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Historical Arch Bridges-Deterioration and Restoration Techniques

Amin Bagherzadeh Azar [1*], Ali Sari [2]

[1] *Institute of Earthquake Engineering and Disaster Management (ITU Graduate School), Istanbul Technical University, Istanbul, Turkey.*

[2] *Faculty of Civil Engineering, Istanbul Technical University, Istanbul, Turkey.*

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Abstract

Historic buildings are the most valuable evidence of cultural heritage. They play an essential role in establishing a tangible link between the past and the present by understanding, interpreting, and tracing the epoch of civilization. Unfortunately, the high costs of restoration, vandalism, and arson take their toll. However, new technologies are having a positive impact on the restoration process and are becoming a suitable alternative to labor-intensive, expensive, and unsafe traditional inspections. Therefore, the role of non-destructive testing (NDT) as a new method is becoming more evident. Faro laser scanning, impact echo, impulse sound testing, and geoelectric tomography as non-destructive methods are leading to the inspection of historic structures to preserve their character. These new methods are representative of the development of non-contact techniques for the examination and documentation of structures. Non-destructive testing examines the internal and external structure of complex building components as well as defective areas, quantifies cracks, and detects near-surface moisture. The objective of this work is to identify new adventurous and traditional methods for the reconstruction of the Turkish arch bridges Dara-1 and Halilviran to determine the appropriate rehabilitation methods and their deterioration of construction materials, damage, and failure patterns. Bridge dimensions were measured using a Faro laser scanner, which allows inspectors to capture and evaluate data from bridges and structural components without permanently altering them. The laser captures bridge dimensions by scanning cross-sections of the structure in the horizontal and vertical planes. The data is exported in the form of point clouds that represent all visible aspects and actual dimensions of the bridge in 2D and 3D models. In comparison between traditional and laser scanning methods, the main advantages of the applied method are the time savings on-site and the creation of a three-dimensional model of the structure, which can be used to collect precise and accurate surface data of objects in a non-destructive manner.

Keywords: Historic Bridges; Methods of Restoration; Arch Bridges; Faro Laser Scanner; Destruction.

1. Introduction

The protection and preservation of monuments are the most critical issues for the continuity of history that require attention. The history of bridges looks back over the past centuries to improve people's lives, promote the economic and social well-being of society, but also meet military needs and overcome natural obstacles. Unfortunately, in recent years, research has focused exclusively on modern cable and concrete bridges, while historical bridges have not yet received special attention. However, in industrialized countries, masonry bridges are still widely used, mainly for their cultural and structural value. Although they are all unique symbols of cultural heritage, some natural or man-made hazards cause significant damage, some of which is irreparable. During these natural or man-made impacts, such as floods or earthquakes, the bridges have been partially or completely damaged. To address this damage, repairs have been made to the historic arch bridges. The success of the repair work depends on both a detailed archaeological-historical survey and a detailed structural engineering assessment, which are being conducted together. It is very important to find answers to questions such as the date and time of construction of the structure, whether there was an interruption in the

* Corresponding author: azar19@itu.edu.tr

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construction process, the scheme and sequence of damage to the structure, and what repairs and reinforcements were made to the structure. Then, the repair method is determined, such as partial or complete demolition, regional repair or strengthening, eliminating excess weight, balancing mass and stiffness distribution, improving structural interaction between arches and feet, and strengthening the bridge foundation system. When repairing damage, the main goal is to restore the old strength of monuments without compromising their historical structure.

Erdal's work dealt with the control and maintenance management of bridges. In this study, the types of deterioration of stone bridges were investigated [1]. Ural et al. provided general and structural information on historic arch bridges. They presented structural damage to arch bridges in the Karadeniz region and presented repair and strengthening procedures. They pointed out repair and reinforcement techniques applied to stone arch bridges [2]. Yucel & Namli studied the effects of water and other factors on the deformation of bridge piers and abutments. They concluded that the deformation around the bridge pier is closely related to the flow regime, the bed material, and the foundation type, and that it is necessary to study the specifications of the flows and the measures against the deformations occurring in the bridge foundation area, as well as the velocity changes and the pressure range, in order to determine the most suitable bridge foundation type based on these data [3]. Firat & Eren studied the effects of applying FRP reinforcements to the damaged arch of a masonry bridge. The reinforcement technique was numerically modeled for the arch using a structural analysis program. They compared the experimental and numerical results [4].

Bayraktar et al. studied the effects of finite element model improvement on the earthquake behavior of historic bridges. They selected the Sinik Bridge in Trabzon for this study. They then compared the dynamic properties of the bridge determined experimentally and theoretically. Based on these data, they updated the finite element model of the bridge and created a model as realistic as possible [5]. Alaboz investigated the current condition of the architectural Sinan bridges in the Marmara region, determined the causes of damage, and developed appropriate repair recommendations [6]. Koc investigated the effects of different FRP strengthening techniques that can be applied to damaged stone arch systems. For this purpose, the reference specimen was loaded to failure, and six specimens other than the reference specimen were initially damaged at 75% of the collapse load of the reference specimen. The tests showed that FRP strengthening techniques have a great impact on the resistance of masonry bridges and improve the load-carrying capacity of the bridge [7]. Korkmaz et al. performed a dynamic analysis of the historic Timisvat stone arch bridge in Rize. They compared the displacement and stress values obtained from the analyses. Through the analysis, they proposed a suitable model that shows how the finite element models affect the restoration of the historic arch bridges [8].

Alpaslan et al. studied the results of dynamic analysis in the case of strengthening by applying stiffer material to undamaged and damaged areas of a historic masonry bridge. In the dynamic analysis, they showed that the damaged elements of the historic structure negatively affect the behavior of the structure due to load transfer [9]. The static behavior of masonry arch bridges depends to a large extent on the quality of the material, such as mortar. Therefore, it is important to pay attention to the material used during restoration because it should not only reinforce the structure but also be compatible with it. Due to the insufficient properties and incompatibility of Portland cement with many natural stones (the injection of cement mortar and the use of reinforced concrete increase the dead weight and rigidity of structures), lime mortar has become very popular instead of Portland cement in the restoration of historical structures. In fact, Portland cement is problematic as a restoration material for natural stone bridges because it has low chemical and physical affinity with traditional building materials, and soluble salts such as calcium sulfate and sodium salts are sometimes present in Portland cement that attack concrete [10]. However, lime mortar has disadvantages that may mean it is not always the right choice for restoration. Slow carbonation is one of the main causes of the declining use of lime mortar, which is necessary to make the mortar harder and more durable. Compressive and flexural strength measurements, as well as X-ray diffraction (XRD) and thermal tests, are used to determine the degree of carbonation of the mortar. It is known that it can take many years for lime mortars to reach full carbonation [11].

