ILLYRICVM ROMANVM

STUDIOLA IN HONOREM MILOJE VASIĆ

EDITED BY

Ivana POPOVIĆ
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CONTENTS

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Trajan's Bridge – Analysis of Apolodorus' Design Concept*

Abstract. *– For Trajan's bridge it could be said, and with good reason, that when it was built it represented one of the architectural wonders of Europe at that time. Trajan's bridge is one of the few architectural creations about whose appearance we can judge with a level of reliability. According to written sources and its preserved remains and, primarily, on the basis of the renowned representation on Trajan's column, we know that the support elements of the bridge, both on the river bank and in the riverbed, were masonry structures. Above the masonry pillars in the riverbed there was the wooden latticed structure of the bridge, many details of which were represented on the aforementioned column in Rome. One of the most interesting issues regarding the bridge itself is the method of its construction in Roman times. Considering the twenty pillars placed in the Danube riverbed using caissons and the 55 meter span between each pillar, the construction of the bridge was, in itself, a great architectural achievement. The significance of the bridge's structure is still great in contemporary analyses of Roman bridge construction and wooden scaffolding.*

Key words. *– Bridge, wooden and masonry structures, scaffolding, Roman antique architecture, Apollodorus, Trajan*

The bridge, the construction of which was initiated by the emperor Trajan, was designed by the architect Apollodorus in the period between the years 103 and 105. The structure bridged the Danube River and was intended as one of the main elements of communication between the newly-established Dacia province and the other territories of the Roman Empire and became known as Trajan's Bridge. The main support structure of the bridge consisted of 28 support pillars, of which only eight have been explored in the course of archaeological investigations. These are four bank pillars on the Romanian side of the river and four on the Serbian bank. The pillars on the Serbian side were investigated in 1979, under the directorship of M. Garašanin and M. Vasić.[1] All the pillars except

[1] Гарашанин, Васић 1980.

* This text is a result of the project *Romanization, urbanization and transformation of urban centres of civil, military and residential character in Roman provinces on the territory of Serbia* (No. 177007), funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

Figure 1. Representation of Trajan's (Apollodorus') Bridge on Trajan's Column
(selected representation of the construction by the author after photograph in R. Vulpe 2002, 178–179)

the one closest to the bank are preserved in the foundation zone together with partial remains of walls above that zone. Only the fourth bank-side masonry pillar with a platform for the wooden structure is preserved more than 8 meters above the foundation zone and remains the best preserved part of Trajan's Bridge on the Serbian side. The pillars that were built into the riverbed and which supported the arched wooden structure of the bridge and the wooden platform on top of it are not visible today above the surface of the river and are preserved in very poor condition. They were examined by hydrographic and geophysical sonar methods and later modelled and analysed using photogrammetric methods.[2]

Sources for the appearance of the bridge construction

The main literary sources that provided information regarding the appearance and method of the bridge's construction are the texts by Cassius Dio, Procopius and the poet Tzetzes.[3] It must be taken into account that the text by Cassius Dio, as the earliest of the preserved texts, was written a century after the bridge construction. According to information from the writer himself, the bridge did not exist anymore because Trajan's successor – Emperor Hadrian – ordered the destruction of, most probably, only the wooden parts of the bridge.[4] The bridge was built between the 1st and 2nd Dacian wars, that is, between AD 103 and AD 105, and its span across the Danube was over 1,000 meters.[5] Cassius Dio provides valuable

[2] On first recordings of the underwater bridge remains using sonar see Gušić 1996, 259. About most recent geophysical investigations of the remains of Trajan's Bridge in the Danube riverbed see Vučkovic et al. 2017, 17–19. Particularly about recording the remains of the caisson structures see Каровић, Ђорђевић 2004, 64–67.

[3] On earlier literary and historical sources see in more detail in Гарашанин, Васић 1980, 8. On representation of the bridge in the scene 98–99 on Trajan's Column see Vulpe 2002, 178.

[4] About disputability of this information also see Гарашанин, Васић 1980, 8.

[5] Length of the bridge between the pillars with platforms that we will discuss later in the text was 1,068 m and that information generally corresponds to the measurements given by Cassius Dio (naturally in Roman feet). Total length from the entering portal on the Serbian bank to the portal on the Romanian bank was 1,130 m. About this see Gušić 1996, 260.

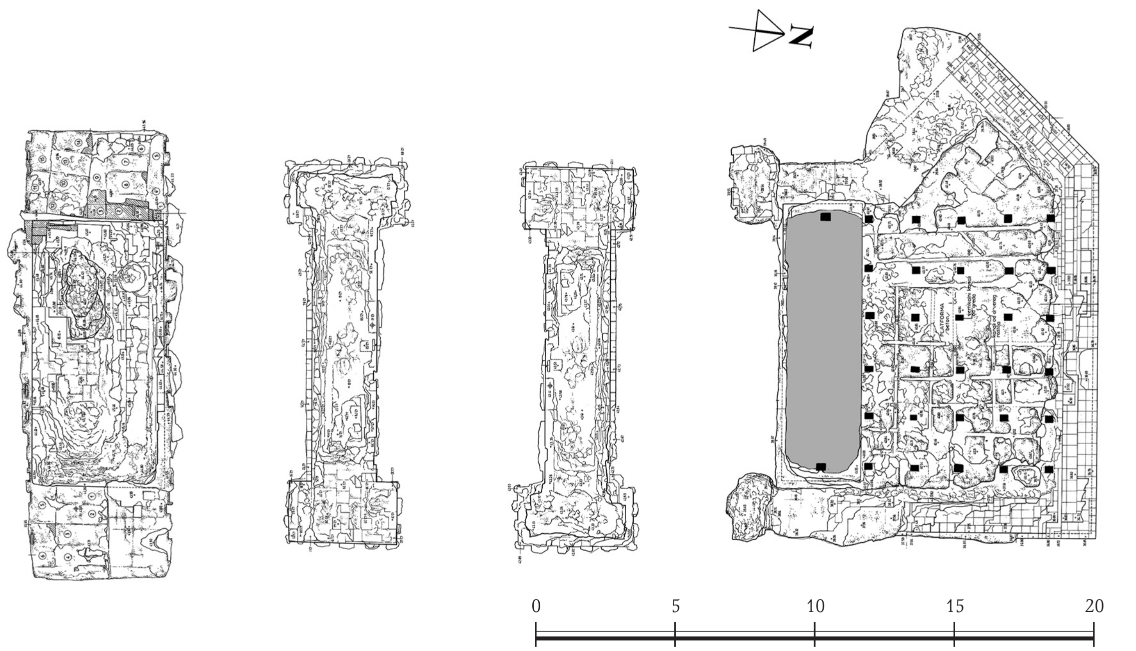

Figure 2. Ground plan of the remains of the masonry construction of the bridge (documentation in the Institute of Archaeology, in Belgrade)

information regarding the size of the bridge – that it had twenty pillars (he obviously knows only about the pillars in the riverbed) spaced at a distance of 170 Roman feet (ca 50 m), with the width of each pillar being 60 feet (18–19 m). The bridge, excluding its foundations, was 150 feet (50 m) tall.[6] Among other data, Dio indicates that the distance between the support pillars in the riverbed from axis to axis of the supports was 170 Roman feet (56–57 m) and that this is seven times greater than the distance between the supports on the bank, which was around 6.15 m. Dio also provides information about the width of the pillars in the riverbed, which were 60 Roman feet. The distance between the facing walls of each neighbouring pillar, i.e., the span of the wooden arched supports above the river was 32.5 m (110 Roman feet). The poet Tzetzes points to the fact that Apollodorus used wooden chests, caissons, during the construction of the pillars.

