Insights into the Collapse of the Asciello Masonry Bridge in Benevento

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Abstract. This contribution focuses on detecting the causes of the collapse of the Asciello Bridge, located in Cautano, in the Benevento area, Italy. The bridge was built in the 1860s. Towards the end of World War II, it was demolished during the retreat of the German Nazist army and subsequently rebuilt in the early post-war years. In the 1960s, the bridge collapsed, likely due to a landslide, and was never reconstructed.

This study investigates the bridge collapse using the discrete element method. The numerical analysis was conducted on a 2D geometry reconstructed from a point cloud obtained via laser scanning. The bridge geometry was carefully discretised using rigid elements with unilateral contact, featuring Mohr-Coulomb friction at the interfaces. The arch geometry was reconstructed following an in-depth geometrical and damage analysis. Specifically, the portion of the bridge still standing was directly derived from laser scanner data, whereas the collapsed section was hypothesised by referring to engineering principles outlined in post-war technical treatises and, importantly, in analogy with its "twin bridge" built near it. A parametric kinematic investigation was performed for several imposed increasing settlements simulating a landslide affecting an abutment of the bridge. The parametric study confirmed that the collapse was caused by differential settlement, characterised by a horizontal displacement component of approximately 90 cm, with an inclination on the horizontal plane between 15 and 25°.

Keywords: Masonry structures · Masonry Bridges · Foundation settlements · Displacement capacity · Distinct element method · Rigid blocks

1 Introduction

The masonry arch has been used for several thousand years. As early as 3500 BC, the Sumerians had developed the technique of assembling stones into an arch

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shape to construct roofs for their buildings [15]. Although proper arches existed, the Romans were the first to recognise their potential for bridge construction [5]. The expansion and effective governance of the Roman Empire across Europe and the Mediterranean region relied on the use of bridges to develop transport infrastructure for military mobility, trade, communication, and urban water supply. From that period up to the 19th century, numerous masonry arch bridges, tunnel linings, and viaducts were built to support transport infrastructure development throughout Europe. The introduction of new construction materials such as iron, steel, and reinforced concrete in the early 1900s led to a decline in the construction of masonry arch bridges. Nevertheless, many thousands of stone and brick masonry arch bridges still exist across Europe, most built between the second half of the 19th century and the early decades of the 20th century. Many of them are still a key infrastructural asset in the European system. Indeed, in the UK, approximately 40,000 bridges (40% of the total) are still in use [49], while in Spain, the railway network contains over 3,000 masonry arch bridges, accounting for 45% of the total [36]. In Italy, the railway network alone contains nearly 10,000 masonry arch bridges. Of these, around 20% have a span of 2 to 5 m, 11.5% range between 5 and 10 m, and 8.5% exceed 10 m. Most of these bridges were built after the establishment of the Kingdom of Italy, that is, between 1860 and 1920 [12].

Since the seminal work of Heyman [27,28], it was understood that cracks are not a structural concern [18,45] as arched structure can experience large deformation till the collapse as demonstrated in experimental tests [10,17] or through numerical analyses on digital models [14,19,33]. Because of this, several methods were developed to assess the stability of masonry structures, using revised version of the graphic statics [6–8,43,48], rigid blocks [29,44], or continuous approach [11,20,34,39,41,42], finite element approaches based on limit analysis [4,52,53], or adopting complex constitutive relations [9,13,21,26,37]. Numerical solutions based on limit analysis for masonry arch and bridges experiencing pier settlements are proposed in [16,22–25,30], or considering the direct interaction among soil and structure as in [32]. Restricting to real arch bridges, several scientific studies regarding masonry bridges were proposed for evaluating the load-carrying capacity of masonry arch bridges subjected to traffic loads [33,57] or assessing their performance under earthquake loading [51]. However, only a few numerical simulations investigate the vulnerability of masonry arch bridges to pier settlements. In particular, path-following analyses conducted on 2D or 3D finite element models of multi-span masonry bridges subjected to scour-induced settlement are presented in [35,56,58,59] or in [48] using Airy stress potential [1,40,46,47]. In [31], the authors propose a novel artificial intelligence-based approach to assess the stability and identify the causes of cracks in masonry structures, with a real-case application to the Deba masonry bridge in Spain. The reader is referred to [55] for a detailed review.