The mechanical properties and high porosity were other factors that contributed to Portland cement overtaking lime mortar in popularity [12]. Therefore, the selection of appropriate methods and materials for the restoration of historical monuments is complicated. However, prior to restoration, a proper evaluation process should be considered to ensure that structures meet the appropriate requirements. It is crucial to regularly repair historical monuments and develop appropriate salvage projects to protect heritage by bringing it to light without neglecting its unique cultural values. In recent years, there has been a trend towards the use of non-destructive and less destructive testing methods (NDT and MDT). The technology for in-situ experimental assessment of structures has greatly improved and is widely used. There are various non-destructive testing methods used in the evaluation and testing of masonry arch bridges, such as sonic/ultrasonic, electromagnetic, electrical, and infrared thermographic methods [13]. Each NDT method provides different information about the physical properties of the masonry structure. Faro laser scanning is one of the most commonly recommended NDT methods for masonry arch bridges. It is a relatively fast technique that provides a qualitative overall picture of the exterior envelope. This technique has proven to be very useful as it provides valuable information about the geometry. It is an advanced technology for metric documentation of structures, mainly due to the high measurement rate over the structure surface with millimeter accuracy [14, 15]. The precise geometry data obtained by laser scanning has been shown to be an input for the creation of large and realistic numerical models.

2. Geological and Characteristic Features of Case Study

2.1. Anatolia in Turkey

Anatolia is rich in numerous monuments and bridges of architectural and art historical importance in all parts of the country. Most of these bridges date back to the Roman and Ottoman periods. In the Roman and Ottoman periods, various bridges were built with different characteristics, which differed in elements, composition, construction techniques, and use of materials according to the characteristics of the site and the period of construction [16, 17]. Stone arch bridges are widely used in this era because of the presence of natural materials in the area, the ability to withstand vertical loads due to their high dead weight, and the ability to carry traffic loads due to their simple but effective structural system. The Dara I Bridge (Figure 1) in Mardin Artuklu and the Halilviran Bridge (Figure 2) in Diyarbakir were first built in the Roman period and have survived until today thanks to extensive interventions and repairs during the Ottoman period.

Figure 1. Dara Bridge

Figure 2. Halilviran Bridge

These bridges and regions connecting different parts of the cities have hosted dozens of civilizations and religions, as well as ethnic groups with different cultures that have lived together in solidarity for hundreds of thousands of years. Throughout history, this region was an important caravan city, and the war routes remained in the hands of Rome and Byzantium for a long time after the rule of the Persians.

2.2. Dara - Halilviran Bridges

Dara Bridge, 30 km from Mardin province, is an old border settlement in Oguz village. It is located 8 km from the Mardin-Nusaybin highway at the junction of the Mesopotamian plain and the Tur Mountains to the north. Dara, which was built as a military base, is located in a chain of "limes" consisting of towns and military forts. It was built for defensive purposes on the eastern border of the Roman Empire. The bridge, which belongs to the group of round arch bridges with three arches, the central arch being wider and higher than the others, is today partially destroyed. No parapet remains were found on the east and west facades, and collapses were observed. The structure has a length of 26.60 m, a width of 7.15 m, and a height of about 5.30 m. Halilviran Bridge is 20 km away from Diyarbakir. It is located above the Devegecidi watercourse. There is considerable loss of substance on both sides of the deck. The structure is built of regularly hewn stones. The central arch of the bridge is a round arch that rises on the rocky ground in both directions of the riverbed. The bridge, built to cross the river barrier, is a masonry structure with seven arches. The total length is 132 meters, and the carriageway width is 5.10 meters. The height of the bridge above the ground is 8.50 meters. The spans of the arches are 6.80 meters, 7.00 meters, 6.90 meters, 6.95 meters, 6.90 meters, 6.95 meters and 5.95 meters from west to east. The last arch in the east (7th arch in the row) has a slightly different shape and is kept lower than the others, a pointed arch that looks very similar to the round arch.

2.3. Methodology

Laser scanners were used to digitize objects of various sizes, from small diagnostic artifacts to large, complex sites of monumental architecture. The demonstration study was conducted to investigate the technical feasibility of using laser scanning technologies to record the as-built condition of historic bridges. Three-dimensional (3D) laser scanners were used as the instrument for the non-destructive acquisition of precise and accurate surface data on objects. These devices use an infrared light beam to calculate the distance to an object and record it as data points with spatial coordinates. This data is then analyzed using various types of computer software to create a detailed image (Figures 3 and 4) with coordinates and dimensions. During the course of the project, the scanner will be placed at several locations inside and outside the bridge so that all visible surfaces of the bridge can be documented.

The distance to the objects defining an area is calculated, as well as their relative vertical and horizontal angles. After all visible parts of the bridge have been scanned, the software files are linked to the FARO Scene software. With this software, a person can identify the targets placed before the scan and use them to link or append one scan to another. It is also possible to use different techniques or software to filter out extraneous images (e.g., a vehicle driving over the bridge or background vegetation). Once a bridge is fully assembled from all the individual scans, it can be exported as a point cloud that contains all the visible aspects and actual dimensions of the bridge. This collected point cloud can be converted to the actual shape of the object and exported to AutoCAD software. Once a point cloud is exported to AutoCAD, it can be divided into multiple cross sections, and from that point, two-dimensional (2D) and 3D models of the bridge can be created. Figure 5 clearly shows the methodology used to achieve the objective of this study.

