Life-Cycle of Structures and Infrastructure Systems

Editors
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MS16: Assessment of existing masonry arch bridge infrastructure
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The role of history in the structural assessment of a multi-span masonry arch bridge

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ABSTRACT: The long history of an important multi-span masonry arch bridge built in 1336 in Lecco, Italy, across the Adda River and still in use today is presented here. The study was one of the preliminary stages of an extensive structural investigation project that led to prescriptions on the current use and management of this bridge. The objective is to describe the historical-constructive evolution of the Azzone Visconti Bridge, named after its creator and Lord of Milan; because of its complex and long history, the bridge appears today as the structural assemblage of several substructures. The intent is to present a comparison of different structural modeling approaches, already adopted in the safety assessment of the bridge. Finally, the possibility of implementing the valuable information recovered from the historical study (e.g., existing material heterogeneities, cracking patterns, and past interventions) into alternative analytical models is discussed.

1 INTRODUCTION

Historical bridges are an important part of a country's cultural heritage because their evolution has accompanied the history of a civilization, ready to overcome natural obstacles and facilitate exchanges with neighboring populations. However, in times of battle they were often subject to attack, demolition and reconstruction. For this reason, many of them are registered as protected architectural heritage. Some of them have survived many centuries of use through constant maintenance but have undergone numerous transformations to better adapt to the new demands of the 20th century. Not only external agents, but also increased vehicular traffic, as well as increased maximum allowable accidental loads, represent possible damage factors for the structure. To ensure safe working conditions, the load-bearing capacity of these bridges must be evaluated and demand levels carefully assigned.

The long history of an important multi-span masonry arch bridge built in 1336 in Lecco, Italy, across the Adda River and still in use today is presented here. The study was one of the preliminary stages of an extensive structural investigation project that led to prescriptions on the current use and management of this bridge. As part of an institutional collaboration between the Politecnico di Milano (Lecco Campus) and the Municipality of Lecco, extensive research activity involving different disciplines and research groups was initiated in 2014, with the aim of investigating the load-bearing capacity of the bridge, under the scientific coordination of the last author.

This paper focuses attention on the Azzone Visconti Bridge, a masonry arch bridge that was for centuries (until 1955) the only road connection between the two banks of the Adda River, the only outlet of Lake Como, and is still an important access route to the city of Lecco (northern Italy). The bridge had several abutments and drawbridges and, after later enlargement, now has 11 spans of different sizes. The bridge is considered to be the most important medieval evidence in the city, and is one of the most impressive masonry works in the entire region.

The bridge has been profoundly modified in the 20th century. Because of its complex and long history, it now evidences the structural assemblage of several substructures and has thus lost its homogeneity, becoming more vulnerable.

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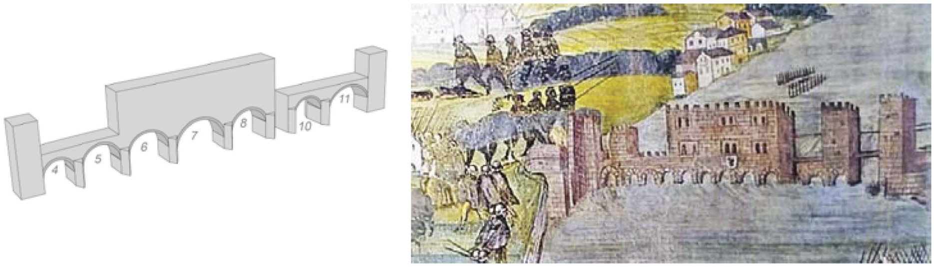
The intent is to present here a comparison of different structural modeling approaches, of varying degrees of sophistication, that have already been adopted in bridge safety assessment. Finally discussing the possibility of implementing the valuable information recovered from the historical study (e.g., existing material heterogeneities, cracking patterns, and past interventions) into alternative analytical models.

2 THE HISTORIC-CONSTRUCTIVE EVOLUTION OF THE BRIDGE

The Azzone Visconti Bridge (also known as *Ponte Vecchio*) is a historic masonry arch bridge built in the 14th century, consisting of ten piers, eleven arches and two abutments, one on the east side of Lecco and one on the west side of Malgrate of the Adda River. It has an overall length of about 133 m and an average deck width of about 6.2 m. Although the bridge appears today to be very different from the original construction, it remains one of the most important examples of military engineering from the Middle Ages.

