Trajan's Bridge: The World's First Long-Span Wooden Bridge

Triple segmented arches supported the long spans to build this bridge over a wide, turbulent river under the watchful gaze of hostile forces.

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One of most admired structures of the Roman Empire is the 3,600-foot-long, twenty-span wooden bridge on stone piers bridge built by Emperor Trajan and his chief engineer Apollodorus over the Danube River between 103 and 105 A.D. The Roman Empire then encompassed much of what is now Europe, the Middle East and the north coast of Africa. To connect and expand this vast empire, Trajan built permanent roads and bridges to move his legions and trade. The Romans are best known for their stone buildings and bridges, but many bridges were constructed with wood. These bridges were built for conquest, such as Caesar's Bridge over the Rhine River and Trajan's Bridge. Trajan's Bridge was the longest bridge in the world when it was built and it has remained so for many centuries. It was built over a turbulent river in the vicinity of an enemy and was a wonder of the world.

Trajan

Trajan was born in Spain and was the first emperor of Rome not born there. His mentor was Nerva Cocceius. Nerva was made Emperor at an old age. Cassius Dio Cocceianus (Dio) in his history of Rome, written around 230, wrote that Nerva "to counter his enemies in the Senate and throughout Rome... ascended the Capitol and said in a loud voice: 'May good success attend the Roman senate and people and myself. I hereby adopt Marcus Ulpius Nerva Trajan.'"[1] Trajan was then governor of Germany and the senate appointed him Caesar. Soon after, Nerva died and Trajan became emperor in 98.

One of Trajan's first challenges came from Decebalus, the leader of the Dacians, who occupied the lands (now Romania) to the north and east of the Danube River (then called the Ister River). The Dacians made raids across the river into the Roman province of Moesia. In the past, to counter these incursions, the Romans, under Domitian, fought battles with Decebalus or his predecessor in

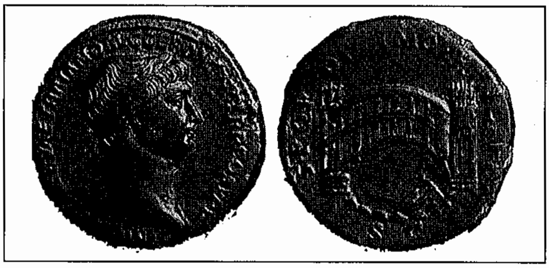

FIGURE 1. A coin issued in 105 showing Trajan and an idealized single-span bridge on the reverse.

69, 85 and 89. In the course of these wars, if the Romans needed to cross the Danube, they did so in boats or on a bridge of boats.

In 101, according to Dio, Trajan "took into account [the Dacians'] past deeds and was grieved at the amount of money they were receiving annually, and he also observed that their power and their pride were increasing" and sent his legions into Dacia.[1] Decebalus, sensing his defeat, "had sent envoys even before his defeat... and reluctantly engaged to surrender his arms, engines and engine-makers, to give back the deserters, to demolish the forts, to withdraw from captured territory. . . This was after he had come to Trajan, fallen upon the ground and done obeisance and thrown away his arms. He also sent envoys in the matter to the Senate, in order that he might secure the ratification of the peace by that body. Trajan celebrated a triumph and was given the title of Dacicus."[1] But apparently Decebalus had no intention of relinquishing power to the Romans. Shortly after his defeat he "was collecting arms, receiving those who deserted, repairing the forts, sending envoys to his neighbours and injuring those who had previously differed with him."[1]

Seeing this, Trajan, between the years 103 and 105, in order to facilitate the future passage of his legions into Dacia, ordered Apollodorus to build a permanent bridge across the Danube. In 106, shortly after the bridge was finished , the Senate declared Decebalus an enemy, and Trajan decided to conduct the war against him in person instead of entrusting it to others. Dio wrote:

> Trajan, having crossed the Ister [Danube] by means of the bridge, conducted the war with safe prudence rather than with haste, and eventually, after a hard struggle, vanquished the Dacians. In the course of the campaign he himself performed many deeds of good generalship and bravery, and his troops ran many risks and displayed great prowess on his behalf. . . Decebalus, when his capital and all his territory had been occupied and he was himself in danger of being captured, committed suicide; and his head was brought to Rome.[1]

It is clear that Trajan made use of his great bridge to conquer his enemy and maintain control of his new province. To protect his permanent bridge, Trajan built forts on both sides of the Danube, remains of which still survive. Decebalus, however, remains a hero in Romania and a large image of him is carved in the rock face of the Iron Gates just upstream of the bridge site. His image has also appeared on recent Romanian stamps.

