwards that exceeded the value of six degrees from vertical combined with a noticeable tilt forward, these deformations had led to the emergence of important cracks and the falling of blocks from the central part of the arch.

For the particular issue of the monitoring of the changes in the geometry of the arches, digital elevation models with regard to their respective reference cylinders of both intradoses (arches 1 and 3) were obtained and represented as contour levels over the photographic development of each arch. In 2019 (two years from the previous occasion), a new photogrammetric record was conducted, this time focused only on the intradoses. The information was processed in order to obtain updated elevation models related to the reference cylinders and the patterns of contour lines compared so as to detect changes in this period.

As for the retrospective study with old photographs and bearing in mind the existing images, it was decided to work only with downstream general views. In the first place, the 3D line model obtained in 2017 was matched to the image of arch 3 taken in 1970 (see, figure 5), in this case, the drawing fitted well the background picture, consequently, it can be concluded that there has been no change bigger than the level of detection of this graphical method.

On the contrary, the analysis in arch 1 showed discrepancies of around 60 cm between the drawing from 2017 and the picture taken in 1970 (figure 6) by the centre of the arch. This magnitude is large enough to be considered meaningful. The same task was repeated with images from 1990 obtaining an intermediate position, in which the central part of the arch was around 30 cm lower than the situation measured in 1970.