2.1 *From the origin in the 14th century to the 17th century*

The bridge was built at the behest of the Lord of Milan, Azzone Visconti, between 1336 and 1338, connecting for the first time in the territory the two banks of the Adda River, which until then had belonged to the Duchy of Milan and the Republic of Venice. The bridge was equipped with a stronghold, a central tower and a larger one towards Lecco, while the two heads were equipped with a ravelin (Figure 1a,b). The bridge was also defended by three drawbridges, placed at the fortifications, and was armed with bombs and thrusters. In the 17th century, those who wanted to cross had to pay a toll managed by a consortium composed of several co-owners, nobles from Lecco and Milan, as well as of a monastery.



(a) (b)

Figure 1. Azzone Visconti Bridge: a) model of the 1st phase, mid 14th century (bridge as a fortress with only 8 spans, adapted from di Prisco et al. 2019) and b) detail of the fresco depicting the Battle of Lecco and the bridge with the fortress, in the Medici castle in Melegnano (MI); dating of the painting estimated between 1544 and 1555 (adapted from Comandù et al. 2005).

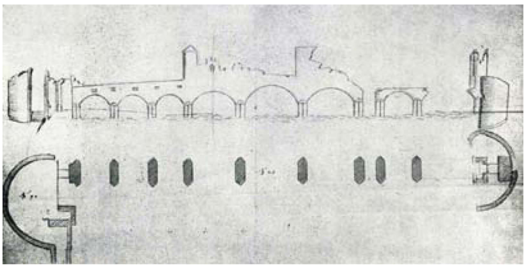


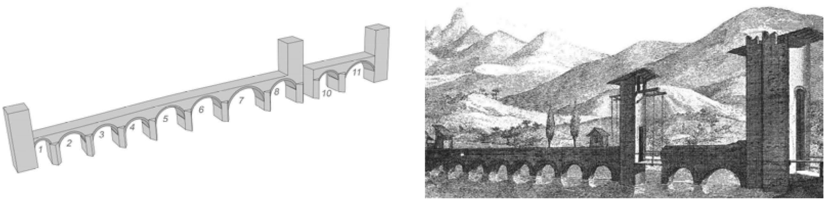
Figure 2. The bridge after 1533, when the great tower was destroyed and already with 11 spans (courtesy of Ambrosiana Library of Milan).

The Azzone Visconti Bridge was originally built with eight arches. The bridge was later expanded in two phases (1350 and 1434) to 11 arches to widen the cross section of the river, favoring faster water flow and reducing flooding in the Como area. The bridge has undergone continual modifications over time due to wars and the water level of Lake Como. In fact, the Adda River is the only emissary of the lake, and the bridge piers constitute an obstacle to the water flow. For this reason, due to repeated flooding of Como at the far end of the other closed branch of the lake, the riverbed was lowered even in the last century and the piers were consequently consolidated.

After the wars fought by Gian Giacomo Medici, known as the Medeghino in 1531, the bridge was severely damaged (Figure 2) (Belloni et al. 1992) and, in the early 17th century (1600-1608), it was renovated on behalf of the Spanish Governor.

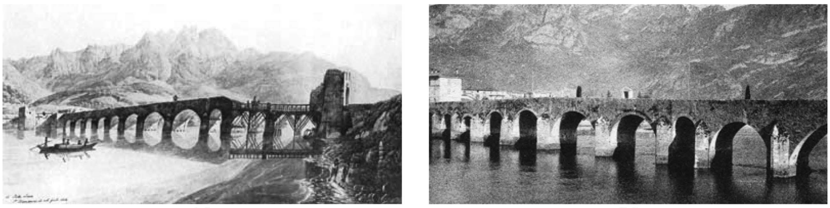
2.2 *The 18th and 19th century*

Its strategic and economic importance would last for centuries (Figure 3a,b), until the last battle won by the Austrian-Russians of the Holy Alliance against the French and Cisalpine troops between April 25 and 27, 1799. On that occasion, the French blew up an archway to slow down the enemy's passage and flight, and this damage would not be repaired until after the end of Napoleonic rule (Figure 4). As a sign of gratitude for the victory, a small chapel was erected in the center of the bridge (Figure 4b), but which is no longer present. In the 19th century, the abolition of the military stronghold of Lecco gave the start to many changes made with the intention of facilitating transit. The lateral towers were demolished to facilitate the passage of carriages (Figure 4).