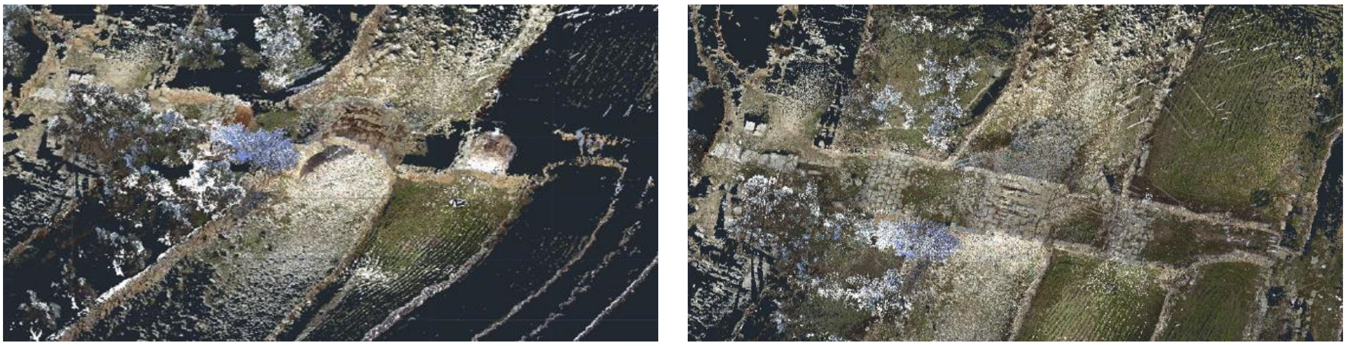


Figure 3. Laser Scanner measurement of Dara Bridge

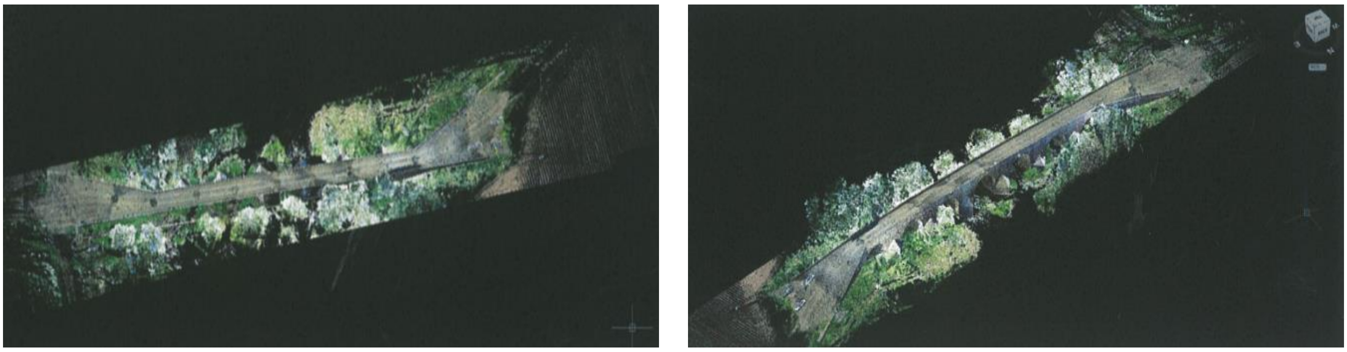


Figure 4. Laser scanner measurement of Halilviran Bridge

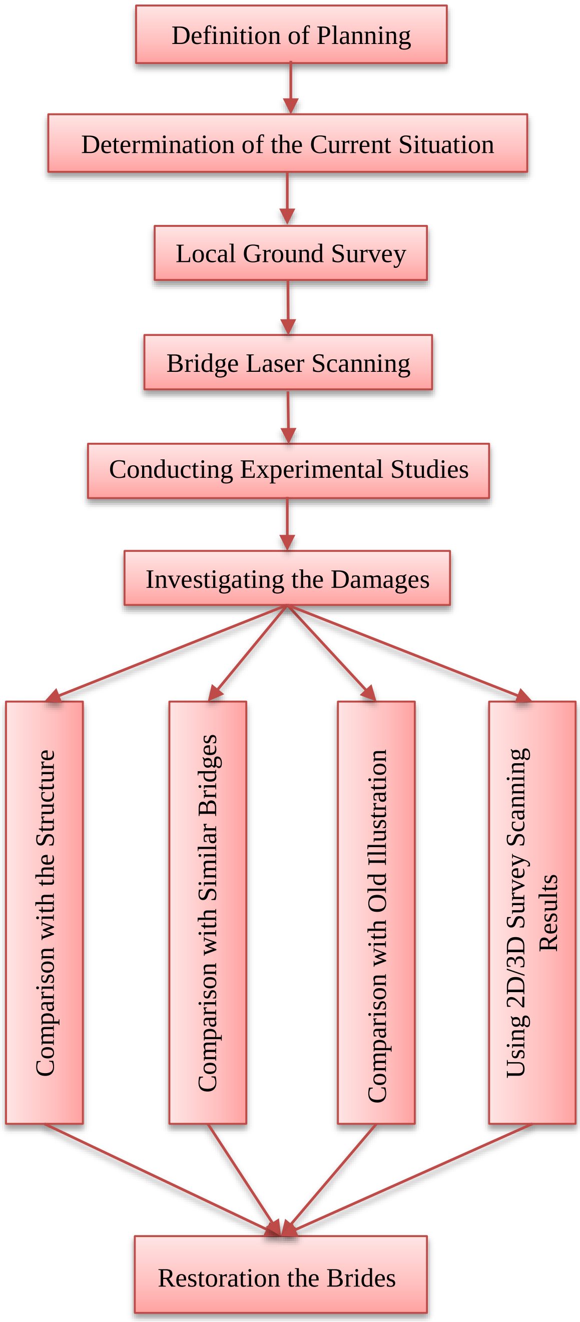


Figure 5. Clearly shows the methodology used to achieve the objective of this study

3. Damage and Deterioration Elements of the Case Study

The technical reasons for bridge damage must be clarified prior to any rehabilitation and restoration. Generally, bridge damage is due to natural and human causes, so determining the cause of the damage will lead to the desired result. A masonry bridge consists of main and secondary structural elements. Foundations, piers and abutments, arches, parapet walls, and wing walls are the main structural components. In contrast, breakwaters, flood control arches, and supporting arches are considered secondary structural elements that had different shapes and structures in different periods [18–22].

3.1. Foundation

The foundation is the lowest part of a bridge. Various materials and techniques have been used for masonry bridge foundations, such as wooden piles, which are particularly suitable and ideal for bridges with weak soil properties. The foundation system of the bridges in both case studies is located on the rocky subsoil. Foundation erosion and material loss were observed in both bridges (Figures 6 and 7). This damage is usually due to changes in soil conditions, a lack of protection of the foundations, and deterioration of their materials, which can lead to serious problems with the durability of the bridge structure and, in some cases, even the destruction of the bridge. During floods, large stones are carried away by the water and break onto the Halilviran Bridge. The bridges are subjected to the impact of these objects in addition to the hydrodynamic pressure. Weak stones are broken, and the mortar between the stones has dissolved due to these impacts. On the other hand, the height of the water causes a change in the riverbed. These phenomena damage the soil and erode the foundations of the bridges, causing cracks and fractures and damaging the piers of the two bridges. In addition, the vegetation surrounding the foundations favors the erosion of the stones. The roots have penetrated the foundations, allowing water to effectively dissolve the mortar and promote erosion of the stones through capillary moisture via groundwater to the foundation.

Figure 6. Erosion on the foundations of Bridge

Figure 7. Large stones and trees are carried onto the bridge

3.2. Piers and Abutments

Abutment foundations transmit high pressure to the earth, subjecting them to large deformations and different displacements that endanger masonry arch structures since they lead to a lack of horizontal and rotational restraint at the base of the arch, which in turn can lead to uplift and eventual collapse. In both cases, the piers are made of rectangular, finely hewn sandstone, but the internal fills of the piers were not observed. Like the piers, the abutments in the lower part of the Dara Bridge are also severely damaged (Figure 8). The water causes corrosion of the embedded rock and a decrease in the mechanical strength of the piers and abutments. Vegetation was observed on the Halilviran piers (Figure 9). This vegetation can mask existing damage during an on-site inspection and is responsible for existing capillary cracking on the abutments and piers, both of which contribute to accelerating the deterioration of the bridge and its materials. In addition to plants damaging the structure with their roots, various species of fungi and bacteria have also been found on the stones. Moisture has also damaged the stones of the piers and abutments, as water has penetrated the masonry in both cases. At the same time, the persistent moisture in both cases leads to rot, the loss of mortar joints, and the softening of the stone in the masonry.