The bridge was depicted on coins and on Trajan's column in Rome. The simplified bridge representation on coins minted by the Roman senate in AD 105 is noteworthy first of all because of the visual representation of the portal at the beginning and the end of the bridge and the existance of three figural representations on its top. Regarding the bridge representation on coins, the usefulness of this data had already been called into questioned by scholars.[7]

The representation on Trajan's column is the most precise of the bridge (Fig. 1). The bridge's remains, literary and historical sources and the representations on Trajan's column and coins offer sufficient data for the analysis of Apollodorus' concept of the bridge construction.

In order to provide a safe crossing point for the army from one bank to the other of the Danube it was necessary to build the bridge quickly, but the structure had to be very stable. The project to

[6] Гарашанин, Васић 1980, 8.

[7] *Ibid*., 9.

Figure 3. Remains of the masonry pillars of Trajan's Bridge on the Danube river bank (documentation in the Institute of Archaeology, in Belgrade)

build the bridge would need to have been adapted to those circumstances. The concept of the bridge was based on applying a proportional module design, which was typical for the Antique period.[8] Proportional division was applied to establish the position of the bridge supports. In such a way, the building of the bridge was also divided into certain number of longitudinal segments. As with every great architectural achievement of the ancient times, one of the certainly most interesting problems concerns the method used to build such a wonder of Antiquity, particularly bearing in mind all the engineering knowledge and innovative creativity of the ancient Romans. When analysing the method of construction of Trajan's Bridge, it is necessary, starting from the archaeological results obtained in 1979 and available written sources, to observe, independently, those sections of the bridge built on the solid ground of the river bank and those of the bridge over the river itself.

Masonry bridge structure on the Danube river bank

The most important data about the remains of the bridge construction on the river bank was provided by archaeological investigations conducted by Milutin Garašanin and Miloje Vasić.[9] The masonry pillars on the river bank had an elongated rectangular shape with reinforcements on the ends (fig. 2). The pillar that is, today, closest to the bank was built simultaneously with the stone platform for the wooden bridge structure that was leaning onto the pillar's longer side. The pillar and platform shared a joint foundation.

In order to lay the foundations for the masonry pillars on the bank, first pits of a suitable shape and size had to be dug into a layer of compact river gravel. Then, wooden piles were inserted in the river gravel along the pit edge and large wooden planks were attached to their external sides. Impressions of these wooden planks and piles remained visible on the foundations (fig. 3). In the prepared pit, the *opus caementicium,* consisting of small pieces of broken stone and lime mortar, was poured and was tightly packed to create as strong and compact foundations as possible. The foundations of the masonry pillars are

[8] On proportional model of designing Trajan's Bridge written in extenso С. Гушић; in С. Гушић 2015, 77–78.

[9] Гарашанин, Васић 1980, 7–24.

somewhat wider than the pillars themselves. A course of bricks was applied over the foundation bases of the masonry pillars to level the foundations. The external faces of the pillars on the bank were covered with large square stone blocks.

The length of the first and last masonry pillar shafts is 9.80 m, while the length of the second and third pillars is 9.40 m. The second and third pillars are of a similar width, at around 2.35 m. The pillar closest to the bank is also the best preserved one and its height is 8.30 m above the upper surface of the foundation. It is 2.95 m wide, while the pillar supporting the portal is the widest, at 4.70 m. The distance between the masonry pillars on the river bank was between 5.40 and 6.50 m.

The masonry pillars on the river bank had an additional extension of the foundations on their east and west sides, in order to further reinforce the pillars. The remains of stone blocks were found inside the wall mass of the mentioned reinforcements of the first masonry pillar on the bank. The monumentality of this pillar in comparison to the other pillars is explained by the existence of a portal raising above it that was used as an entrance to the bridge. The representation of Trajan's Bridge in the scenes 98–99 on Trajan's Column, built also by Apollodorus, indicates that the portal was resting on the first masonry pillar, looking at the bridge from the approach side.[10] The appearance of the portal could be assessed on the basis of the mentioned representation on Trajan's Column as well as on the coins minted by the Roman Senate to honour the building of the bridge.[11] According to the representation on Trajan's Column and coins, the portals had just one arched opening of a monumental size. The arch of the portal was decorated with archivolts having complex mouldings and above the portal opening a pedestal was made for the sculptures, which are most prominent on the mentioned coins. The crown on top of the portal as well as the capitals supporting the archivolts of the arches also displayed an architectural complexity.

The first investigators supposed the existence of masonry arches above the masonry pillars on the river bank.[12] Considering the height and thickness of the masonry pillars and the 6.15 m distance between the pillars that actually represented the span of the arches, it is certain that such arches did exist. Confirmation for such an opinion can be seen on the representation of the bridge on Trajan's Column in Rome.

Above the arches, there must have been masonry structures built down to the apexes of arches in order to guarantee their stability, and to prevent any horizontal movement in relation to the supports due to the pressure from above. This situation is particularly necessary for the masonry pillar closest to the Danube bank, which would have been in contact with the wooden supporting structure of the bridge above the river surface. Support of the arch above that pillar was not secured in any other way except by the reinforcements that were on the eastern and western ends. This is also confirmed by the representation of the bridge on Trajan's Column. Although simplified, that representation still depicts, in a sufficiently concise way, the shape and position of the arch in relation to the pillar, the contact with the wooden structure as well as the position of the masonry constructions above the arches.

Masonry structure in the riverbed

The results of the investigations that recorded the remains of the bridge pillars in the river provided, first of all, more precise information about the position of the twenty supports in the riverbed, but also about the condition of the wooden caissons, which the Romans used to make the foundations for the pillars.[13] Most important for the realisation of the masonry structure was Apollodorus' idea to use caissons to make foundations for the masonry pillars in the riverbed.