(a) (b)

Figure 3. Azzone Visconti bridge: a) 2nd phase model, end of 18th century (11-span bridge with towers and drawbridge, adapted from di Prisco et al. 2019); b) view of the bridge, 1760-1771, etching of G.C. Bianchi (Giulini 1760).



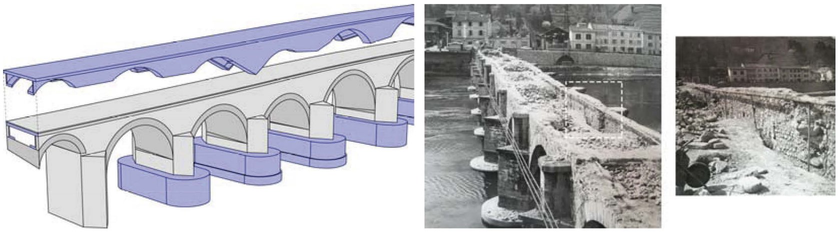
(a) (b)

Figure 4. Azzone Visconti bridge: a) in 1806 (water-colour by P. Birmann) with two demolished towers and two arches destroyed after the Napoleonic damages and b) with reconstructed arches and a small chapel visible in the center of the bridge in the early 20th century (extracted from Resegoneonline.it 2014).

2.3 *The 20th century*

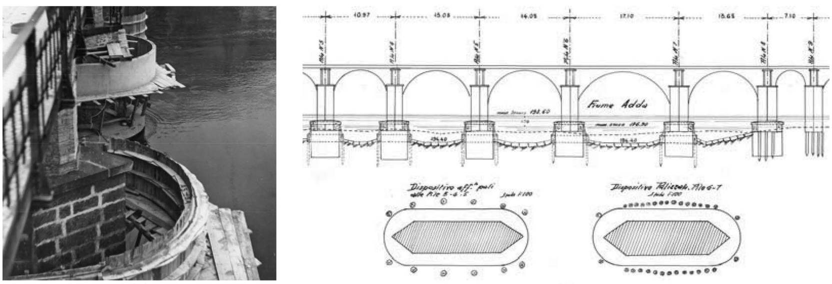
In 1909-1910 the existing bridge deck was enlarged by means of cantilever steel beams to host a tramway and to cope with the increasing traffic. Additional engaged piers were added on both sides to support the cantilevers (visible in Figure 5b). In 1949-1950, a radical intervention was carried out by Prof. Eng. A. Danusso: a) to facilitate the outflow of the river, the riverbed was lowered by about 2 m; b) to protect the bridge piers, the foundations of 7 piers were strengthened; c) the foundation of each pier was reinforced by introducing a large diameter steel encasing ring, about 5 m deep, filled with concrete and constrained at the top by an additional reinforced concrete (RC) outer ring (Figure 6); d) to widen the roadway, the deck was completely removed (Figure 5) and a continuous RC caisson was inserted between the two masonry spandrel walls and filled with coarse granular material (mix of pebbles and mortar). The caisson was made square or U-shaped, depending on the varying height between the extrados of the arches and the deck. e) In addition, the engaged piers (or pilasters) added around 40 years earlier above the cutwaters, were removed.

Three arches damaged by the out-of-plumb of the piers were strengthened. External pedestrian footbridges were also added using cantilever steel beams and RC slabs resting on the aforementioned beams. Over the next 70 years, after this invasive intervention, no further work was carried out other than routine maintenance. Figure 7 shows a view of the bridge as it appears today.