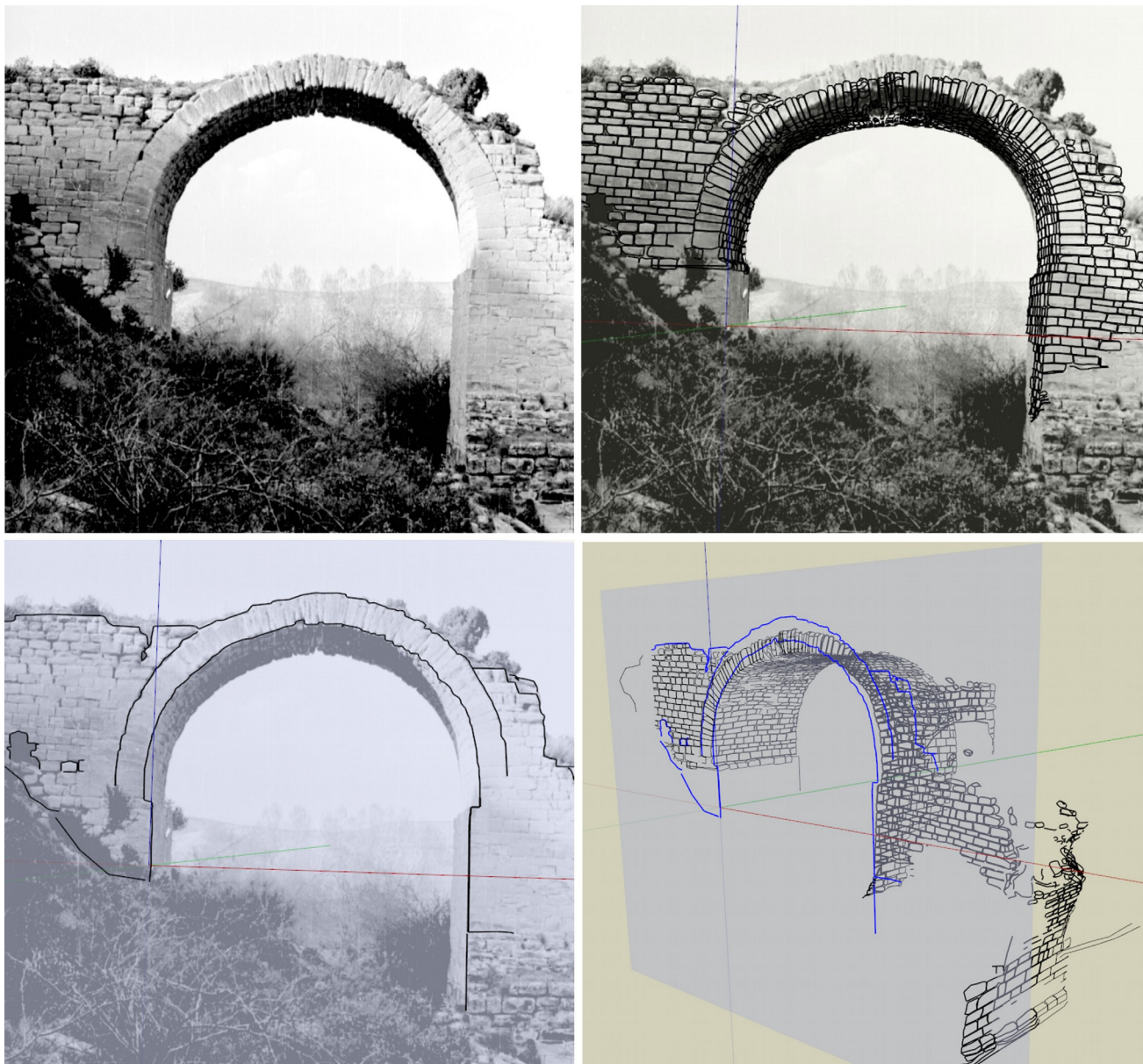


Figure 6. Change in the shape of arch 1 from 1970 to 2017. Upper left, photograph from 1970. Upper right, the same photograph with the line drawing of 2017 adjusted by means of the location of the vanishing points. Lower left, tracing the profile of the arch in 1970 on a plane coinciding with the downstream front of the bridge. Lower right, the profile of the arch in 1970 (in blue) together with a partial view of the 3D line model of 2017 (in black).

5. RESULTS AND DISCUSSION

The graphical method provides a first idea of the evolution of the arches during last decades. On the one hand, arch 1 has undergone significant changes that can be visually noticed by comparing old pictures, where the profile was almost semi-circular, and their current situation with a clear system of hinges and considerable deformation from the semi-circular shape. The metric analysis of the photographs provided values from this deformation: up to 60 cm in the central part of the arch. On the contrary, for arch 3, no significant discrepancies from 1970 to 2017 were detected.

Turning now to the evolution in the period 2017-2019, which has been monitored through the models of the intradoses, the following image (figure 7) shows the case of arch 1. The contour interval is relative to the radius of the reference cyl-

inder (approximately 5 metres, hence, a change of 1% stands for 5 cm). Going back to the model situations depicted in figure 3, it can be seen that the pattern of contour lines fits well with the situation identified as “S4b”, that is to say, a system of hinges that is more aggravated in one of the fronts (downstream). The set of contour lines regarding 2019 shows a worsened situation as compared to 2017, as can be seen in the green (positive) lines in the centre of the map and the magenta ones (negative) on the right, by the riverside.

Taken together both the retrospective study and the 2017-2019 monitoring of arch 1, it seems clear that there is a progressive increase of the leaning outwards of the pillar near the river. From the geometrical point of view that was used in figure 3, the trigger for the pattern of contour lines is a clockwise rotation of the pillar with respect to an axis perpendicular to the downstream elevation.

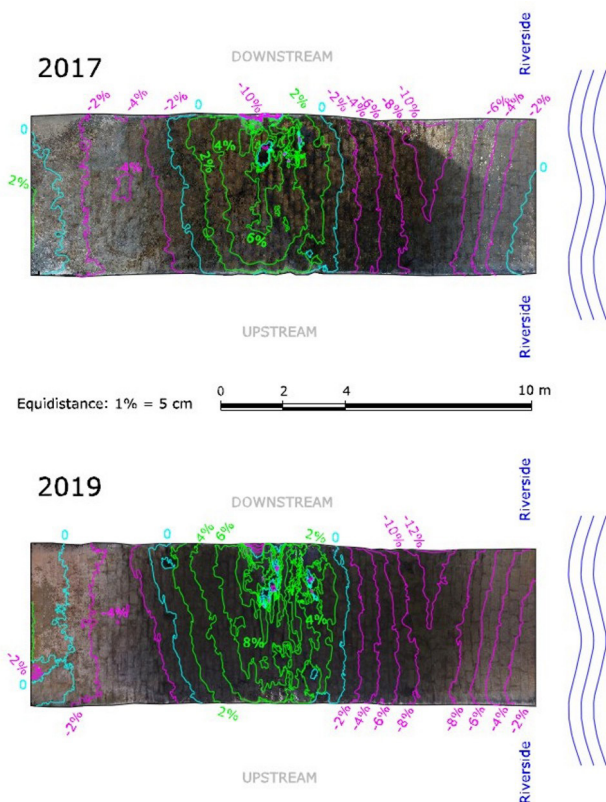


Figure 7. Contour lines showing the digital elevation model from the reference cylinder in 2017 (top) and 2019 (bottom) of arch 1. It can be seen the worsening of a situation similar to the one indicated as “S4b” in figure 3.