The coin shown in Figure 1 has an image of Trajan on one side and on the reverse an image that many believe represents his bridge across the Danube. The writing on the coin on the front face reads: "IMP[ERATORI] CAES[AR] NERVAE TRAIAN AVG[VSTVS] GER[MANICUS] DAC[ICUS] P[ONTIFEX] M[AXIMUS] TR[IBVNICIA] P[OTESTATE] CO[N]S[VLI]V P[ATRI] P[ATRIAE]," or "TO IMPERATOR TRAJAN AUGUSTUS, CONQUEROR OF THE GERMANS, CONQUEROR OF THE DACIANS, PONTIFEX MAXIMUS, WITH TRIBUNICIAN POWER, CONSUL FOR THE FIFTH TIME, FATHER OF THE COUNTRY." On the reverse, the writing is: "S[ENATVS] P[OPVLVS] O[VE] R[OMANVS] OPTIMO PRINCIPI," with "optimo principi" being a title conveyed on Trajan by the Senate meaning "best prince."

The image of one span of the bridge is meant to be symbolic. The three arched ribs, while not exactly as built, are numerically correct, as are the gateways at the end of the bridge. The symbology of the steps at the end of the bridge is incorrect since chariots, wagons and machines of war would have to pass from the bridge to land by some type of ramp or approach structure. It also appears that the coin maker thought Trajan and his legions passed through the arches rather than on top of them on a level deck. The image of Trajan, however, is consistent with other images of him on coins and stone sculptures. The fact that the bridge was shown on a coin at all signifies the importance of the bridge to Trajan, the Senate and the Romans. Trajan died in 117 and was succeeded by Hadrian, his trusted ally.

Apollodorus

Apollodorus (see Figure 2) was a Greek from Syria, the province where Trajan's father had been governor and where Trajan served as a military tribune. Apollodorus was born in Damascus, a city that had only recently been annexed to the Roman Empire. He began his career as a military engineer, and came to Rome during Trajan's consulship in 91. When Trajan became Emperor, he made Apollodorus his court architect. In the year 103, after the 101 expedition to Dacia, Apollodorus was ordered to build a permanent bridge over the Danube, probably at or near the site of an earlier pontoon bridge.

In 107, after the defeat of the Dacians, and with monies from the Dacian treasures acquired in their defeat, Trajan commissioned him to build an addition to the Imperial Forum. This project was followed by the construction of Trajan's Column in 113. It was a new kind of monument that told in bas-reliefs the story of the Dacian campaigns on a spiraling marble column.

After the death of Trajan, Apollodorus retained his position as court architect, and was probably involved in the construction of the Pantheon, which began in 118. There were soon disagreements, however, and in 121 Hadrian gave the project, which involved moving the colossal statue of Nero and constructing the Temple of Venus and Rome, to other architects. Dio wrote of this disagreement:

> Apollodorus, who had proposed duplicating the Colossus, was highly critical of the project. . . Hadrian then banished and later put him to death with the reason assigned was that he had been guilty of some misdemeanor; but the true reason was that once when Trajan was consulting him on some point about a building he had said to Hadrian, who had interrupted with some remark: "Be off, and draw your gourds. You don't understand any of these matters." When he became emperor, therefore, he remembered this slight and would not endure the man's freedom of speech. He sent him the plan of the temple of Venus and Roma by way of showing him that a great work could be accomplished without his aid, and asked Apollodorus whether the proposed structure was satisfactory. The architect in his reply stated, first, in regard to the temple, that it ought to have been built on high ground and that the earth should have been excavated beneath it, so that it might have stood out more conspicuously on the Sacred Way from its higher position, and might also have accommodated the machines in its basement, so that they could be put together unobserved and brought into the theater without anyone's being aware of them beforehand. Secondly, in regard to the statues, he said that they had been made too tall for the height of the cella. "For now," he said, "if the goddesses wish to get up and go out, they will be unable to do so." When he wrote this so bluntly to Hadrian, the emperor was both vexed and exceedingly grieved because he had fallen into a mistake that could not be