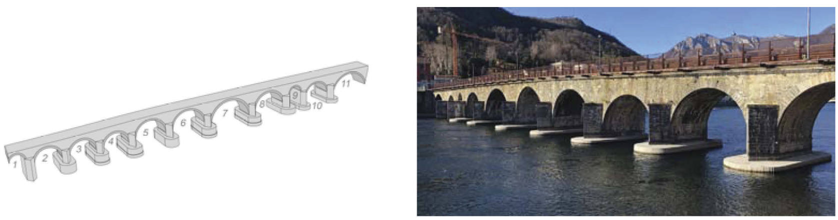
(a) (b)

Figure 5. Azzone Visconti bridge: a) model of the bridge with the most significant strengthening intervention depicted in blue: removal of the original deck and infill, insertion of a continuous concrete caisson and enlargement of the foundations. b) photo before the strengthening when the deck was removed in 1949-1950 and grafted piers were still present. The zoom shows the inner side of the deck after the removal of the infill (courtesy of Lecco Municipality, “Consorzio Fiume Adda” and Ministry of Culture).



(a) (b)

Figure 6. Azzone Visconti bridge: a) strengthening of the piers foundations; b) original drawings of the 1949-1950 project (courtesy of Lecco Municipality, ‘Consorzio Fiume Adda’ and Ministry of Culture).



(a) (b)

Figure 7. Azzone Visconti bridge: a) model representing the current shape (adapted from di Prisco et al. 2019) and b) current view.

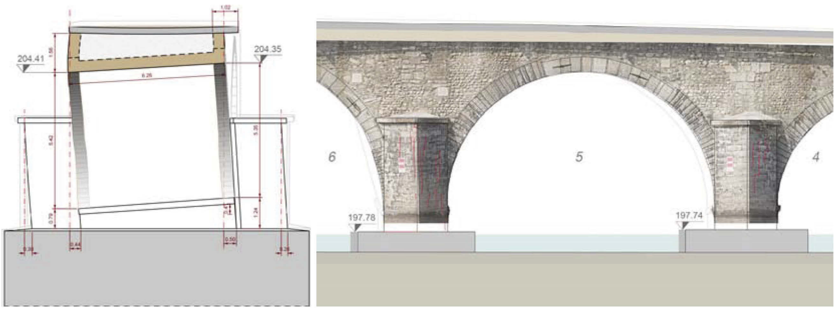
3 REMARKS ON THE HISTORICAL ANALYSIS FOR STRUCTURAL EVALUATION

The bridge has a very irregular geometry, as evidenced by an accurate laser scanner survey (Barazzetti et al. 2016), and has piers with different rotations and very different arch spans, as confirmed by the historical-constructive evolution described above.

Different masonry textures are observed in the spandrels (Figure 8b), from river pebbles arranged in a herringbone pattern in the original arches to roughly cut stones in the modified and/or repaired parts, to more rectangular stones and slabs for the added parts; discontinuities are clearly visible.

Masonry repairs can be observed at the ends of the fortress demolished during the 16th century war (occupying three spans: n. 6, 7 and 8 as in Figure 1). Metallic anchorages placed approximately at the haunches of the arches and arranged in such a way as to have the iron tie-rods in a transverse rather than longitudinal direction are visible (Figure 8b); there is no date of insertion.

The crack pattern, after the last intervention, shows small vertical cracks in the 3 oldest buttresses to the east of the former fortress, where the out-of-plumb of the 5th bay (from the east) already repaired in the 1950s is evident and of about 50 cm (Figure 8a).



(a) (b)

Figure 8. a) Out-of-plumb of the 5th bay southwards and b) photogrammetric view of two piers (south side) at the barrels of arch 5 with the crack pattern survey highlighted in red.

The historical research provided crucial information for future investigations, such as the strong heterogeneity of the bridge structure, modified over the centuries with different constructive techniques. The classification of masonry textures and the crack pattern survey also confirmed the sequence of construction phases showing the discontinuities in the structure highlighted by the historical research (Figure 9), resulting in a refined identification of structural heterogeneities (di Prisco et al. 2019) and helping to better understand the current state of conservation of the bridge. The historical occurrence of damage and cracking, in fact, identifies critical areas that have suffered over time from exceeding the elastic limits of the materials or from the interaction with the river.