The present paper presents a real-case study of the Asciello Bridge in Benevento, Italy, which collapsed more than 60 years ago, most likely due to a



Fig. 1. The remaining of the Asciello Bridge, Benevento, Italy.

landslide (Fig. 1). In this study, the Distinct Element Method (DEM) [2,3,50] is adopted to identify the causes behind its collapse.

2 Asciello Bridge: Historic Information

The remaining part of the Asciello Bridge is located southwest of Cautano, a small village in the Benevento province, Italy (Fig. 2). It was built over the Ienga stream in a depression that facilitated the connection between Cautano and the village of Tocco Caudino. The area surrounding the bridge lacks significant



Fig. 2. The blue dashed rectangle highlights the Asciello Bridge structure. The yellow line represents the new road alignment, while the red dashed line indicates the route served by the bridge until the 1960s. (Color figure online)

natural plains, instead featuring artificially created terraces used for agriculture and other anthropogenic settlements. The slopes around the bridge are steep.

The territory of Cautano is characterised by a complex geological evolution, reflecting the interaction between sedimentary processes and, to a lesser extent, volcanic influences related to the regional structure of Campania. The forma-

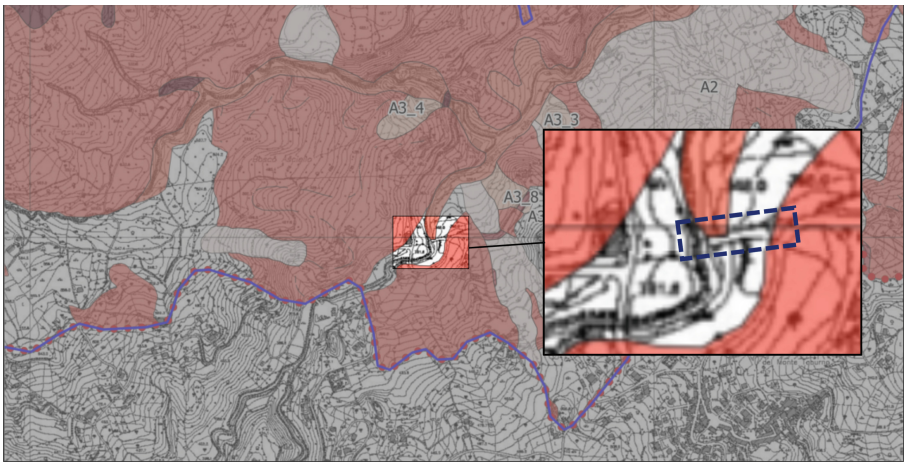

Fig. 3. Geological maps produced by the Cautano administration, with a zoom-in on the Asciello Bridge, show that the right pier (from the viewer's perspective) is founded on an area affected by a landslide.



Fig. 4. Image of the twin bridge (a) and zoom-in on its masonry texture (b), which is identical to that of the Asciello Bridge (c).

tions in the area consist mainly of sedimentary deposits, including clayey and calcarenitic materials, which accumulated during the Neogene in environments alternating between fluvial and marine conditions. In some locations, volcanic materials linked to the Campanian area have contributed to diversifying the local stratigraphy, as evidenced by studies conducted by the National Institute of Geophysics and Volcanology and the University of Naples Federico II.

All information on the historical reconstruction of the Asciello Bridge comes from interviews with local people and technicians, as no official plans or additional documentation related to its construction or collapse have been found. The bridge was built around the 1860s, shortly after the establishment of the Kingdom of Italy. It was blown up during the German army's retreat at the end of World War II. Rebuilt in the early postwar period, it collapsed in the early 1960s. The most widely accepted hypothesis of the collapse is a failure caused by a landslide, confirmed by local testimony and geological maps. Other factors, such as hydrogeological instability or neglect, have been ruled out. Indeed, during one of the many inspections, the bed of the Ienga stream was examined, and the bridge foundations were found to be in good condition, showing no signs of scavenging or erosion, thus excluding the possibility of hydrogeological instability. Regarding the risk of landslides in the study area, reference was made to geological maps produced by the Cautano administration as part of the zone of the municipal urban plan, as reported in Fig. 3. As shown in Fig. 3, there is a landslide movement behind and adjacent to the right side of the bridge, which, as demonstrated in this paper, is the primary cause of the collapse. In 2015, the Ienga stream overflowed, causing additional damage to the remnants of the historic bridge under study.