[10] Гарашанин, Васић 1980, 15.

[11] Tudor 1974, 60, figure 12 (metope), 59 (coins).

[12] Гарашанин, Васић 1980, 16.

[13] On most important archaeological results of underwater investigations of the caisson structures and remains of the bridge pillars in the riverbed see Karović et al. 2004, 64–67.

The caissons were planned as wooden casings consisting of two rows of large oak piles driven into the riverbed. According to some Romanian investigators, the pillars and matching caissons were of a hexagonal ground plan, whereas, according to the opinion of the Serbian investigations, the pillars were of a pentagonal shape with a protruding corner on the lower section of the pillar which was turned upstream.[14] Oak beams of square section were used for making the casings for the caissons.[15] Driving a large number of wooden piles into the Danube riverbed in a rectangular layout was an imposing undertaking. It was preceded by as stable as possible an anchoring of river ferries, smaller vessels or pontoon bridges, from where the piles were driven into the riverbed. It was possible from there to carry out a more precise scaling of the positions and a determination of the polygonal shapes of the pillar bases by marking the borders using tightly stretched ropes above the river surface. The wooden piles were driven into the riverbed within the borders created by the stretched ropes. In order to secure as stable as possible an anchoring of the large number of vessels in the river and also a more secure stretching of the supposed ropes between the two banks, a platform was created on the south slope below the *castrum* Pontes, downstream from the bridge. This platform had earlier been assumed to have been a small dock for storing the material necessary for the building of the bridge,[16] and it remains debatable as to whether the pontoon bridge could have been made on the mentioned vessels, but it is certain that the Romans used pontoon bridges in the time of the Dacian wars, as illustrated on Trajan's Column in scenes 4–5 and 37.[17]

Between the two parallel rows of wooden piles, hydraulic concrete was poured in order to prevent water entering the caisson structure.[18] In such a way, a dry caisson interior was secured where the mass of lime and smaller stones was poured in. It was then tamped to create a very compact mass, *opus caementicium,* in the same way as had been done in the process of building the masonry pillars on the bank.

The pillars that supported the wooden structure of the bridge were built above the thus created foundations. The masonry pillars also had the form of an elongated polygon in the lower section. This shape was set in such a way that the protruding corners of each pillar were facing the direction of the river current, in order to prevent the formation of sandbars or the accumulation of river pebbles and sand next to the sides of the pillars.

The platform built on the Danube bank next to the masonry pillar indicates the method of construction of the platforms of the other pillars in the riverbed that were used to support the wooden structure of the bridge. This means that a similar masonry platform was made on top of each masonry pillar in the riverbed. On the faces of the masonry pillars on Trajan's Column a ledge is noticeable at the transition from the polygonal pillar form in the lower section to the rectangular shape of the pillar in the upper section, above the ridge. The supporting wooden structure on which the wooden arches were resting was constructed on the upper sections of the pillars. Inside the masonry pillars were also encountered vertical holes of a square section.[19] These holes, according to Tudor, could have been the impressions of long ago decayed beams or were ventilation shafts to facilitate the faster drying of the internal structure of the core. The more plausible suggestion, in my opinion, is the first one regarding the inserted vertical wooden piles. Those vertical wooden piles were also arranged in a rectangular layout, but they were obviously not in connection with the structural horizontal grid consisting of wooden beams. It was also visible

14 Bara, Keiser 2015, 197; Karović et al. 2008, 286 and 288, fig. 4, fig. 5.

15 Bara, Keiser 2015, 197.

16 Гарашанин, Васић 1980, 21.

17 Vulpe 2002, 117, 145,

18 According to the Romanian sources, hydraulic concrete was used for the infill, after Bara, Keiser 2015, 197.

19 Tudor 1974, 96–97.

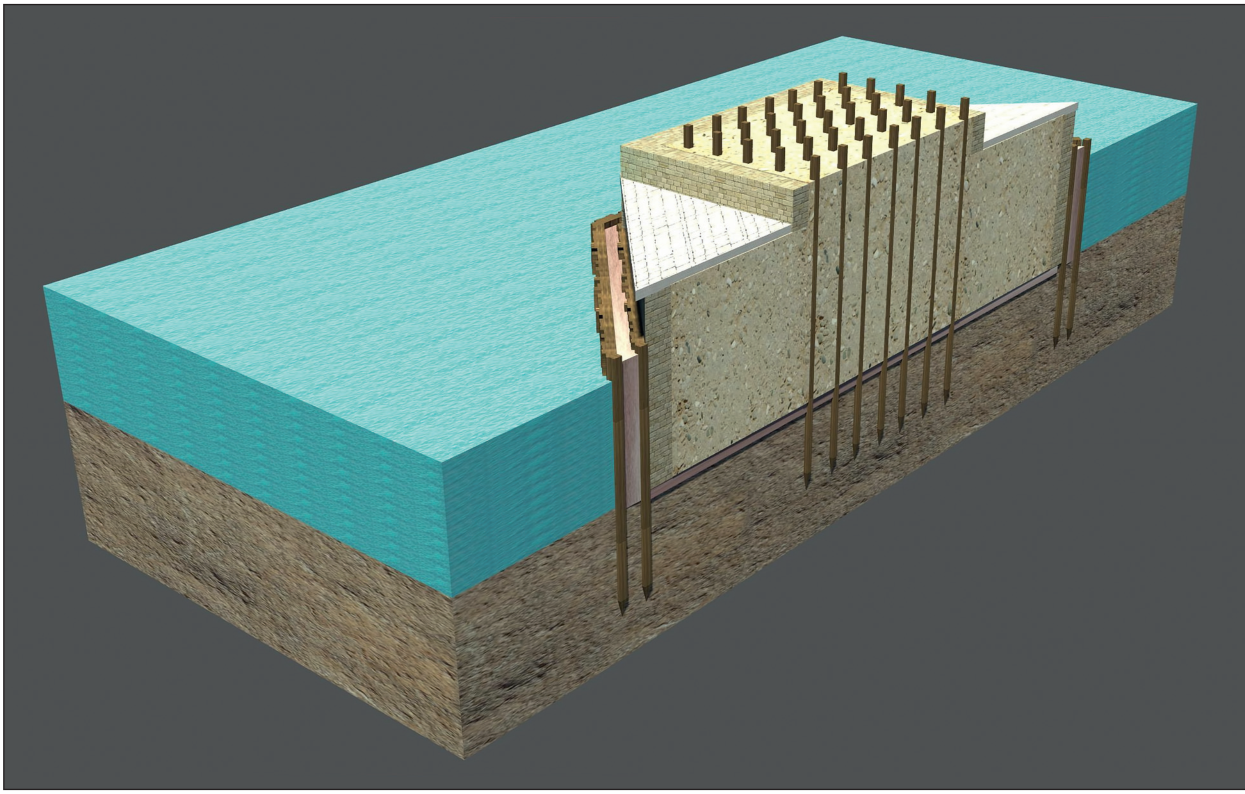

Figure 4. Axonometric section of one masonry pillar and the method of its stabilisation in the Danube riverbed (reconstruction by the author, 3D model V. Milošević)

on the platform on the bank next to the masonry pillar that the vertical piles were not connected with the horizontal wooden grid (fig. 2).[20]