At least six different substructures highlighted in different colors were recognized in Figure 9: i) the central portion highlighted in gray, which corresponds to the original construction; ii) the first extension (green) toward the Lecco shore, built about ten years later; iii) the last pier

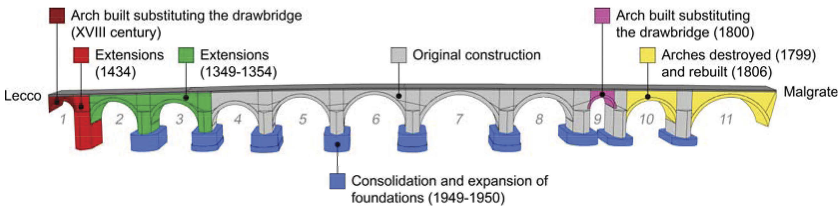


Figure 9. Azzone Visconti bridge: configuration of the historical construction evolution (view of the North side of the bridge, adapted from di Prisco et al. 2019).

finished around one century later (red); iv) the arch built to replace a drawbridge (magenta) at the end of the 18th century; v) the last two arches toward Malgrate (yellow) destroyed in 1799, and rebuilt 7 years later and, finally, vi) the consolidation of the pier foundations in the middle of the last century.

Although in similar cases greater accuracy must be used in modelling the discontinuities and different properties of the masonry must be taken into account, in this precise case, the massive intervention carried out in the 1950s achieved such a stiffening of the deck that it dominated over the underlying inhomogeneities and discontinuities, at least with respect to gravitational forces. Therefore, it can be assumed that the homogeneous models adopted up to now and presented in Martinelli et al. 2018, Zani et al. 2019, 2020 succeed in representing well the actual behavior of the structure.

4 MODELLING APPROACHES FOR HISTORICAL MASONRY BRIDGES

To analyze the response of the Azzone Visconti bridge subjected to a specific load configuration imposed during an acceptance load test, several interpretation models were set up during the investigation (Figure 10). Specifically, limit analysis models using the RING software (RING 2021) and two-dimensional (2D) finite element (FE) analyses implemented in Abaqus (Dassault Systèmes 2016) were developed for the central arches 6-8; additional three-dimensional (3D) FE models, also implemented in Abaqus, were employed to simulate the response of the entire bridge.

RING (Figure 10a) is a simplified and user-friendly analysis tool based on the rigid block limit analysis technique and designed to quickly check the adequacy of masonry arch bridges against the most recurrent failure modes. The 2D FE model depicted in Figure 10b is made with beam-type and plane stress elements combined with translational springs simulating the soil and the infill materials. The full 3D FE model (Figure 10c) is made of solid elements combined with rotational and translational non-linear springs representing the soil. In the 2D FE model the nonlinearity was partially accounted for assuming the tensile strength of the arches equal to zero and assuming a rigid-plastic generalized constitutive relationship with strain hardening and non-associated flow rule for the soil (Nova & Montrasio 1991). The 3D FE model accounted for the material nonlinearity in most of the bridge components by means of the concrete damaged plasticity model (Lubliner et al. 1989; Lee & Fenves 1998). A detailed description of the 2D and 3D FE models is herein omitted but can be found in Martinelli et al. (2018) and Zani et al. (2020), respectively.

Table 1 reports the potentials and limitations of each modelling approach observed in their practical application. The following factors/effects have been considered: (1) role of spandrel walls (if present), (2) role of infill material, (3) transverse behavior, (4) reproduction of existing cracking patterns and local damage, (5) reproduction of material heterogeneities, (6) reproduction of strengthening intervention(s), (7) soil-structure-interaction beneath the foundations, (8) rapid prediction of the ultimate bearing capacity and (9) ease in creating the model and extracting the results.

Table 1. Potential of the modelling approaches described in Section 4 (Y: yes; P: partly; N: no).

	RING model			2D FE model			3D FE model		
Factors/effects	Y	P	N	Y	P	N	Y	P	N
Spandrel walls			•		•		•		
Infill material	•				•		•		
Transverse behavior			•			•	•		
Cracking patterns and local damages		•			•			•	
Material heterogeneities	•			•			•		
Strengthening intervention(s)		•			•		•		
Soil-structure-interaction beneath the foundations			•		•		•		
Rapid prediction of the ultimate bearing capacity	•				•				•
Ease in creating the model and extracting the results	•			•					•