With respect to arch 3, the next image (figure 8) shows the contour lines from 2017 and 2019, in this case, the radius of the reference cylinder is approximately 10 metres and, therefore, changes in 1% stand for 10 cm in the interval. As can be seen, the pattern of lines is similar to the situation “S2a” in figure 3, that is to say, a lowered arch without break. Besides, it can be seen that the contours of both epochs are very alike and, therefore, that no substantial changes has been produced during this two-year period.

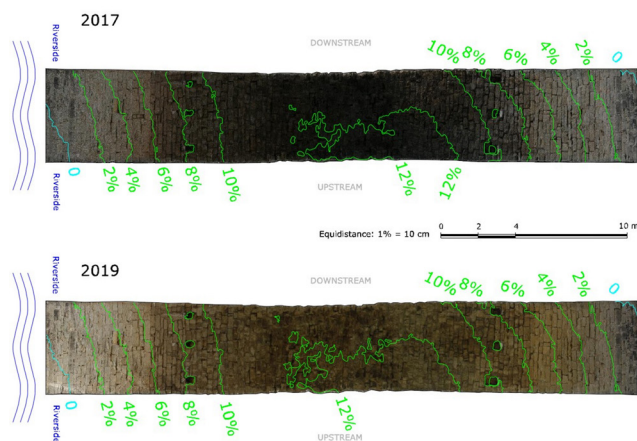


Figure 8. Contour lines showing the digital elevation model from the reference cylinder in 2017 (top) and 2019 (bottom) of arch 3. It can be seen a steady situation of the kind indicated as “S2a” in figure 3.

Altogether, the above data indicate that the arch 1 has undergone a significant deformation from the seventies to now with a noticeable change in the geometry of the arch (related with the leaning of the pillar) with differences that reach 60 cm, the emergence of cracks, hinges and falling voussoirs. Looking closer to the current state, the two-year analysis (2017-2019) based on the geometry of the intrados shows that the dynamic is still active and, thus, that the stability of this arch is clearly in jeopardy.

On the contrary, considering now arch 3, neither the long-term study based on the comparison with old photographs nor the two-year monitoring of the intradoses showed significant differences. All this leads to believe that its situation is stable.

In order to contextualize these results and assess their validity and implications, it could be adequate to reflect upon the methodology used. Beginning with the monitoring of the intradoses, it can be said that this procedure has the advantage that it does not need a complete model of the bridge; moreover, the part of the arches that is employed usually is accessible and unobstructed. This is not quite the case for arch 1, since there is no safe access to the lower part due to the vegetation and risk of rock falls but, even here, the use of drones for visual inspection and taking photographs allows collecting enough data to obtain results.

In addition, intradoses gather much information about the state not only of the arch itself but also concerning the whole structure. Besides, the dataset is easy to elaborate and it can be represented in a visual way, which makes the interpretation easier. The source for the metric information is a point cloud, a product that can be generated from different methodologies (such as photogrammetry or laser scanning), consequently, the proposed method is technologically neutral.

In this work, cylinders are used as reference surfaces over which measuring the state of the intradoses. It is important to state that at no time we are considering that the arches were semicircular in origin, neither that any value associated to a particular contour level (measured as a percentage of the radius) should be considered, on its own, as a limit value for collapse; on the contrary, lowered arches are perfectly stable providing that the thrust forces are balanced by the lateral supports.

A common reference system for the different epochs is essential in any multitemporal study; in this case, a geodetic network was established in 2017 by means of surveying techniques with a geometric precision of 3 mm and it is materialised by a set of nails and targets implanted onsite, which can be used again for the subsequent campaigns of observations.

Moving now to the metric recovery from old photographs, it can be said that, notwithstanding the scarcity of the available information for each epoch and the uncertainty of the graphical method that was used (the perspective analysis), the methodology used was able to track the deformation of the arch 1 from 1970 to 2017.

6. CONCLUSIONS

This text describes a methodology for geometric monitoring of abandoned bridges. The analysis of this kind of elements is interesting since it is based on the assumption that the stabil-

ity of the structure might be far more compromised than it is accepted for bridges in use. Besides, the lack of maintenance that, for instance, results in the abundance of wild vegetation, makes it difficult to access and hamper the visibility of many significant parts.

The methodology presented in this text is based on a first determination of the precise three-dimensional geometry of the structure to be controlled. Due to the limitations that may arise in the case of derelict buildings, it is necessary to take into account that the completeness of this product may not be possible, therefore, it is interesting to focus on parts that usually are free of obstacles and, at the same time, are able to provide large amounts of useful data, in particular, this article examines the convenience of the intradoses for this purpose. Certainly, the geometric record must be accompanied by a visual inspection of the structure in order to detect signs of damage such as cracks, gaps, deformed areas, etc. The combined use of this information will serve us to hypothesize about the possible dynamics that might be acting over the structure.