Figure 8. Damaged abutment of bridge

Figure 9. Growth of vegetation on the piers

Alterations for functional purposes, the collapse of some parts of both bridges, and the removal of stones for personal purposes such as human vandalism are evident in both cases. Among the significant construction-related damage to the piers and abutments of the Dara Bridge are restorations by inexperienced and unskilled neighbours.

3.3. Arches

They consist of rectangular or wedge-shaped stones called voussoir. Most of the voussoir of the three round arches of the Dara Bridge (Figure 10) are damaged and have deformed over time. Overgrowth is visible on the top of the arch. Several longitudinal and transverse cracks occur on the arch of Halilviran Bridge (Figure 11) under the influence of static and dynamic forces. In addition, some parts of the DARA arch were repaired with inappropriate materials. During the earlier restoration, the poor quality of the mortar could be seen, so that some stones could be easily removed.

Figure 10. Damage arch of the Dara Bridge

Figure 11. Arch of the Halilviran Bridge

3.4. Spandrel Wall

Triangular pieces of wall between the extrados of the arches and the roadway (McAfee, 1998). In the case study bridge, the construction technique observed in the abutments is repeated in the spandrel walls, which suffer from vandalism and moisture (Figure 12).

Figure 12. Spandrel wall of Halilviran Bridge

3.5. Breakwater

Breakwaters were built next to the upstream facade of the piers to protect the bridge from high tides and swift currents. The breakwater of Halilviran Bridge (Figure 13) suffers from fouling, which contributes to compaction, but also leads to deficiencies in the waterproofing. It suffers from softening and loss of mass due to persistent moisture. In the long run, sedimentation has effectively compensated for the erosion of the bridge breakwater. On the other hand, the breakwater of the Dara has also been completely deformed and ruined over time.

Figure 13. Breakwaters suffer from vegetation and deformation

3.6. Roadway

The Dara roadway has completely deformed over time, and the Halilviran alignment (Figure 14) has suffered some damage. The roads between the two case study bridges are paved with cut and small gravel stones. Vegetation was found in both cases. The existing vegetation can promote compaction, but on the other hand, it can also cause waterproofing and capillary drainage problems. The absorption of water in porous materials significantly affects the behavior and material properties of the Dara. In addition, weak cohesion between material particles, such as two adjacent elements (Figure 15), an inefficient and non-existent drainage system, a lack of waterproofing, capillary absorption of water from the soil and atmosphere, insufficient maintenance, and weak frost resistance of the material affect the stability and esthetics of the whole structure. On the other hand, inadequate covers and drainage systems can allow rainwater to enter the bridge body. The Dara is backfilled with low-quality crushed and cut stone, resulting in imbalances in fill thickness and core weight. This condition leads to an unbalanced distribution of stiffness and regional damage as the material expands during high temperatures in the summer and freezes in cold winters. On the other hand, the absence of drains leads to crystallization and consequent rotting of the steel elements embedded in the bridges, resulting in the demolition of the load-bearing section. In addition, both bridges are exposed to acid rain, which leads to various stresses and damage to the deck and other components due to inadequate drainage and waterproofing.

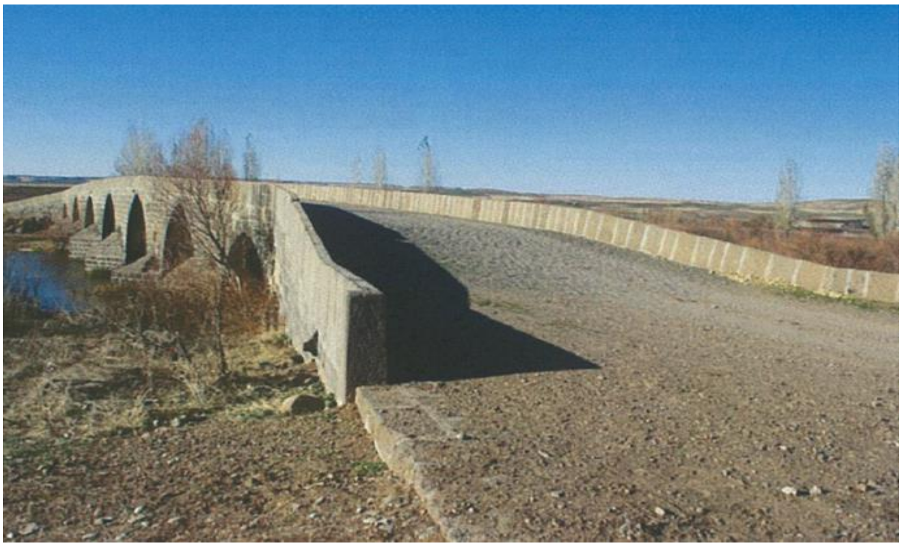


Figure 14. Halilviran bridge roadway

Figure 15. Weak adhesion between adjacent elements

In addition, structures, especially historic bridges, have suffered from the seismic behavior of earthquakes in recent centuries. When historic structures built in earthquake zones are carefully examined, traces of seismic retrofitting and ruins can be found. Earthquake damage has occurred mainly in the middle of the arches in the form of cracks and detachment of the deck, which can cause irreparable damage to the bridges. These ruins can serve as clues for seismic retrofitting and contribute to current restoration projects for proper rehabilitation [23]. According to historical findings, historic masonry bridges were not designed to withstand seismic events, unlike modern bridges made of reinforced concrete and steel or with seismic isolation [24–27]. As a result, they occasionally collapsed partially or completely during earthquakes.

Turkey is one of the most earthquake-prone countries and is frequently hit by destructive earthquakes. The country is located in a tectonically active region of the earth and has two major fault zones, the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ), so historic bridges in Turkey have been exposed to many earthquakes throughout history, and this should be taken into account when restoring and strengthening old bridges. On the other hand, bridges throughout history were built for a specific purpose, such as military use and transportation of war supplies; therefore, the destruction of a bridge helps enemy forces immensely. For this reason, bridges have also been damaged during wars in past centuries. In addition, the aging of masonry results in a continuous deterioration of the safety level of a structure, both in terms of operational and load-bearing capacity, compared to its original condition. In addition to the aging process, geotechnical or hydraulic problems are often the cause of structural damage [28].