The very existence of vertical wooden beams is of importance to our subject. Only filling the caissons with concrete was certainly not sufficient for the stability of the masonry pillars in the riverbed. A stronger connection of the pillar foundations to the riverbed could have been achieved by using vertical wooden piles, which would have been driven into the riverbed in a distinct spatial layout before pouring in the concrete (fig. 4). Examples of such a procedure in Roman engineering, especially regarding the foundations of structures with a distinct occurrence of groundwater, have been discussed on many occasions in academic literature. This is particularly so where Roman architecture in Western Europe is concerned.[21] Therefore, the vertical impressions of beams identified in the walls of the pillars represent, in fact, the impressions of wooden piles that connected the pillars to the riverbed.

Wooden structure of the bridge above the river

The arched structure spanning the distance between each masonry pillar was made of wood, judging by the representation of the bridge on Trajan's Column. The selection of wood for building Caesar's Bridge across the Rhine was certainly a model for Apollodorus. His selection for the wooden structure was pragmatic – to build an

[20] Nemteanu 2011, 119, сл. 7.

[21] Ulrich 2008, 80, Fig. 5.5; Lancaster, Ulrich 2014, 176. In our territory, similar vertical wooden piles (so called pilotis) with metals tips (caps for inserting in the riverbed) have also been found in Sremska Mitrovica (Sirmium); see Jeremić 2016, 109.

arched structure of bricks or stone required much smaller spans i.e., distances between the pillars. Building stone arched structures with a greater number of supports at smaller distances would have posed a few problems. First, the river current would have been slower as the sandbars next to the bridge pillars would have accumulated and this would have jeopardised navigation on the Danube, which was very important for the Romans. Second, the very realisation of the masonry structures would have taken much more time and this would not have been convenient considering the immediate needs of the emperor and his army. The timetable imposed on Apollodorus required that the construction of the foundations, masonry pillars and the wooden structure of the bridge would have needed be carried out simultaneously at the position of each pillar in the riverbed.

When discussing the wooden bridge structure, it is essential to point out that oak was used. Some beams on the Romanian side were preserved and after their removal from the river they were housed in the Drobeta – Turnu Severin museum.[22] If fir had been used, greater lengths could have been achieved because of the length of straight fir tree trunks. It was not the case here though, so the wooden beams used for the construction of the wooden bridge could not be of such great length, as would have been the case with fir trees.[23]

As we have already mentioned, the wooden railing or grid consisting of horizontal longitudinal and transversal beams was built over the top surface of the masonry pillars. Then, a support frame structure for the support of each wooden arch of the bridge was constructed on those railings. The main support of this frame structure consisted of many beams (four at least) in the shape of the letter *M*.

The modern approach to building bridge structures suggests that supports were made for the wooden arched girders, then the arches and finally the platform above them. It is clear that the arched structure could not have been realised from below, even with the use of vessels, as they would have provided insufficient support for the beams, which should only then be placed and consolidated in the actual position. However, when carefully studying scenes from Trajan's column, one detail particularly draws our attention where the method of building Trajan's bridge is concerned. These are the concentric arched supports arranged in three levels. These levels were connected with wooden beams, arranged radially. In the contact zone of the wooden structure and the masonry pillar on the Danube bank, in the scene from Trajan's Column, three levels of wooden arches have their bottom ends extended to the horizontal wooden railings/grid on top of the masonry pillars on which they were resting.[24] In such a way, the top level of the arched supports could have been crossed with the *M*-shaped frame supports via the masonry pillars.

It is possible, according to this detail, to determine the method of execution of the wooden bridge structure. First, as we have already mentioned, the *M*-shaped supporting frames were made, that is the *M*-frames (fig. 6.1). The slope of the beams that Apollodorus predicted was adapted to oppose the horizontal shear thrust of the future wooden arched supports between the individual pillars of the bridge. The *M*-frames were secured at the top with horizontal beams

[22] Tudor 1974, 99; Bara, Keiser 2015, 197.

[23] Generally recommended length of oak beams in civil engineering that rest only on their ends, i.e., without additional supports between the ends is around 5 m. Recommended maximal length of oak beams in civil engineering is around 10 m. According to Ulrich 2008, 106, the length of oak beams used for Trajan's Bridge was around 8.5–9 metres.

[24] This detail could not be seen on other pillars but only on the first one, which is on the Danube bank. However, if in the mentioned scene the beams on other pillars were represented in the same way as on the first pillar, it would not be possible to recognise in that case the supporting frame structure above the masonry pillars. It should be taken into account that the representation of the Danube bridge was depicted schematically and showing its most important elements, while we do not see most of the secondary elements. Likewise, the individual arched supports are depicted as if they were made of four supporting beams, which is less probable, bearing in mind that a span of around 30 metres was bridged with arched wooden structures.

Figure 5. Position of the machinery for vertical load lifting in the process of building the wooden structure (reconstruction by the author, 3D model V. Milošević)

arranged transversally and longitudinally and over them the bridge platform could have been made as wide as the frames, and those frames were supported from below by diagonal wooden struts (fig. 6.2). The lifting of large quantities of wood, especially the long wooden beams, could not have been achieved by human force alone. Apollodorus anticipated, without doubt, that the construction of the wooden bridge would mean arranging and retaining heavy beams for the wooden arched supports in a specific position and at a certain angle, and for that human power would not be sufficiently precise. The use of the machines was crucial in the process of making the wooden bridge structure. Setting up the pulleys used for balancing heavy building elements could have been realised only on those spots that were sufficiently stable. The machines for vertical load lifting could not have been installed on unstable bases, that is, on some kind of vessel or temporary pontoon bridges. In the case of Trajan's Bridge across the Danube, the only sufficiently stable points along the route of the anticipated bridge were the recently built support pillars (fig. 5, fig. 6).

After raising the basic supporting M-frames, two slanting beams were placed in such a way that each of them started from the furthermost supports of the M-frames and ended at the middle of the corresponding outer branch of the support. A. Richmond commented earlier that the struts depicted on Trajan's Column were not accurately represented.[25] According to his opinion, in order for those beams to function properly as supporting struts and, by their position, prevent any bending of the supporting M-frames, they should have been placed from the middle of the supporting plane of M-frames towards the middle of the external branches. However, Galliazzo explained the beams as elements of the series of radial beams connecting the three levels of the arched supports.[26] In my opinion, those beams had a con-

[25] Richmond 1982, 35.