It is worth noting that a few hundred meters north of the Asciello Bridge, there is a "twin" bridge (see Fig. 4). This bridge was likely built around the same period as the Asciello Bridge and has undergone subsequent structural rehabilitation works after World War II. Figure 4 shows a photo of the twin bridge, where the rehabilitation works are visible, particularly the construction of a reinforced concrete arch. The masonry texture is the same as that of the Asciello Bridge, as shown in 4. The bridge is currently operational.

3 Geometry Reconstruction

The Fig. 5 shows the 3D point cloud of the Asciello Bridge obtained through laser scanning. The southern and northern paraments are shown in the orthophotos in Fig. 6. The southern parament is the focus of the 2D analysis presented in this paper. The stone blocks were extracted from the nearby Campoli quarry. As can be observed, the masonry texture is regular, consisting of roughly shaped stones and regular joints, both vertical and horizontal. As depicted in Fig. 6, the left side of the bridge shows a sub-vertical transverse crack. This crack is present on both the southern parament, which is the subject of the study, and the northern one, although less pronounced. The reconstruction shown in Fig. 7 highlights that the sub-vertical crack identifies an area that has rigidly rotated

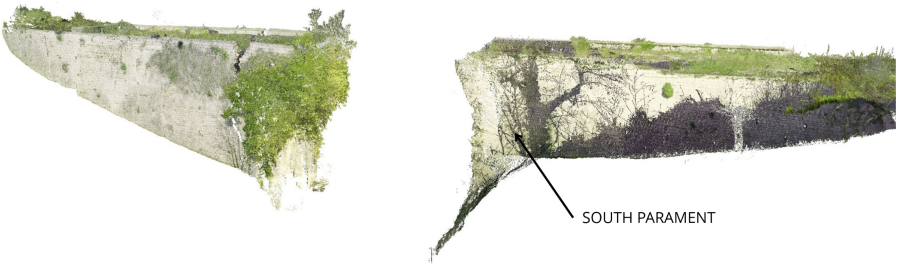

Fig. 5. 3D Point cloud reconstruction of the Asciello Bridge obtained through laser scanning highlights the southern parament, which is the focus of the 2D analysis presented in this paper.

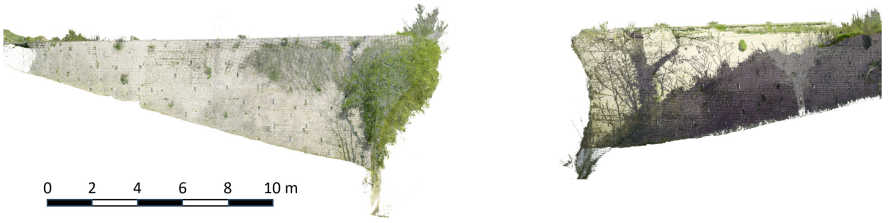

Fig. 6. Orthophoto of the north and south parament of the bridge.

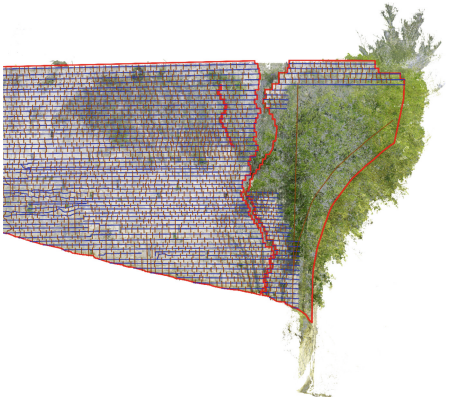

Fig. 7. Zoom-in on the reconstruction of the left abutment of the southern parament. The sub-vertical crack delineates a macroblock that has rotated approximately 2° clockwise. This rotation most likely occurred after the collapse.

by approximately 2° clockwise from the viewer's perspective, likely triggered after the collapse. The whole bridge geometry was derived using laser scanner data for the still-standing portion, while the collapsed one was reconstructed by referring to engineering principles outlined in post-war technical treatises and, importantly, in analogy with the twin bridge (see Fig. 8).

4 Numerical Investigation

This section reports the main steps followed to set the numerical model and perform the subsequent numerical investigation. In particular, Sect. 8 illustrates the model considered for the numerical campaign performed and summarised in Sect. 4. The DEM investigation is performed considering rigid blocks and lumping all block and joint stiffness properties into the normal and tangential stiffnesses of the contact interfaces following the procedure reported in [38]. The contact between blocks was modelled with the Mohr-Coulomb friction law defined by zero cohesion and a friction angle of 35°. The arch geometry was reconstructed following an in-depth geometrical and damage analysis.