4. Restoration Techniques

Stone and other materials of this type are resistant to compression and shear but cannot withstand large tensile forces, so masonry arch bridges were designed to be under constant compression. However, they were susceptible to damage from horizontal forces caused by earthquakes. Therefore, the proper rehabilitation solution for a bridge must be selected considering the structural behavior of the bridge and the existing damage. In order to select the most efficient repair and strengthening techniques, an essential first step is to develop practical maintenance / preservation, and rehabilitation measures to understand the causes of deterioration and apply appropriate rehabilitation approaches. Three sources of remediation measures were used in the case studies: Comparisons within the structure, with similar bridges, and old photographs (Figures 16 and 17). At the same time, 3D surveying provides data on the surfaces of the structure. Information about the cross-section of the bridge was collected based on the damaged parts, and attempts were made to find the removed elements using old photographs. Unobserved parts, especially the foundations, were supplemented with data from the literature. Most of the literature deals with Roman foundations, and some with Ottoman foundations. Based on this information, a 2D reconstruction drawing was then created using the collected data on the damaged parts of the bridge.

Figure 16. Halilviran Bridge (Cevdet Çulpan 1970)

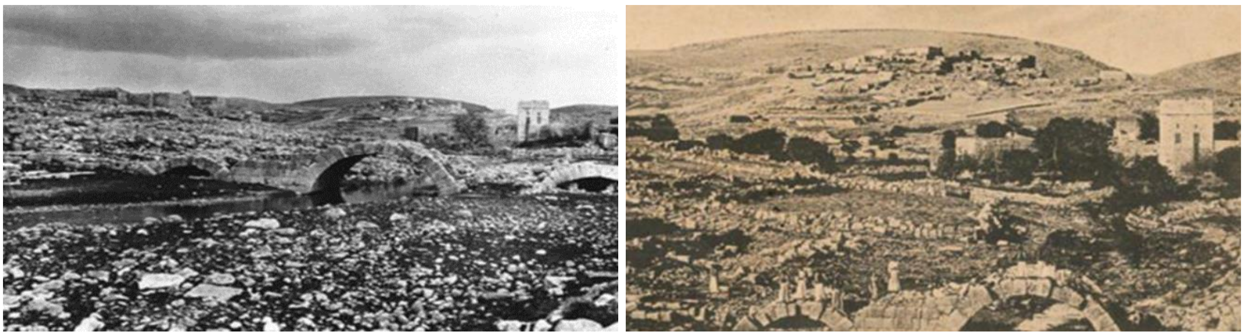


Figure 17. Dara bridge 1900 (Cevdet Çulpan 1970)

Based on this information, a 2D reconstruction drawing (Figures 18 and 19) was created using the collected data on the damaged parts of the bridge, a literature review, and an old photograph, and then fifteen construction phases were defined.

	Deteriorated and Damaged Stones
	Roadway Accumulated Soil
	Vegetation
	Embankments in the structure and in the river
	Stone loos mass
	Removed stone
	Deteriorated and Damaged Stones

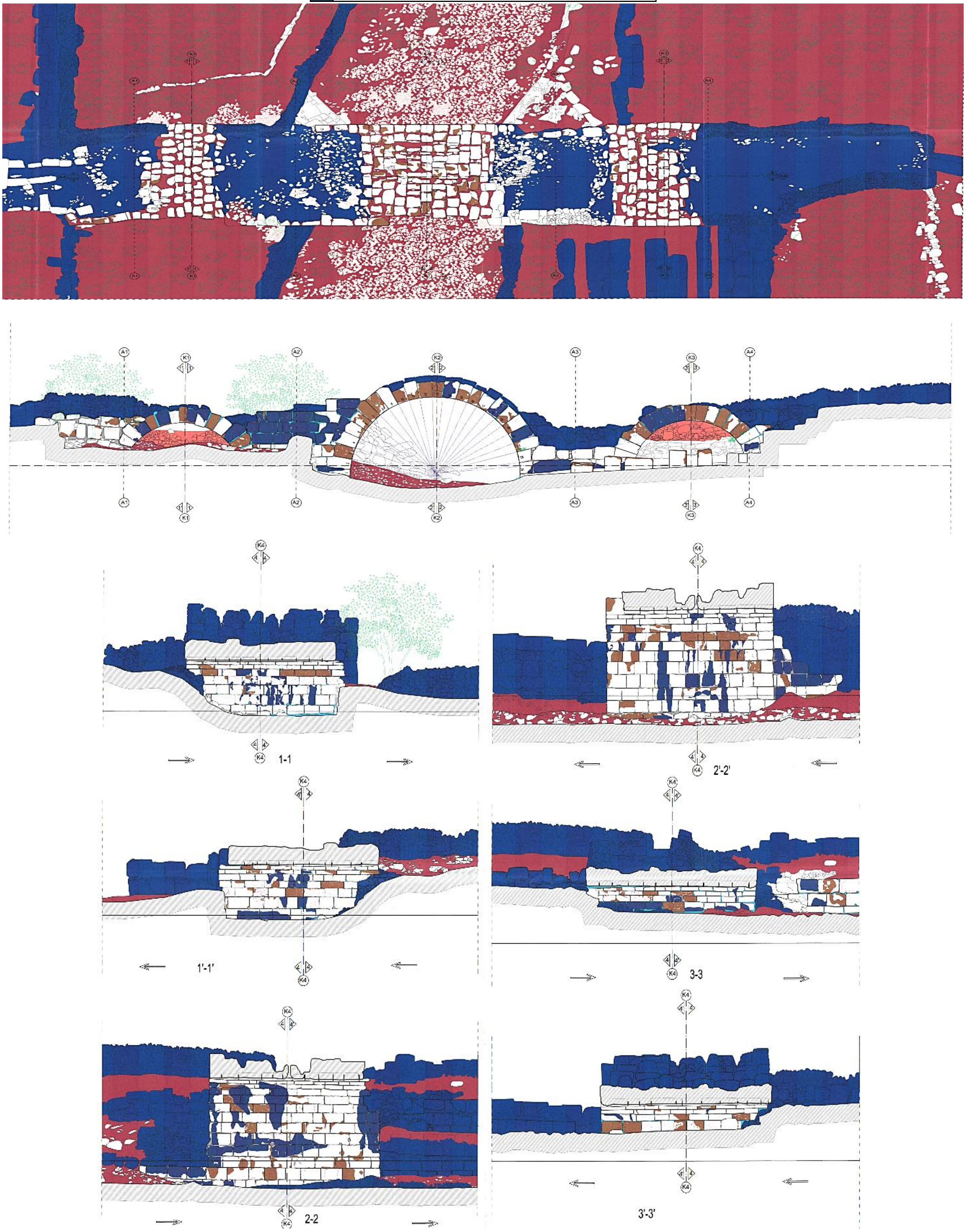


Figure 18. 2D plan of DARA Bridge

	Deteriorated and Damaged Stones
	Roadway Accumulated Soil
	Vegetation
	Embankments in the structure and in the river
	Stone loos mass
	Removed stone