[26] Galliazzo 1994, 323, Fig. 6.12.

structive role in the next phase, as the first beams of the top and middle level of the arches could be supported by being connected to them (fig. 6.3). Such an assumption is based on the thesis of O'Conor, according to which the three levels of the arches would be more stable if their supports were shifted towards the vertical axes of the masonry pillars.[27]At the same time, the joining of the slanting beams with the first beams of the supporting arches would be the only logical explanation for the function of the slanting beams below the supporting M-frames. It would, however, mean a somewhat different appearance of the connection of the arched supports to the retaining M-frames than has already been suggested by Ulrich and Lancaster and according to the earlier reconstructions proposed by Galliazzo.[28] Therefore, in the reconstruction in this work, the earlier solution by Edgar Dipere is accepted, where the supports of the upper level of the arches were placed on the vertical axis of the masonry pillars.[29] Such a solution corresponds best with the bridge representation on the column in Rome, and primarily with the position of the initial beams on the first supporting wooden arch.

With the previously described structure of the supporting M-frames and the slanting beams below them it was necessary to solve the issue of the arrangement of the first beams of the arched supports (fig. 6.3). After their bottom ends were placed in the predicted position, their top ends were gradually rotated to reach the required angle. The controlled process of rotating the heavy beams must have been realised using machines with sacks of sand used as counterweights. By gradually discharging sand from the slashed sacks, as had been done from ancient times, it was possible to carry out the process of rotation and to maintain the heavy beams in the required position above the riverbed. There was a possibility in this phase to strengthen the protruding beam ends of the top level using M-frames over horizontally laid beams in a transversal position relative to the line of the bridge.

Judging by the representation of the wooden structure of the bridge on Trajan's Column, it was necessary in the further course of the construction to consolidate the protruding beam ends of the lower level and to extend the new beams for each level and crisscross them with wooden strips in a radial direction. In order to temporarily consolidate the protruding beam ends of the lower level, it is certain that diagonal wooden struts, supporting those ends, temporarily rested on the crown of masonry pillars (fig. 6.4).[30] The extension of the walkway wooden platform on each side above the individual pillars was also possible, and necessary, in order to allow, in the next steps, the extention of the new beams from all three levels of the wooden arched supports of the bridge.

Within the scene depicting the bridge on Trajan's Column there is yet another strut on the last pillar next to the frame supports that was braced on its lower end to the point of the intersection of the frame supports and the first beam of the top level of the arched supports (fig. 6.5). These struts provided the consolidation of the extended wooden walkway. The points where the mentioned struts were consolidated with the walkway platform and the points where the struts were consolidated with the middle rows of the arched supports established secure supports for placing wooden collars in a radial direction (fig. 6.6)[31]. It was possible to use the same strips used for the collars to also consolidate the beams of the lower row of arched supports and to remove the struts below them that started from the crowns of the masonry pillar segments. It is clear in the representation of the completed Trajan's Bridge on the column in Rome that these struts were missing.

[27] O'Conor 1993, 144.

[28] Lancaster, Ulrich 2014, 167, Fig. 9.5.

[29] After Tudor 1974, Fig. 8, 25–26, 30.

[30] More precisely, it relates to the ridge separating the lower beak-shaped section of the masonry pillar and the upper section, which is rectangular. That ridge is clearly visible on the bridge depicted on Trajan's Column.

[31] On our drawing, the collar was depicted as one beam. However, the collar consists of two beams, one parallel to the other on both sides of the beams, which they were supposed to reinforce.