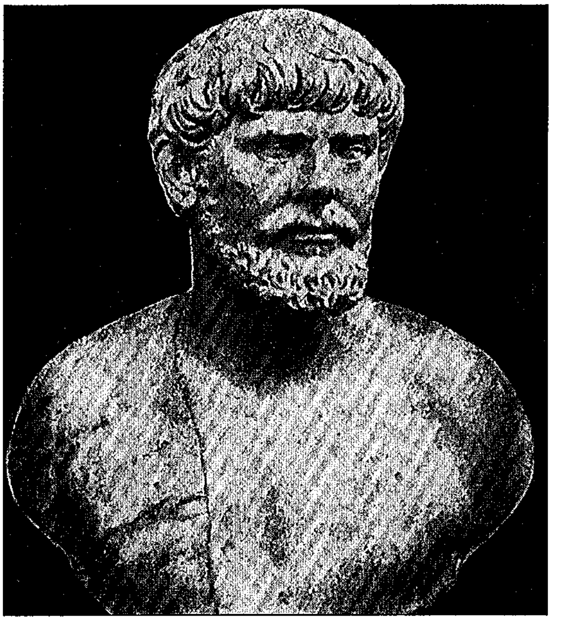

FIGURE 2. Apollodorus.

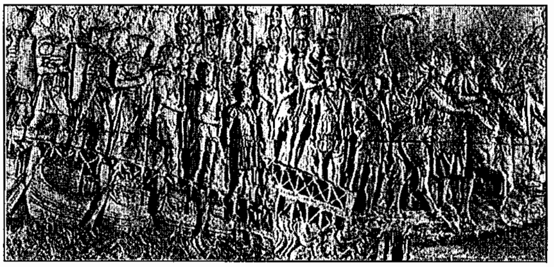

FIGURE 3. Trajan' s pontoon bridge, probably at or near future bridge site. (Note the double truss was over a wider part of the river.)

righted, and he restrained neither his anger nor his grief, but slew the man.[1]

The Bridge – Ancient Descriptions

Dio gave the most well known description of the bridge in his *Roman History* when he wrote:

> Trajan constructed over the Ister [Danube] a stone bridge for which I cannot sufficiently admire him. Brilliant, indeed, as are his other achievements, yet this surpasses them. For it has twenty piers of squared stone one hundred and fifty feet in height above the foundations and sixty in width, and these, standing at a distance of one hundred and seventy feet from one another, are connected by arches. How, then, could one fail to be astonished at the expenditure made upon them, or at the way in which each of them was placed in a river so deep, in water so full of eddies, and on a bottom so muddy? For it was impossible, of course, to divert the stream anywhere. I have spoken of the width of the river; but the stream is not uniformly so narrow, since it covers in some places twice, and in others thrice as much ground, but the narrowest point and the one in that region best suited to building a bridge has the width named. Yet the very fact that river in its descent is here contracted from a great flood to such a narrow channel, after which it again expands into a greater flood, makes it all the more violent and deep, and this feature must be considered in estimating the difficulty of constructing the bridge. This, too, then, is one of the achievements that show the magnitude of Trajan's designs, though the bridge is of no use to us; for merely the piers are standing, affording no means of crossing, as if they had been erected for the sole purpose of demonstrating that there is nothing which human ingenuity cannot accomplish. Trajan built the bridge because he feared that some time when the Ister was frozen over war might be made upon the Romans on the further side, and he wished to facilitate access to them by this means.[1]

Dio's description must be considered in light of the image on Trajan's Column. It was built only eight years after the construction of the bridge.

Trajan's Column & the Dacian War of 106

Trajan's Column is almost 30 meters in height and was a contribution of the Senate of Rome to Trajan's forum. It was made from twenty large blocks of marble, carved on the outer face with a spiral frieze presenting the story of Trajan's Dacian Wars. A statue of Trajan once stood on top of the column (the present statue of St. Peter on the top dates from 1588). The base of the column is a massive cube containing a number of small rooms, the innermost of which was Trajan's tomb chamber. The sculptures in bas-relief spiral up the column in chronological order from the ground to the top. Near the top of the column, one portion of the band shows the Emperor Trajan with his master builder Apollodorus and soldiers presenting an offering before the wooden bridge over the Danube.