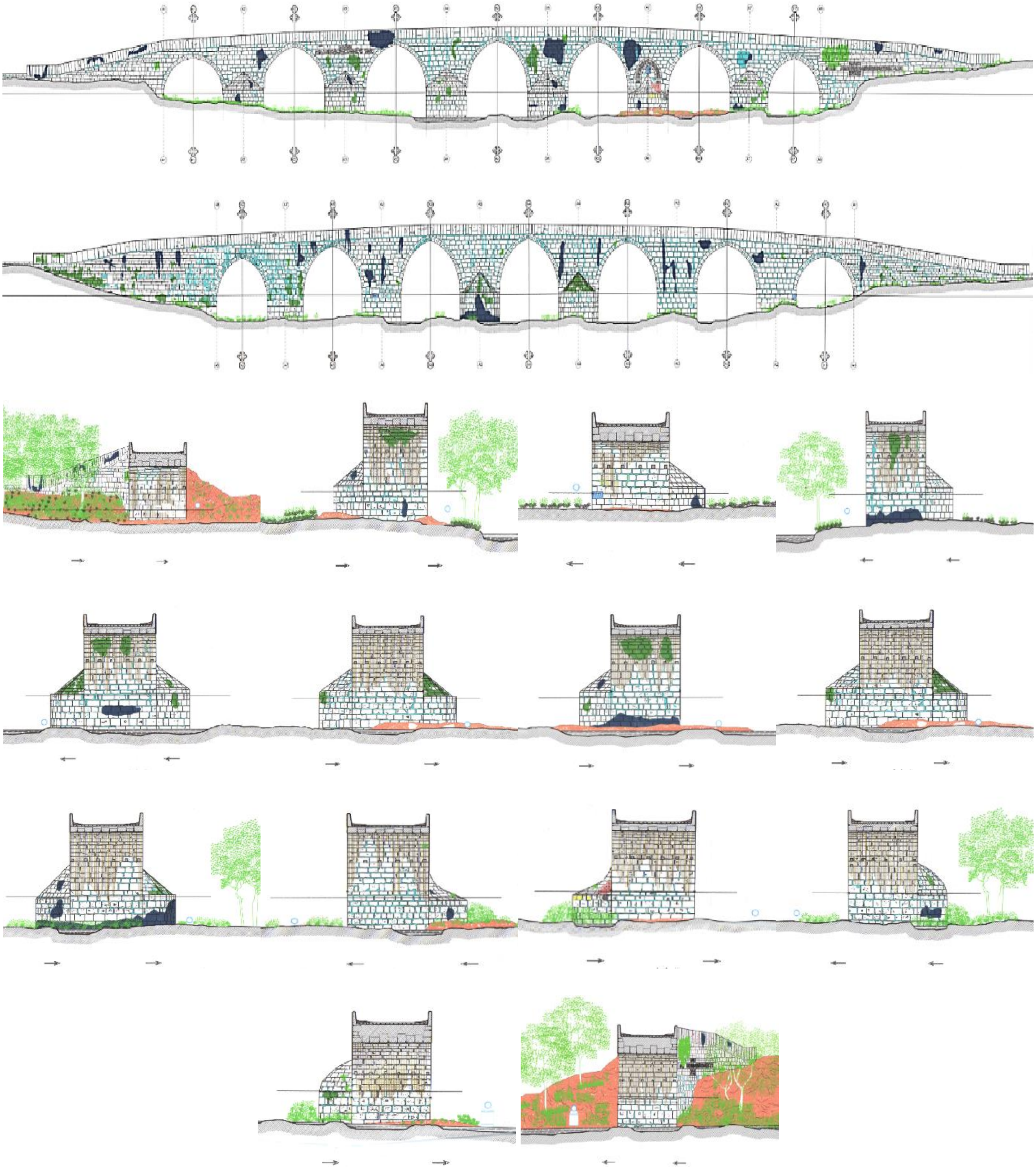


Figure 19. 2D plan Halilviran Bridge

- Prior to restoration, the propagation (activity) of the cracks had to be verified using control seals. If the cracks were stabilized and no enlargement of the cracks occurred to prevent and repair them, we could limit the traffic load of the bridge and its speed to acceptable limits to perform the restoration. However, since it is a time-consuming and expensive process, it is only considered for the Halilviran Bridge.

- Both bridges, especially the DARA, suffered material losses due to soil conditions, a lack of foundation protection, and erosion. This condition caused serious problems with the durability of the bridge structure and led to the demise of the bridge. Proper maintenance of the riverbed near the bridge will prevent this damage, and strengthening and consolidation of the bridge foundations with a reinforced concrete layer is being considered.
- Due to the use of unsuitable and inferior materials, deterioration and detrimental changes were observed on both bridges. When the mortar joints were lost, resulting in a loss of mechanical strength for the elements. In order to restore the integrity of the bridge, improve its protection, and increase its resistance, a repointing of the mortar in the joints between the masonry units of the bridge was considered. The composition of the mortar used for repointing the masonry joints must be carefully considered. The lime-based mortar should match the color of the existing masonry as closely as possible. These mortars should be as resistant as possible to the severe climatic conditions of the region (high humidity, contact with waves) while being compatible with authentic materials.
- The pavement of the bridge has suffered considerably over time due to cattle traffic. It was subject to vandalism by villagers who, on high-water days, removed stones and threw them into the river to watch the pebbles slide across the surface of the water. This vandalism, along with the effects of weather and the passage of time, has resulted in the unfortunate loss of material. Some stones in the arches are completely unconnected. Due to the deformations of the structural system and the displacements in the past, the arches in Dara made of shaped stones cannot be considered monolithic components. Moreover, loss of mass was observed in all types of stones, but especially in the stones of the upper structure. Therefore, demolition and reconstruction are considered for some parts of the bridges (Figures 20 and 21), taking into account the remaining parts, the characteristics of similar bridges, and the parts identified as a result of the comparative study. This method is efficient for repairing cracks and localized damage and improving the structural quality and load-bearing capacity of the bridge. The materials used must have the same properties as the original ones, and the mortars must have a low retraction capacity. It should be noted that before dismantling the elements, the bridge must be suitably supported to prevent its demise. All dismantled elements must be numbered beforehand so that their reconstruction can be carried out as accurately and efficiently as possible.
- Pressure grouting is required at some locations for infills and vaults. It is very effective and economical. It also increases the load-bearing capacity and improves the condition of the vault ring by filling cracks and voids in the vaults.
- The stone surfaces of both bridges were partially affected by vegetation. The vegetation posed a significant hazard because it deepened its roots between the stone joints. They were located at the base of the bridge piers and at the front of the roadway, where water entered the stone joints in search of an exit. All elements of the masonry viaduct (arches, end walls, parapet, and wings) should be thoroughly cleaned of efflorescence with a pressure washer and water.
- Tie rods that must be anchored to prevent further outward movement of both cases parapet walls. They consist of a bar that runs the full width of the bridge and should be secured with a nut and washer to hold the wall in place. One of the advantages of using tie rods is that they cause little or no obstruction to traffic. The steel rods should be installed without tension in the transverse direction of the bridge after the holes have been grouted with low pressure.
- In order to give more cohesion to the bridge filling material and improve the properties of the structural elements of the bridge, piers, arch, and foundation, an injection technique should be applied after the repointing works and eventual reinforcement of the bridge arches and parapet walls with steel bars. It consists of injecting voids in the filling material and the existing cracks with a mortar containing lime. Preferably, these injections should be made under low pressure in the direction of the bridge or from the roadway. The injected material should be compatible in its physical and chemical properties with the existing mortar and should be fluid enough to penetrate into narrow voids.
- It is important to consider the waterproofing and drainage of the roadway because the bridges do not have an adequate drainage system or waterproofing. If the drainage system is considered, almost all the problems associated with the lack of waterproofing, such as damage to the parapet, moisture and water infiltration, material deterioration, and mortar loss in the joints, will be eliminated.
- Dust deposits compared to oxidation products and air pollutants (car traffic) have formed crusts of gray color, especially on the stones with mass loss, especially in the upper structure. All this will be cleaned up during the restoration.