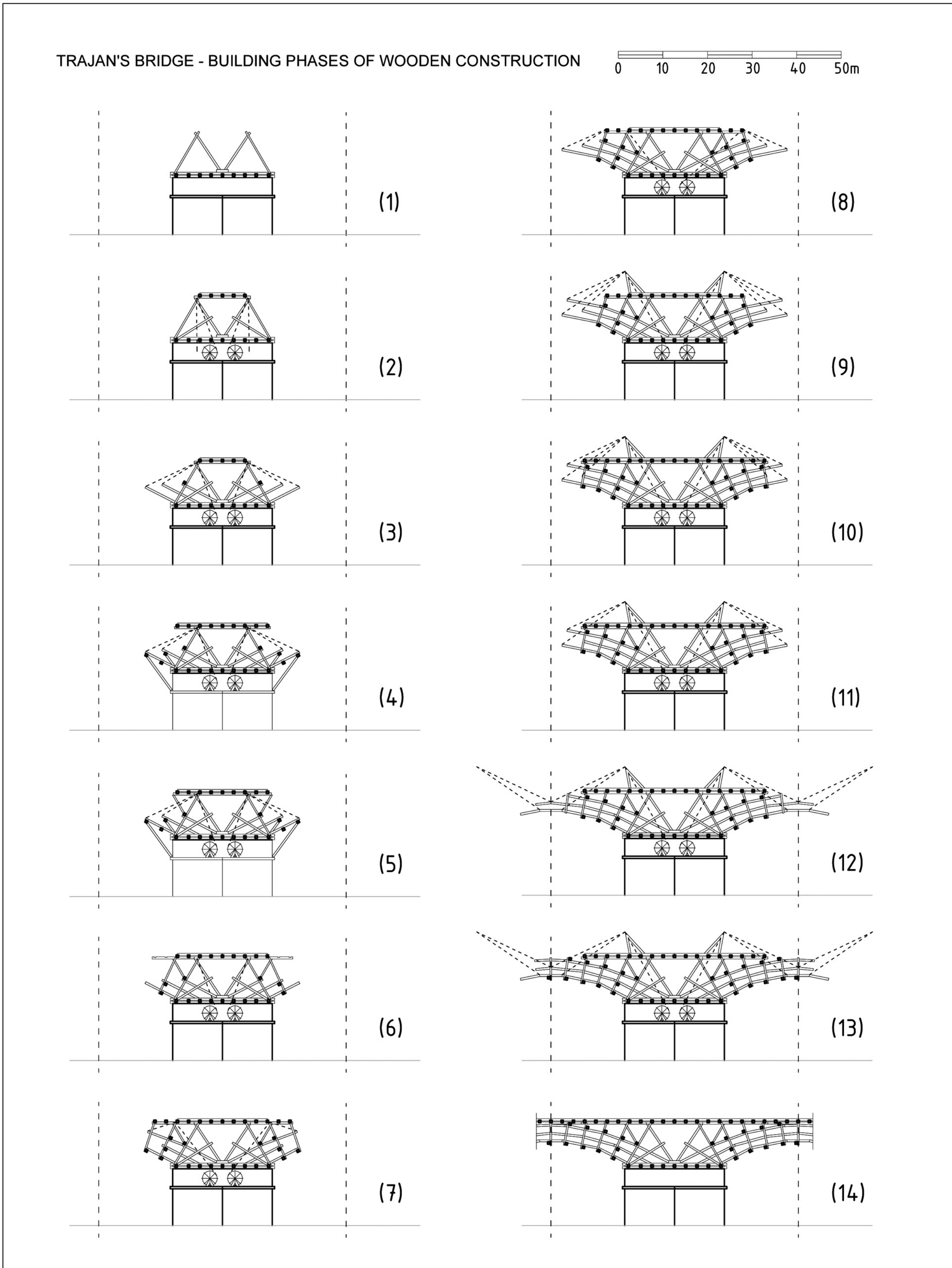

Figure 6. Phases of completing wooden structure on the individual masonry pillars (according to author)

The strips that created the collars also made it possible for the platform to be additionally extended and the middle level of the arched supports to be extended by one beam on each side (fig. 6.7).

In the further procedures of successively extending the platform and the direction of the arched supports, and by arranging wooden collars in a radial direction, the beginnings of the wooden structure of the upper section of the bridge was constructed (figs. 6.7; 6.8). In order that each extended beam was properly supported and then rotated and placed at the required angle there must have been a safe suspension system using ropes and counterweights. The struts and beams of the arched supports considered so far were always placed much lower in relation to the tips of the frame supports. Therefore, balancing the weight of the beams and the counterweights could also have been performed from the base of the frame supports. It is certain that for the initial steps, which we have already described, it would have been possible to carry out the coordinated placement, trussing and balancing in the correct position only on the tips of the M-frame supports. However, at a certain distance from the masonry supports the beams of the arched supports, because of their height, would have been too close to the bridge platform for it to be possible to suspend them securely from there.

Therefore, in the successive steps, devices (like the cranes depicted as triangles in our representation) had to have been used for it to have been possible at all to suspend every extended beam at a satisfactory height (figs. 6.9, 6.10, 6.11). These beams could only have had their other end leaning on the already existing structure of beams of the bridge. Following such a procedure, the platform was successively extended after each newly arranged row of beams for the arched supports. For the last steps (figs. 6.11, 6.12, 6.13) it was much easier to bind the protruding ends of the still unfinished wooden structure by using the collars or ropes from each neighbouring support. Finally, the wooden walkway platform above the apex of the arch could have been completed after the construction and strengthening of the apexes of the arched supports (fig. 6.14). If we take into consideration the previous conclusion that the wooden structure was executed simultaneously above every masonry pillar, this step would have meant connecting all segments of the bridge platform at the same time.

Where the wooden bridge structure is concerned we should leave open the possibility for a different explanation of its structure. Namely, if we take into account the statement of Cassius Dio that the bridge was about 44–45 metres high, then we must take into consideration the possible reconstruction of the bridge suggested by S. Gušić[32], where the bridge was raised in its central section. The gradual increase in height of the supporting masonry pillars of the bridge towards the middle of the span had its justification in making possible the unobstructed flow of the river between the bridge pillars. The foundations of the supports had already reduced the river flow by 30%.[33] This kind of approach means that Apollodorus also took into account unobstructed navigation on the Danube. Regulating the slope of the bridge roadway was only possible by placing stable supports on masonry pillars and stretching ropes between them prior to the construction of the wooden structure. In ancient times, between masonry pillars at around 55 metre intervals and above the river, it was possible to control the fixed slope of a wooden railing and a walkway platform on it only by using stretched ropes. In such a way it was not possible for the mentioned segments of the wooden bridge structure to diverge above the individual supports.

Trajan's bridge is, regarding the method of construction of the wooden structures, closely connected with yet another Roman infrastructural construction used in Antiquity to bridge a river. It is the renowned Pont du Gard viaduct in today's France. No matter how unusual the idea of a resemblance between that aqueduct and Trajan's Bridge seems, such an idea has already been proposed by scholars.[34] There is an evident lack

[32] Гушић 2015, 78.

[33] Гушић 2015, 78.

[34] Paillet 2005, 63, fig. 59.

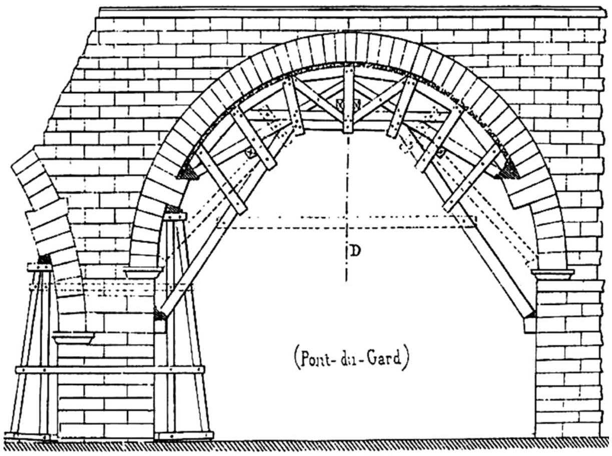

Figure 7. Appearance of wooden construction of scaffolding for building masonry arches on the Pont du Gard aqueduct (after Léger 1875, fig. 13).

of representations regarding the appearance of the wooden railings for the construction of scaffolding for the stone arched supports of aqueducts in the time of the Empire. Consequently, Paillet, where the Pont du Gard was concerned, used the representation of the wooden structures of Trajan's Bridge and pontoon bridges across the Danube. According to Paillet, who quotes earlier assumptions of O'Conor, wooden railings on these bridges were not only used to secure the safe passage of people and goods after the bridge had been built.[35] They also provided sufficiently stable structures (because of their railing structure) for the extension of the bridge sections when building on both sides from each individual pillar until the junction of the sections was reached along the line of the bridge extending across the river. It was possible, according to these authors, to also place wooden machines over the mentioned structures, such as large pulleys for raising the heavy loads necessary for building the scaffolding and stone structures of that aqueduct.[36]

Paillet, however, did not analyse in detail the appearance of the wooden scaffolding necessary for the construction of the stone arches of the Pont du Gard aqueduct in relation to the supporting structure of Trajan's Bridge. The arches of the aqueduct offered sufficient detail for the reconstruction of the appearance and method of fixing of the scaffolding. Some other authors have already dealt with this topic.[37] Particularly distinctive are the positions of the protruding stone courses at the points where the stone arches and protruding arch-stones above the abutments rested. Most authors agree, on the basis of these elements, that the wooden scaffolding for the stone arches consisted in fact of interconnected strut beams and radial beams.[38] In the middle of an arch span, i.e. in its highest segment, therewere also horizontally placed beams. The placement of the struts and the radial beams for the arch scaffolding was always executed next to both sides of each pillar, so there were no additional scaffolding supports in the area at the base of the pillars. It is obvious that this concept of constructing wooden scaffolding is identical to the one applied sometime later on Trajan's Bridge.