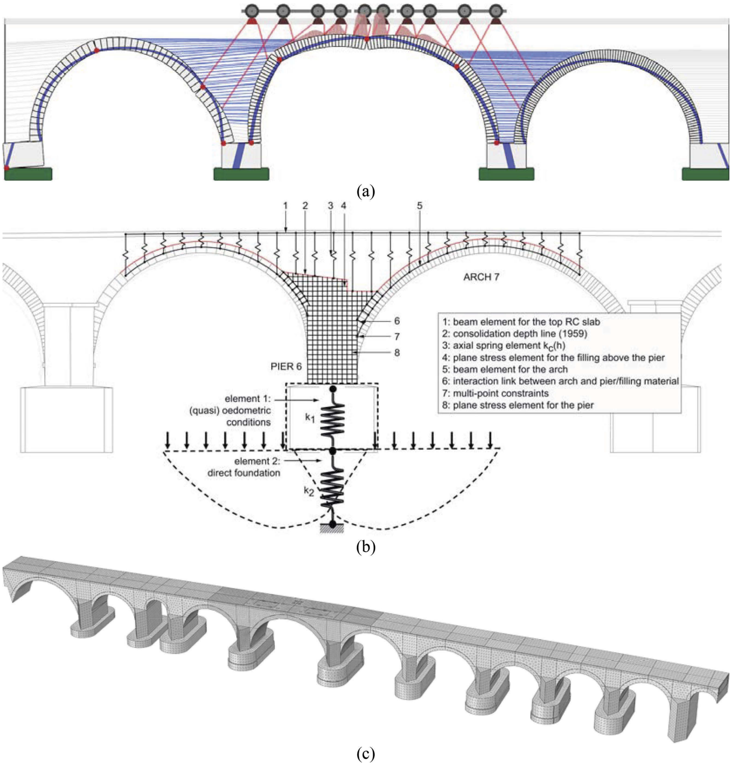


Figure 10. Representation of (a) limit analysis model (aches 6-8), (b) 2D FE model (aches 6-8) and (c) full three-dimensional FE model (adapted from Zani et al. 2020).

Regarding the RING model, the main limitations are due to the difficulty in correctly reproducing reinforcement interventions (such as the presence of a complex RC caisson) and simulating the nonlinear soil-structure interaction beneath the foundations. On the other hand, one of the main advantages – aside from the ease of model creation and results extraction – is the rapid assessment of the ultimate capacity of the bridge with regard to masonry components.

As for the 2D FE model, the main limitations include the difficulty in reproducing the transverse behavior and the partial reproduction of the infill and spandrel walls. The ease in creating the model and extracting the results is one of the main merits.

Concerning the 3D FE model, the main limitation is the computational burden combined with significant effort in model creation and result extraction. Strengthening interventions and transverse behavior can be captured correctly. The 3D FE model also allows reliable reproduction of the nonlinear soil-structure interaction. According to the authors, both the 2D and 3D nonlinear FE models risk providing a less reliable estimate of ultimate capacity than that provided by limit analysis, as the increased sophistication of the simulations could lead to a reduced control over unpredicted numerical phenomena.

5 CONCLUSIONS

The paper presents the historical-constructive evolution of an important multi-span masonry arch bridge (named Azzone Visconti Bridge) built in 1336 in Lecco. The bridge has undergone several transformations over the centuries, growing from the original eight arches to the current eleven. The bridge was also profoundly modified in the 20^{th} century with strengthening works aimed at adapting it to the new requirements of vehicular traffic, but distorting its homogeneity.

A comparison of three different structural modeling approaches with varying degrees of sophistication, namely limit analysis, 2D nonlinear FE analysis, and 3D nonlinear FE analysis, is presented. The potentials and limitations of each approach are highlighted using the Azzone Visconti Bridge as a case study. The strengthening interventions, which played a key role in correctly reproducing the structural behavior of the Azzone Visconti bridge, are difficult to reproduce with limit analysis models and require the use of advanced 3D FE analysis. Correct reproduction of the bridge transverse behavior and soil-structure interaction also requires the use of 3D FE analysis. Limit analysis provides a rapid assessment of the ultimate bearing capacity of ordinary multi-span masonry arch bridges, whereas 2D and 3D FE analyses, given their increasing level of sophistication, require more effort to provide reliable predictions.

Finally, the work also highlights the importance of uncovering and interpreting historical information related to the bridge. For example, the past presence of towers later destroyed may play a decisive role in the over-consolidation of the soil beneath the foundations and can provide useful information about the significant loads sustained by the structure over time.

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