	Excited data of the structure
	Determined as a result of the comparative study
	Completed parts from examples and similar bridges

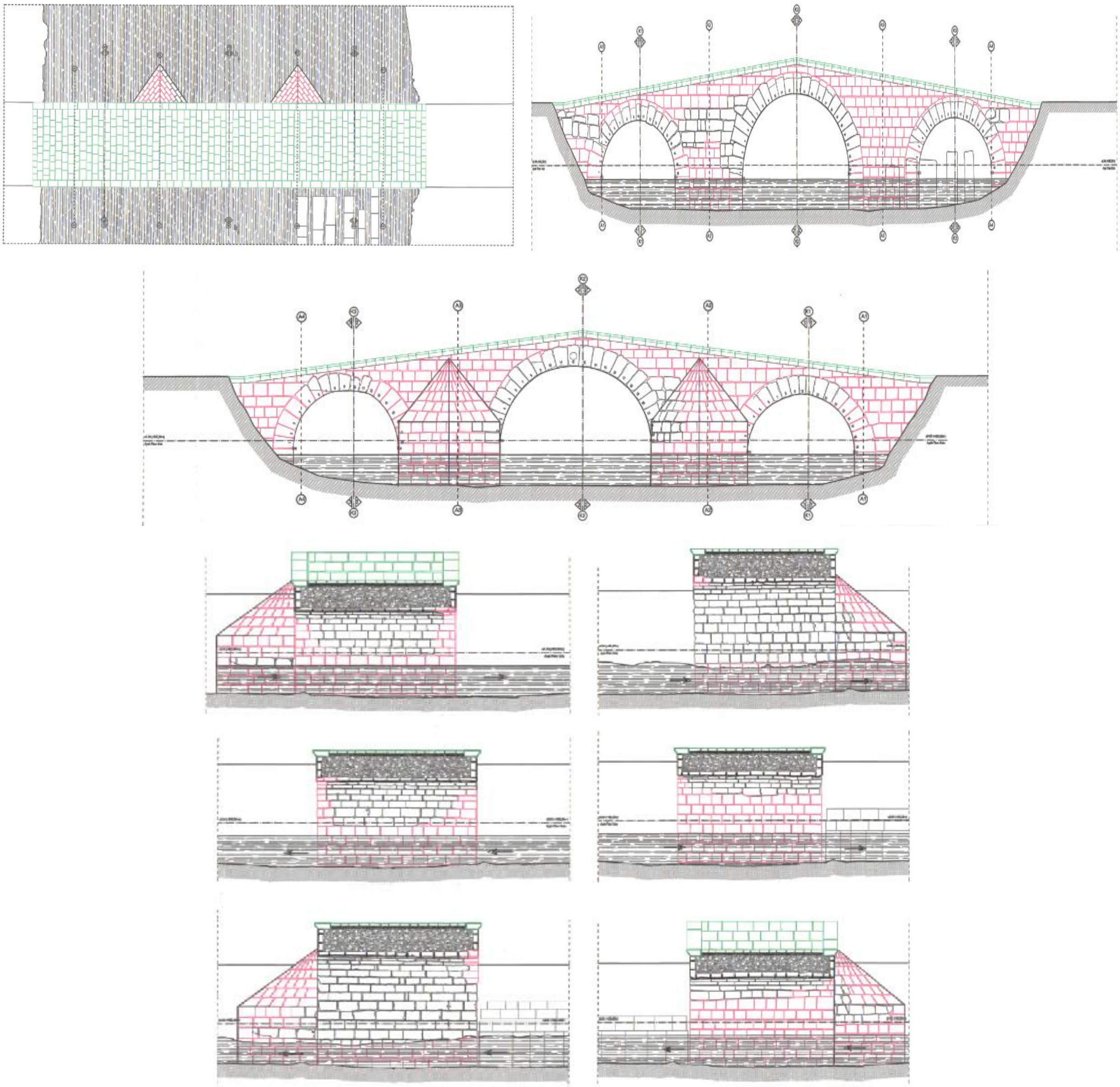
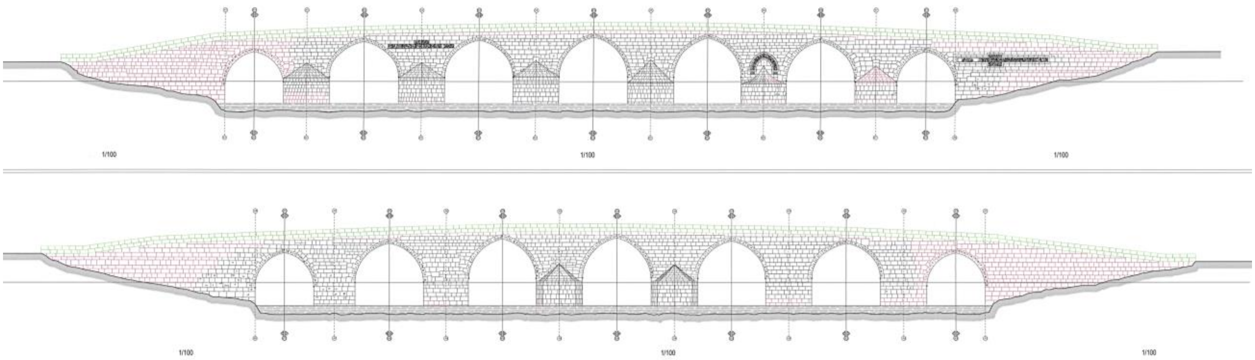