[35] Paillet 2005, 63; O'Conor 1993, 132–144.

[36] I must express here my reservations regarding the leaning of machine on the latticed railings. Namely, the railings could not have been more than 1 metre tall and they were arranged at 9 metre intervals as that was the width of the bridge. Such railings could not have been massive and would not have been adequate for supporting machinary above the river, at least not in the case of Trajan's Bridge.

[37] Léger 1875, fig. 13; Espérandieu 1926, 31; Adam, 1984, 190–191.

[38] We must point to different opinions, like that of Fitchen, although such solutions could not have been applied on Trajan's Bridge across the Danube because there were many supports at the base of the bridge, see Fitchen 1967, 9–13, figs. 2, 3.

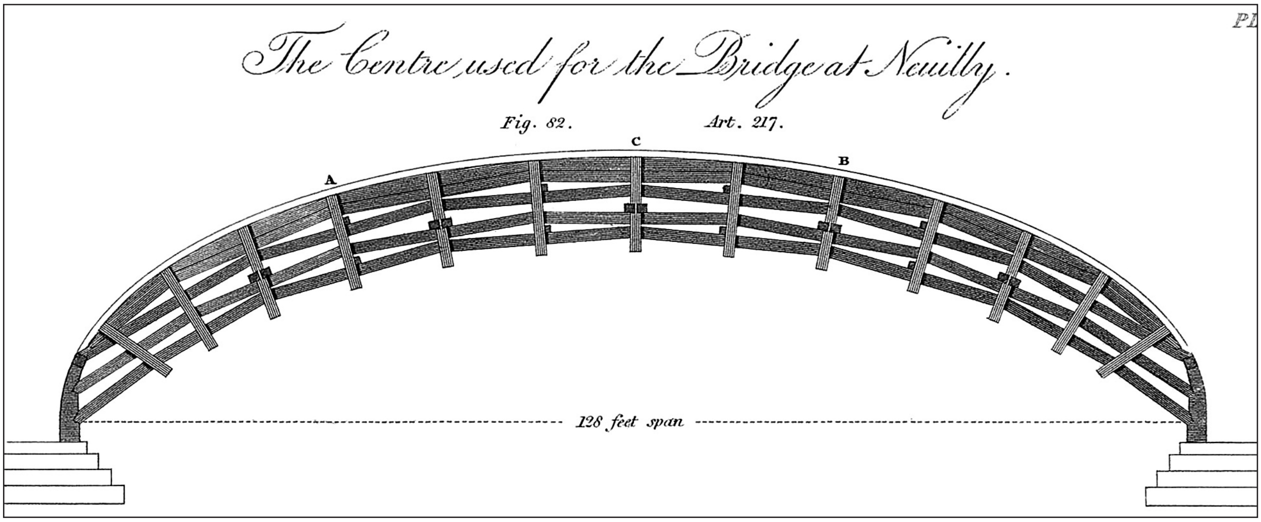

Figure 8. Method of construction of wooden scaffolding for masonry arches in the 18th century, after engraving by J. Davis (Copyright: Civil engineering: three types of wooden centring for bridges. Engraving by J. Davis, 1820, after R. Tredgold. Credit: Wellcome Collection. CC BY. Creative Commons Attribution (CC BY 4.0) terms and conditions: ttps://creativecommons.org/licenses/by/4.0

The previously described method of building the wooden bridge structures remained unknown to European engineers until the 18th century, while the technology of building bridge foundations using caissons was not to be seen until the 19th century.[39] Rare representations of such method of construction could be found in the drawings for the scaffolding for stone arches at the end of the 18th and the beginning of the 19th century[40] (fig. 8).

Conclusion

The building of Trajan's Bridge included the use of caissons, stone and concrete pillars in the river and wooden support structures and platforms above the pillars (figs. 9, fig. 10). The very undertaking to build such a monumental bridge with a combination of constructions of heterogeneous materials was a demanding engineering achievement and drew great admiration among contemporaries. This is clearly evident from quotes from Trajan's biography presented by Cassius Dio, as well as other preserved literary texts and visual representations of the bridge. In contrast to Caesar's Bridge across the Rhine, which existed for only a relatively short period of time and was completely made of wood, the construction of Trajan's Bridge and, primarily, the method of construction used in its foundations and masonry pillars guaranteed its much longer life.

What the reason was for the eventual abandonment of Trajan's Bridge remains unknown as historical sources are not clear concerning that question. According to Cassius Dio, Trajan's heir Hadrian initiated the dismantling of the upper bridge structure, which was is in contrast to Hadrian's policy of the Romanisation of

[39] In the 18th century, French royal engineer Jean Rodolphe Perronet, for the first time, made scaffolding creating wooden arches in three rows for building masonry arches in a way similar to the one described above. The method was not absolutely identical to that of Trajan's Bridge, judging by the bridge representation on Trajan's Column, but is the closest known so far in the history of bridge construction. On this topic see scaffolding representations in: Perronet 1987.

[40] Copyright: Civil engineering: three types of wooden centring for bridges. Engraving by J. Davis, 1820, after R. Tredgold. Credit: Wellcome Collection. CC BY. Creative Commons Attribution (CC BY 4.0) terms and conditions: https://creativecommons.org/licenses/by/4.0