4.1 Discretisation

The parametric investigation was performed using Itasca's 3DEC software. In particular, because of the complexity of the bridge and the related computational demand, the investigation was conducted on a 2D interlocked discretisation. The growing need to work with digital stereotomies that closely reflect real geometries is well recognised and supported by several studies. For further details, readers may refer to [54]. Moreover, to balance the results' accuracy and computational demand, the bridge was modelled using mainly prismatic blocks with dimensions equal to 0.50 m × 0.35 m and unit extrusion depth rather than the real stereotomy. This choice was made so that each block of the model corresponded to approximately 4 real blocks. They are staggered by half a brick between one row and the next. For geometric needs, blocks with a trapezoidal or triangular footprint were used where necessary. Indeed, from a technical point of view, it was necessary to model the stereotomy and interlocking between the stones accurately; while, from a numerical point of view, an excessive number of blocks was avoided, as this would have made the parametric analysis inefficient on several selected scenarios due to the high computation times.

It is worth noting that the stereotomy on the left side, undisturbed by the landslide body, is made with horizontal and vertical mortar joints. The right side of the bridge instead has a counter slope of a couple of degrees, even opposite to that of the road axis. The upper parapet of the bridge was also modelled by placing trapezoidal stones that allow the stereotomy to change slope from horizontal to inclined with a counterclockwise rotation.

4.2 DEM Identification of the Collapse Cause

The DEM analysis is conducted on a reduced model, as shown in Fig. 9. The structural geometry is divided into five different zones based on a hypothetical transverse stiffness that accounts for the material stratification between purely structural elements (arch and piers) and the areas with filling, with a decreasing degree of compaction towards the top, up to the blue parament - not considered in the present analysis. All blue slender blocks of Fig. 9 simulate supports, representing the contacts between the bridge and the soil. In particular, all supports

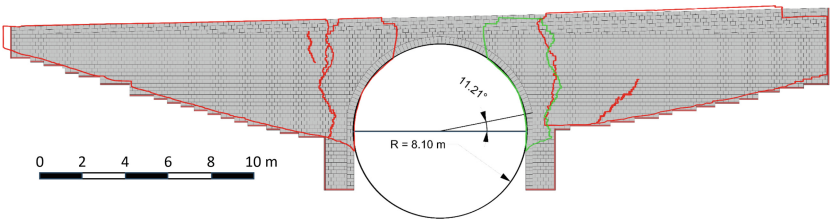

Fig. 8. Bridge geometric reconstruction and digital model with rigid blocks measuring 0.50 m × 0.35 m.

on the right side of the bridge will be used to apply foundation movements, simulating the landslide. The supports on the left side will be considered fixed. As the reader may notice, the left vertical edge of the bridge is not subjected to support conditions to avoid overconstraining the structure. Specifically, the vertical edge on the left part of the boundary, highlighted by the rectangle in Fig. 9, is subjected to surface forces, including a triangular pressure distribution simulating the transmission of the earth's at-rest pressure. The passive earth pressure was not considered for safety reasons. Before performing the parametric analysis, a two-step model calibration was carried out to reduce computational time while minimising errors. The first step focused on the displacement speed of the right supports during settlement. It was observed that speed steps of 0.10 m/s did