Figure 20. Dara bridge reconstruction plan

	Excited data of the structure
	Determined as a result of the comparative study
	Completed parts from examples and similar bridges



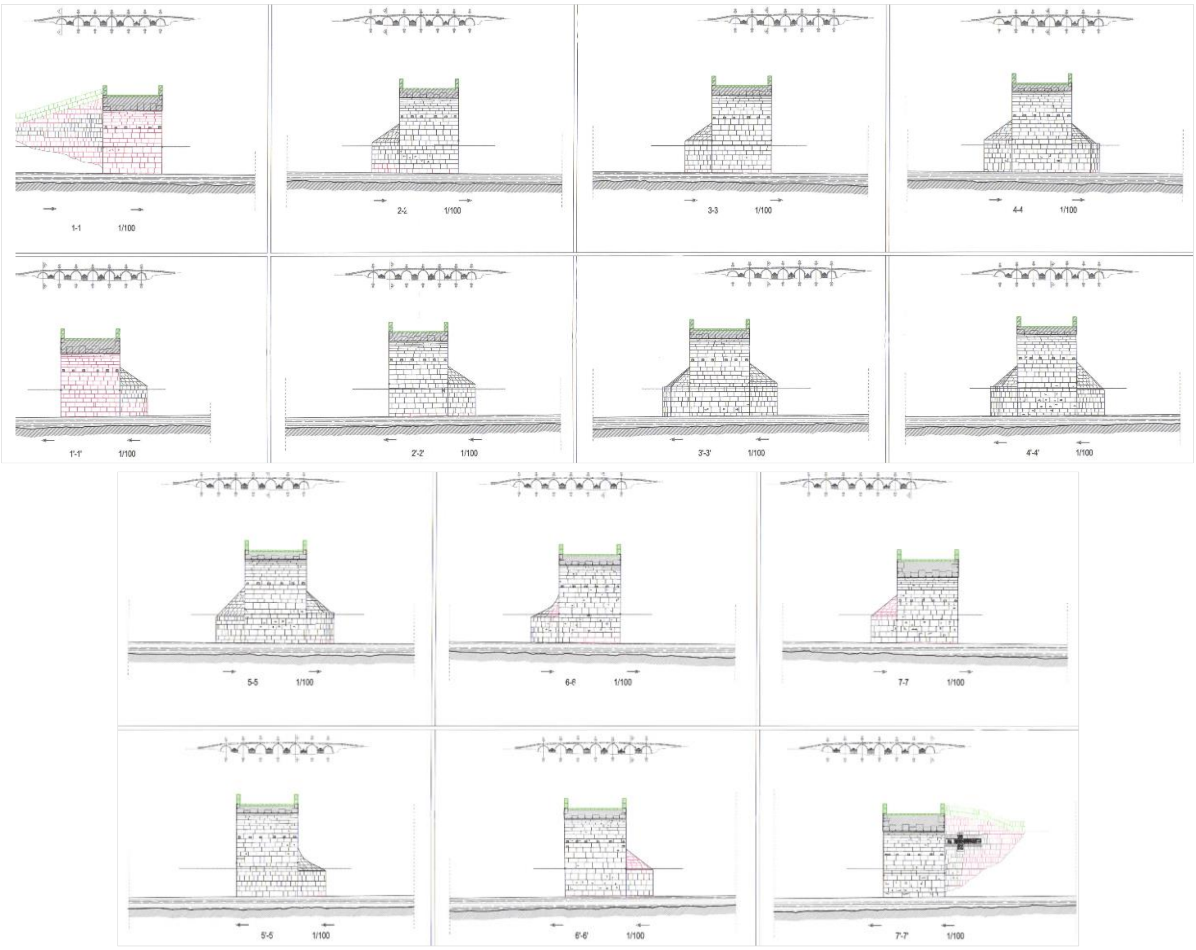


Figure 21. Halilviran Bridge reconstructıon plan

5. Conclusions

Preservation of cultural heritage requires the use of methods that allow condition assessment of historic infrastructure, preferably without damage and with a minimum of follow-up inspections. Visual inspection and geometric laser scanning have proven to be a good combination of methods in this study. Visual inspection remains an important method for evaluating the condition of historic structures because it reveals major defects in various parts of the bridge, while laser scanning provides more detailed information about the outer layers. Non-destructive testing can meet these criteria in a timely and cost-effective manner. It is used to detect defects in the outer layers and provide high-quality images of the outside of the components. The immediate feedback provided by this approach enables more efficient, real-time decision-making for retrofits and maintenance. This study makes an important contribution by demonstrating how the use of NDT approaches can provide accurate data on discrete defects that affect the condition of historic infrastructure. The results presented confirm that laser scanning is an effective NDT method for inspecting historic masonry arch bridges.

In addition, the two-dimensional data generated by laser scanning allows the simulation of realistic modeling scenarios for the entire bridge. This approach captures the entire bridge structure in detail and in a reasonable time frame. It has significant implications for how to address the problem of repairing and rebuilding the structures under study. These methods include strengthening the bridges with materials and techniques that are compatible with the masonry, are as unobtrusive as possible, respect the character of the monument and its surroundings, and avoid any kind of obtrusiveness to the structures. This leads to repairing the masonry with mortar compatible with the old but with better characteristics, injecting mortar to strengthen the masonry in the abutments and piers, improving the scour protection of the foundations, and increasing the load-bearing capacity of the arches by adding composite fillings between the arches and the parapets. The newly added elements blend into the monument through construction method, material, color, and texture so as not to disrupt the esthetics of the structure. In addition, the selection criteria are based not only on structural efficiency and economy but also on knowledge of the techniques and technologies used in the construction of monuments, as well as respect for the original design. This aspect, as well as those described in the previous sections, must always be considered in a historic preservation project. It should not be forgotten that historic bridges, if properly maintained, can continue to serve well for many generations. Therefore, it is highly advisable to carefully examine the condition of a historic bridge in need of repair and decide how best to proceed with the repair. Future work will focus on historic masonry bridges subject to blast loading in terms of three-dimensional modeling approaches, such as those based on FEM (finite element method).

6. Declarations

6.1. Author Contributions

Conceptualization, A.B. and A.S.; methodology, A.B.; software, A.B.; validation, A.S. and Y.Y.; formal analysis, A.B.; investigation, A.B.; resources, A.S.; data curation, A.S.; writing—original draft preparation, A.B.; writing—review and editing, A.S.; visualization, A.S.; supervision, A.S.; project administration, A.B.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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