The first bridge Trajan built across the Danube was a pontoon bridge (see Figure 3), a style of bridge that was used by the Greeks and Romans for centuries. Note the scale problem of men compared to boats and the fact that the boats are side by side rather than 10 to 20 feet apart as was more typical of the time. The image shows schematically that Apollodorus also used a trussed decking, similar to the railing of the bridge shown below, crossing the boats. Trajan and other Roman leaders would usually carry the boats and other war machines along with them on the

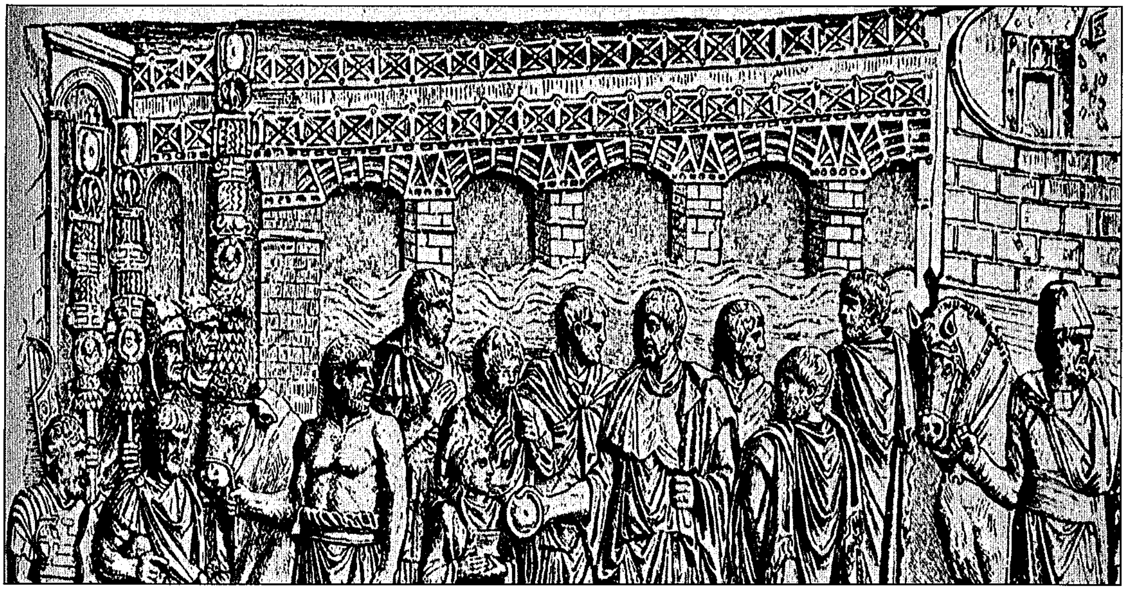

FIGURE 4. Trajan's Bridge, with Trajan in the center with his right hand extended.

way to battle rather than build them on site. The pontoon bridges were temporary structures used to move his legions and war machines across the river. They may have been left in place at this site for a longer period to provide for more legions to cross or for legions leaving Dacia to return to Rome or other provinces.

The permanent bridge is shown in Figure 4. Note that all men in Figure 4 are dressed as Roman Legionnaires except Apollodorus, the Greek, who is shown without a shirt or cape. The image shows the gateways and two arched spans on the left with only five wooden spans. A major masonry structure is also shown on the right, possibly the fort at the end of the bridge.

There is a scale problem with the depiction of the bridge, as shown in Figure 5, especially with the height of railing and the width of the