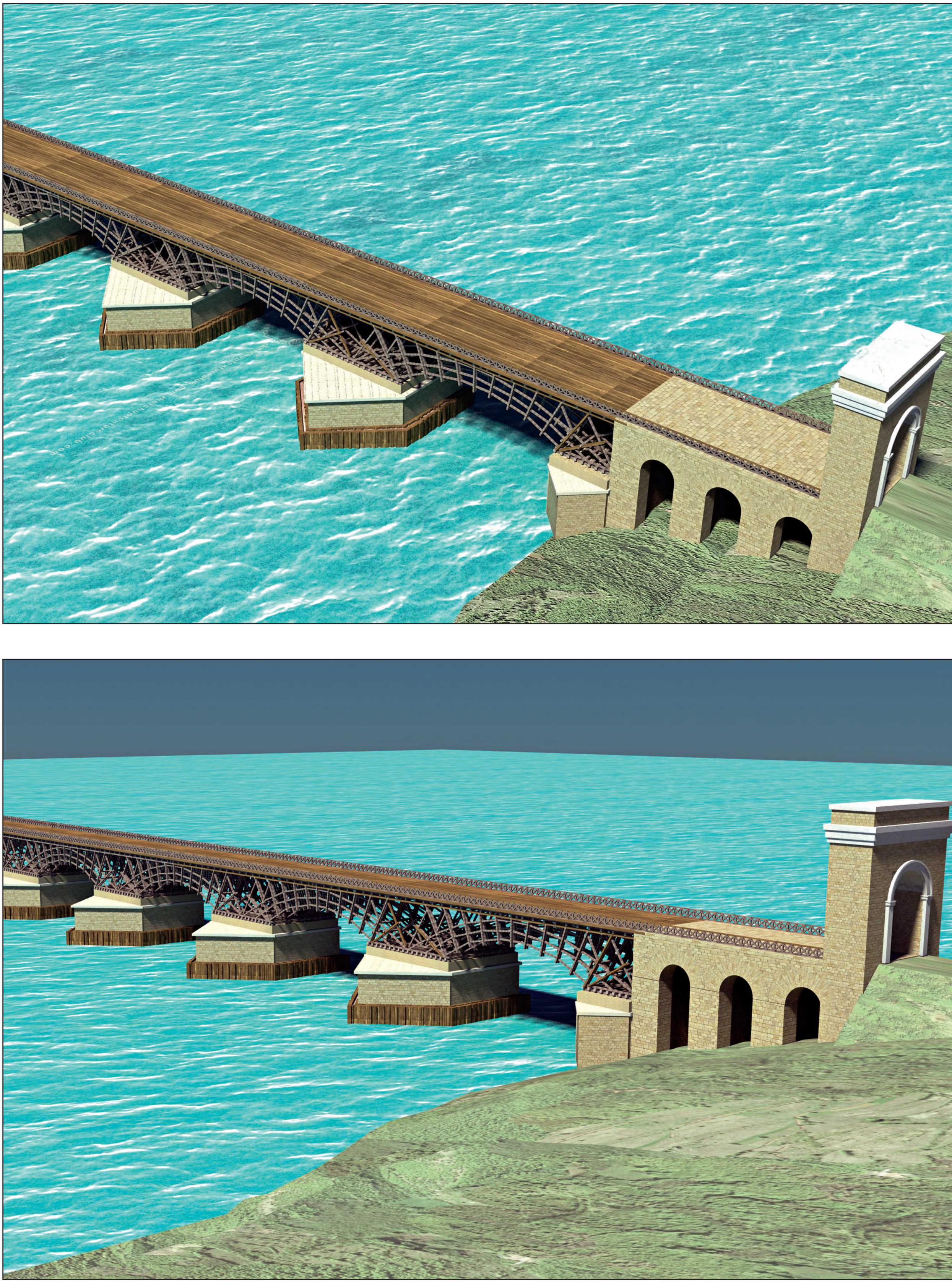

Figure 9. Appearance of Trajan's Bridge (reconstruction by the author, 3D model V. Milošević)

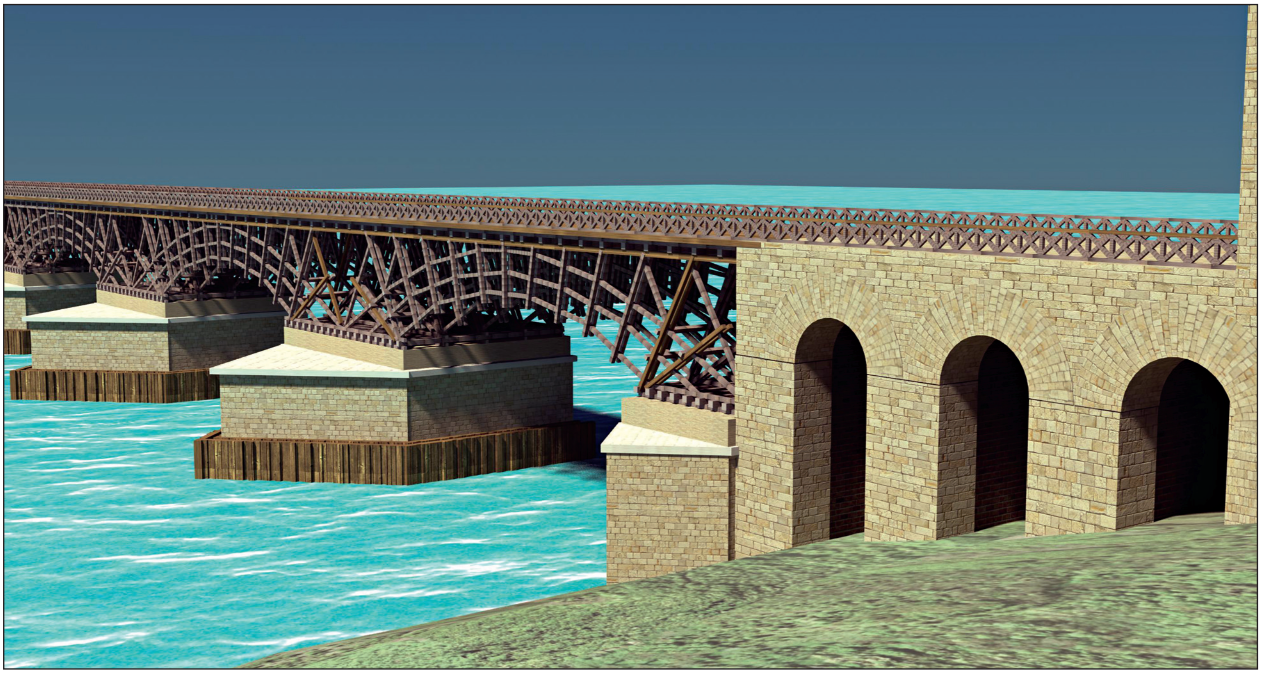

Figure 10. Detail of construction of Trajan's Bridge (reconstruction by the author, 3D model V. Milošević)

the Dacians.[41] There is no information that it was ever restored. The natural decay of the bridge should not be considered out of the question, bearing in mind that it was standing just above the river, which caused extreme annual temperature differences and changes in humidity. This would have had a devastating effect on the structure of Trajan's Bridge and its longevity. Nevertheless, even after the deterioration of the wooden structure, the remaining masonry pillars continued to provoke admiration and an impression of the past grandeur of this imperial engineering project to connect two river banks across the wide Danube waters.

Translated by Mirjana Vukmanović

[41] This statement of Cassius Dio is opposed by the interpretation of Garašanin and Vasić regarding a more fervent policy of Romanisation in the territory of Dacia used by Hadrian to connect that province more strongly to the remaining parts of the Empire; see Гарашанин, Васић 1980, 13; notes 36, 37, 38.

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