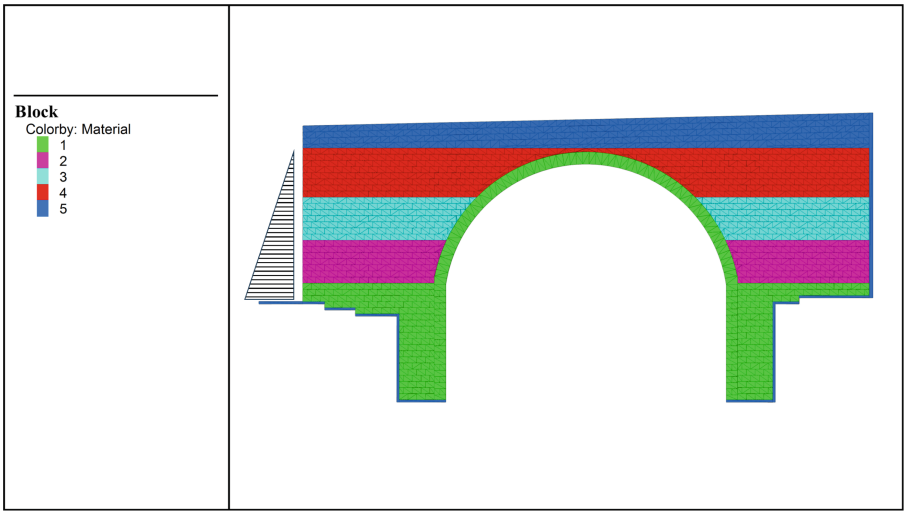

Fig. 9. Reduced geometry considered in the analysis using distinct element software, with subdivision into five structural zones based on the transverse material properties. The area in blue represents the parapet, which will not be included in the DEM numerical campaign. All blue slender blocks represent supports, simulating the contacts between the bridge and the soil. (Color figure online)

not affect the maximum allowable displacement. Consequently, the movement speed of the right support was set to 0.10 m/s. The second step considered the proportional reduction of contact stiffness to decrease computation time. All stiffness values were reduced by 10^3, which did not affect the final displacement but decreased the calculation time by approximately one-third, reducing it from 3 h to 1 h on a laptop equipped with an i7-8700hq Intel processor. The parametric investigation was conducted by varying the inclination of the foundation settlements from 45° to 15° in steps of 5°. The maximum allowable displacement ranged from 1.88 m to 0.95 m. Figures 10 and 11 show the collapse mechanism obtained from the incremental analysis, caused by the right side of the bridge being subjected to an incremental foundation settlement inclined at 45° and 20° with respect to the horizontal plane, respectively.

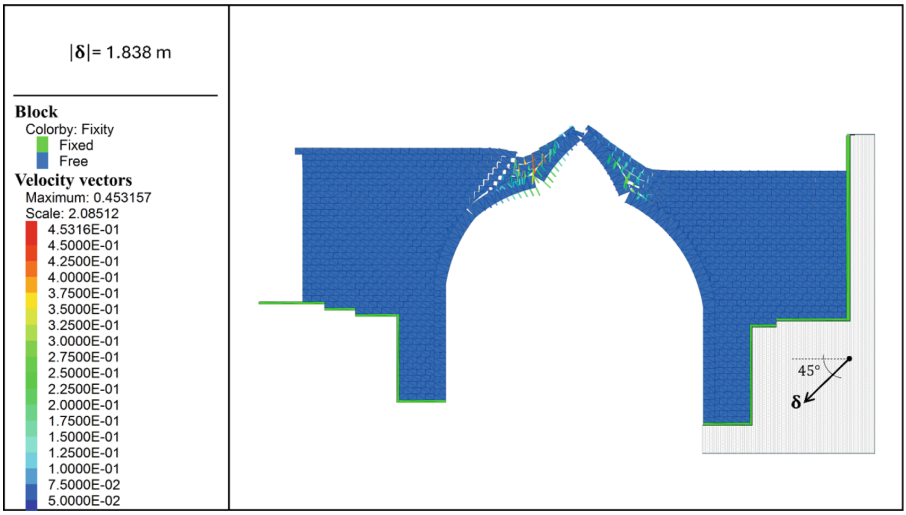

Fig. 10. Onset of the collapse mechanism due to incremental foundation settlement inclined at 45° with respect to the horizontal plane, involving the right side of the bridge. The collapse occurs with a displacement δ of magnitude equal to 1.84 m.

5 Discussion

The main finding is that the collapse was likely caused by a landslide with an average inclination of approximately 20° relative to the horizontal plane, as confirmed by the current overall reciprocal position of the left and right piers. Additionally, it is observed that the reconstructed geometric ratio between the thickness and the internal radius of the arch (t/r) is approximately 1/12. Even considering a non-zero springing angle, this ratio appears too small to guarantee adequate stability for the bridge. This assessment is further supported by