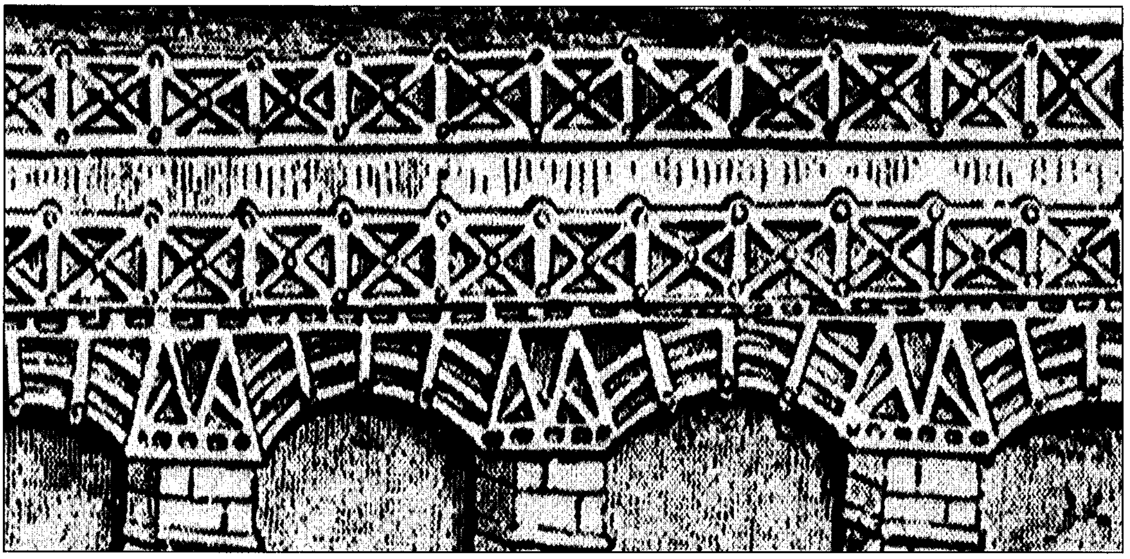

FIGURE 5. A close-up of Trajan's Bridge showing the central portion of the bridge.

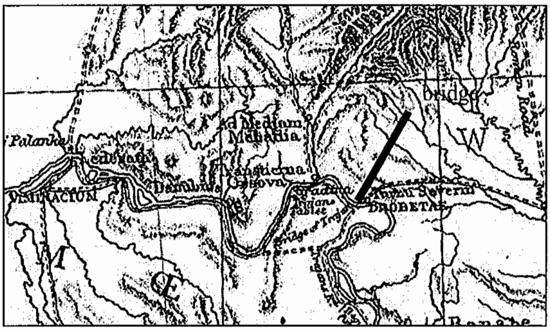

FIGURE 6. The location of Trajan's Bridge at a bend in Danube River near Drobeta. (From Ref. 3.)

bridge. Dio wrote that the bridge was 50 feet wide and the piers were 150 feet high and the span of the arches was 170 feet with 60-foot wide piers. It is clear that the sculptor took some artistic license and was probably trying, with the advice of Apollodorus, to give as close a representation of the bridge as possible given the limitations of space on the column. All early writers refer to a report on the construction of the bridge by Apollodorus but the report, if ever written, has been lost.

Later, during the reign of Hadrian, Trajan's successor, the bridge deck was destroyed, since Hadrian "was afraid that it might also make it easy for the barbarians, once they had overpowered the guard at the bridge, to cross into Moesia, and so he removed the superstructure."[1] Apparently the deck and piers were rebuilt by Emperor Constantine about 328, or a new bridge was built nearby.[2] It is not known how long that bridge survived, but it was surely gone prior to the reign of Justinian in the sixth century.

Bridge Location

The Roman road network was extensive throughout the empire, but Trajan wanted a better access from Viminacium, shown on the left side of the map in Figure 6, the westernmost and nearest point of contact of his line of march, and subsequent route into Dacia. The road crossed the Trajan's Bridge below the Iron Gates at Orsova.

The Danube River was very wide north and west of the bridge site, near present-day Orsova, where it worked its way through the Carpathian Mountains in what was called the Kazan Defile in a vertical-sided gorge with heights of upwards to 2,000 feet and with a width of as little as 350 feet, with rapids approximately 1.5 miles long. The depth of the river in places was 30 fathoms (or 180 feet). Below the gorge the river became wider again and at the bridge site it was over 3,000 feet wide. One of Trajan's and Apollodorus's major road projects was building a road that was cut into the westerly face of the defile. The road in places was built on cantilevered wooden structures tied into rock. This road is now below water level due to the construction of a dam downstream. The present-day Drobeta-Turnu Sevin occupy the northerly (easterly) end of the bridge.