The second step consists of imaging how these active mechanisms would modify the three-dimensional model. For instance, in the explained case, the changes of the developed representation of the elevation models of the intradoses due to the sinking of the vault and the leaning of one of the pillars (both without and with breakage). Then, the comparison of the results generated in different epochs—as the ones in 2017 and 2019—allows checking whether the suspected mechanisms are actually active. As the 3D models of the intradoses were done by photogrammetric techniques the accuracy of these differences is in the range of a few millimetres. For reasons of simplicity, the 3D models were compared after developing their geometry on a cylinder of reference, this way, the comparison are done only in one significant coordinate (distance to the cylinder), which makes easier both the representation and the interpretation of the results.

On the other hand, the metric analysis of archival images has some limitations in terms of the possibility to retrieve information and, also, as far as the accuracy is concerned. If only sparse images are available it is possible to resort to the reconstruction of the perspective but, in this case, only measurements based on relations of parallelism/perpendicularity and the inclusion in planes can be obtained; for the Mantible bridge, the element drawn was the profile of the arch on the downstream elevation plane. The uncertainty of this graphical method can be estimated in several centimetres, however, the discrepancies between the epochs are many times bigger (around 60 cm between 1970 and 2017) and, hence, the values have to be considered as meaningful. Summing up, this technique will be useful if, on the one hand, the element of interest shows an adequate geometry on the pictures, that is to say, with clear vanishing points and, on the other hand, the magnitude of the changes is big enough to be detected.

As a final note, we will add that, concerned by the state of the bridge, the Logroño city council commissioned an underwater inspection of the pillar in August 2019. The examination detected that the river flow has eroded a large gap in the ground under pillar. This hole is around 40 cm high, goes along the entire width of the pillar (6 metres) and penetrates more than 2.7 metres (45). Therefore, the external part of the pillar is not directly supported by a solid column of rock

but by a cornice that, what is worse, is being washed and enlarged as time goes by. The undermining of the pillar is coherent with the deformation patterns that have been tracked both in the backwards analyses (in relation with the photographs from the 1970 and 1990) and the study of the active dynamics (by means of the changes in the intrados detected between 2017 and 2019), which supports the validity of these approaches for the geometric monitoring of constructions and, in particular, abandoned bridges (figure 9). Finally, it might be opportune to note that an important intervention on the starlings of the arch 3 was done during the decade of the eighties and that, as a result of these works, the flow of the river may have strongly incremented the erosion under the pillar in arch 1.

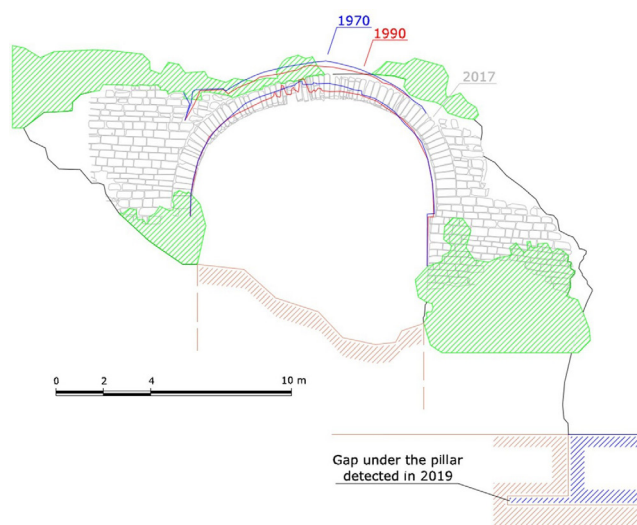


Figure 9. Retracement of the elevation of the downstream profile of arch 1 (1970, 1990 and 2017), with the indication of the gap in the riverbed under the pillar that was detected in 2019.

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ADDENDUM

After years of neglect, the arch 1 mentioned in this text collapsed on the night of 24 to 25 January 2021. The sad news of the loss of this element of heritage should drive us to reflect on the fact that, sometimes, public administrations do not take the warnings regarding cultural heritage seriously or that the administrative procedures to put in place corrective actions are not rapid enough. In any case, we would like to end on an optimistic note: the technologies exist and we are able to predict the evolution with sufficient time to avoid the disasters, all that is needed is the will.

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