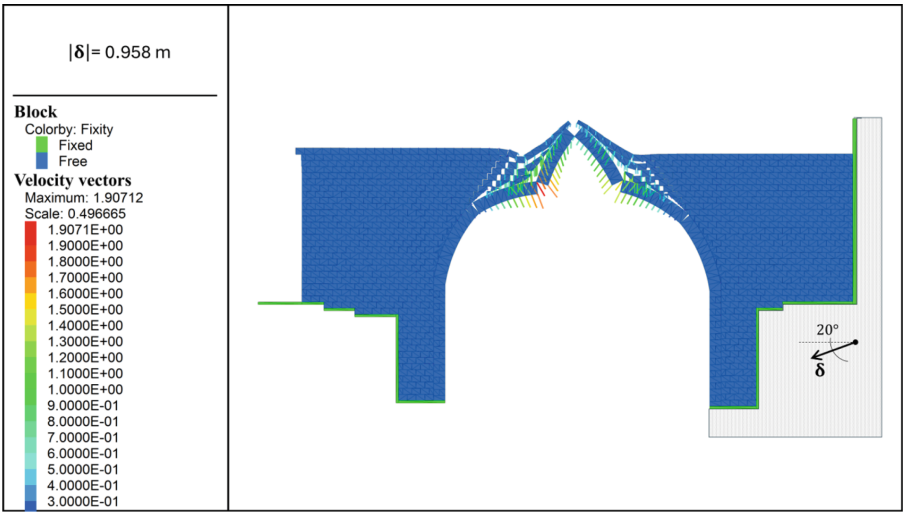

Fig. 11. Onset of the collapse mechanism due to incremental foundation settlement inclined at 45° with respect to the horizontal plane, involving the right side of the bridge. The collapse occurs with a displacement δ of magnitude equal to 0.96 m.

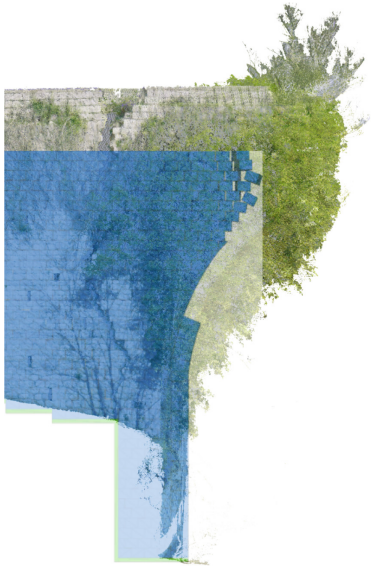

Fig. 12. Overlay of the remaining part related to the left abutment resulting from the incremental displacement analysis with 20° and the current geometry. Although it would need an additional clockwise rotation of 2°, the virtual geometry matches the existing geometry very well.

the fact that the twin bridge underwent rehabilitation works involving the central arch with reinforced concrete, indicating that the Asciello Bridge arch was likely undersized as well. As demonstrated by the numerical analyses, the reduced arch thickness resulted in a low maximum allowable displacement, approximately ranging from $\frac{1}{8}r$ to $\frac{1}{4}r$ of the inner radius for subhorizontal and 45° inclined settlements, respectively. This displacement capacity is about half that of semicircular arches with t/r ratios of 0.15 or 0.20.

Lastly, the geometry of the existing left part of the bridge coincides, except for small motions that occurred in the following decades, with the one coming from the numerical analysis of the digital model as shown in Fig. 12.

6 Conclusions

The main objective of this contribution was to investigate and identify the causes of the collapse of the Asciello Bridge over the Ienga stream in Benevento, Italy.

The parametric investigation demonstrated that the collapse that occurred during the 1960s was due to a landslide affecting one abutment, confirming testimonies collected from the people and technicians of Cautano. Moreover, the proposed study demonstrated that the overall inclination of the landslide should be approximately 15°–25°. The geometry reconstructed through point cloud data and using information from the twin bridge showed that the Asciello Bridge arch was most likely undersized. This resulted in a low displacement capacity, estimated at around 1 m. The study also demonstrates how integrating data from laser scanners and digital image processing enables detailed and in-depth model analysis, providing valuable insights into the development and stratification of the construction techniques used throughout the bridge's history.

However, the analysis presented in this paper cannot be considered exhaustive since, from a structural perspective, further steps would require three-dimensional modeling of the existing geometry and a more accurate survey of the bridge piers. These operations were made impossible by the presence of debris and vegetation in the riverbed. In situ investigations would also be necessary to define the characteristics of the foundation structures and the ground. Despite these limitations, the analysis conducted allowed us to determine, with a good degree of approximation, the cause of the collapse.

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