Later Roman Descriptions

Procopius of Caesarea was the next ancient writer to describe the bridge site. Writing around 550, his book entitled *Buildings* (*De Aedificiis*) discussed mostly the works of the Emperor Justinian. He did refer, however, to Trajan's Bridge, or the remains of the bridge:

> And not far from Zanes there is a fort, Pontes by name. The river throws out a sort of branch there, and after thus passing around a certain small portion of the bank, it turns again to its own stream and is reunited with itself. It does this not of its own accord, but compelled by human devices. The reason why the place was called Pontes, and why they made this forced diversion of the Ister at this point, I shall now make clear.
>
> The Roman Emperor Trajan, being of an impetuous and active temperment, seemed to be filled with resentment that his realm was not unlimited, but was bounded by the Ister River. So he was eager to span it with a bridge that he might be able to cross it and that there might be no obstacle to his going against the barbarians beyond it. How he built this bridge I shall not be at pains to relate, but shall let Apollodorus of Damascus, who was the master–builder of the whole work describe the operation. However, the Romans derived no profit from it subsequently, because later on the

bridge was completely destroyed by the floods of the Ister and by the passage of time. At the same time Trajan built two forts, one on either side of the river; the one on the opposite bank they named Theodora, while the one in Dacia was called Pontes from the word — for the Romans call a bridge *pontem* in the Latin tongue. But when boats reached that point, the river was no longer navigable, since the ruins and the foundation of the bridge lay in the way; and it is this for this reason that they compel the river to change its course and to go around in a detour, so that they may keep it navigable even beyond that point.[4]

It is clear from Procopius that the bridge was in ruins in the mid-sixth century and was obstructing navigation on the river. To make it navigable, they apparently dug a canal around the northerly (Romanian) end of the bridge. This approach seems to have not been easy to do since the river had already removed a great deal of the bridge and its piers. Tudor and others believed the channel that Procopius described was a branch of the Danube when Trajan built his bridge.[5] If it were so, then it would have required that Trajan build another small, low-level bridge over the branch in addition to the main bridge over the river. The primary reason for their belief was that they called the fort on the Serbian side Pontes, the plural of *pont*, the Latin word for *bridge*. There is also a suggestion on Trajan's Column that a low-level bridge existed on what is now the Serbian side of the river.

In the twelfth century, John Tzetzes, a Byzantine poet from Constantinople, in his *Chiliades*, a series of letters, utilized Dio's work using the same dimensions for the width and height of piers as well as the same span and number of piers.[6] He did, however, add information on the construction of the bridge. His main addition, based on the testimony of Theophilus, a Roman leader, a proconsul in Constantinople, was the fact that the foundations were placed in caissons. He wrote that the caissons were 120 *pieds* (a French *pied* is equal to 1.06 English feet) long and 80 pieds wide. These values are much larger than Dio's pier dimensions and are probably incorrect. It is possible that Theophilus may have had access to Apollodorus's work, but such access has not been confirmed.[6] The Greeks had no word for *caisson* but most translators use the word *caisson*. Unfortunately, many scholars do not place much trust in Tzetzes's work since he frequently worked without original sources, mostly working from memory and oral testimony.

Another reference to the bridge, four hundred years later, was by the famous architect and bridge engineer, Andreas Palladio in 1570 in his *Four Books of Architecture*. He wrote of the bridge:

> Exceeding great and worthy of admiration was that which Trajan built, to subdue the Barbarians over the Danube, opposite Transilvania, on which were inscribed these words: PROVIDENTIAL AUGUSTI VERE PONITFICIS VIRTUS ROMANA QUID NON DOMET? SUBJUGO ECCE RAPIDUS ET DANUBIUS (BY THE FORESIGHT OF AUGUSTUS, THE TRUE PONTIFEX WHAT CAN ROMAN EXCELLENCE NOT TAME? BEHOLD, EVEN THE RAGING DANUBE LIES BENEATH THE YOKE.)[7]

Unfortunately, Palladio did not present his visualization of the bridge, even though he did give a drawing of the earlier Caesar's Bridge across the Rhine River. Tudor believed that this inscription was false, as do some other historians.[8] It is interesting, however, that Palladio many years earlier accepted the authenticity of the inscription.

The next writer to visit and write about the bridge was Ludovici Ferdinandi Marsilli (Marglisi) in 1698.[9] His letter to the Reverend Bernardum De Montfaucon, first published in 1715, reviewed the building of the bridge, based on Dio, and then described the remains of the bridge at the time. His map of the site, published later, and the forts at both ends is shown as Figure 7. Many of the piers were still visible at the time of his visit as were the remains of the forts and walls around them. He did not show any islands in the river, nor a channel on the southern side, at the site of the bridge as some earlier and later historians found.

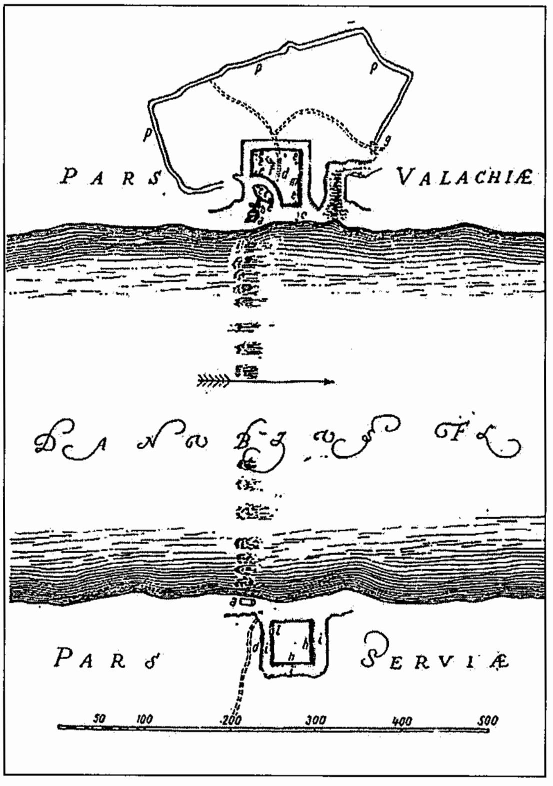

FIGURE 7. Marsigli's map of the site.

Montfaucon's book (second edition, published in 1722) contains information from Marsigli's letter of April 17, 1715, but also includes a magnificent engraving in Book IV, second part, of the bridge, based largely on the image from Trajan's Column (see Figure 8).[10] This image is perhaps the first detailed published version of the bridge and was published well before any image of details of the bridge on the column were made available by photography.

Figure 8 shows five wooden spans with masonry arches at the left end and forts at each end of the bridge. The close-up of a typical span gives in greater detail than the column image the framing of the span and assumed that there were five radial members. It is interesting to note that the framing over the two piers is not identical and that the bridge is shown with a slope from left to right. A profile of the bridge, similar to Popovici's,[11] developed in 1931, indicated that the bank on the Romanian side of the river was significantly higher than the bank on what was then the Yugoslavian side of the river (now Serbian), so the bridge may have been on a slope. The fort on the right is similar to what was depicted on Trajan's Column but the approaches on the left are significantly different.

Description by Marsigli

Marsigli later presented his findings in his own six-volume book originally published in Latin in 1726.[12] This work, translated into French in 1744, was the first lengthy description of the bridge that included fine illustrations. Marsigli gave a brief history of the bridges along the Danube based on the ancient works. While some ancient writers did not believe the site at Severin was the place where Trajan built his bridge, Marsigli concluded that anyone who examined his description and figures would be convinced that the two structures on each bank and the remains of the piers in the river were evidence of the bridge.[12]

Marsigli was a colonel in Emperor Leopold I's Austrian army between 1681 and 1704, and he was stationed along the Danube between 1689 and 1691. He was a military engineer who mapped routes for the army and built bridges and fortifications, as well as an antiquarian and historian. During this period, he studied and measured, among other things, the ruins of Trajan's Bridge and the forts at each end. Later, in 1703–1704, he was expelled from Austria for high treason when he and a colleague surrendered a fort prematurely, in Leopold's opinion, and he returned to Bologna, Italy. It was at this time period he wrote his six-volume set on the Danube River.

Marsigli's plan showed several middle piers gone, or at least not visible, along with the fact that the bridge approach on the northerly shore made a turn to the right to enter the walled fort named Drobreta.[12] It also appeared that the discharge of a side branch of the river was located just downstream from the bridge. Marsigli also disagreed with Dio on the number of piers and arches. Based on his survey of the site and its remains, Marsigli indicated that there were twenty-three piers and twenty-two arches, while he noted Dio called for twenty piers and nineteen arches.[12] He gives two lengths of bridge: 440 and 443 French *toises* (2,813 and 2,832 feet, respectively). (A toise is equal to six pieds [French feet]

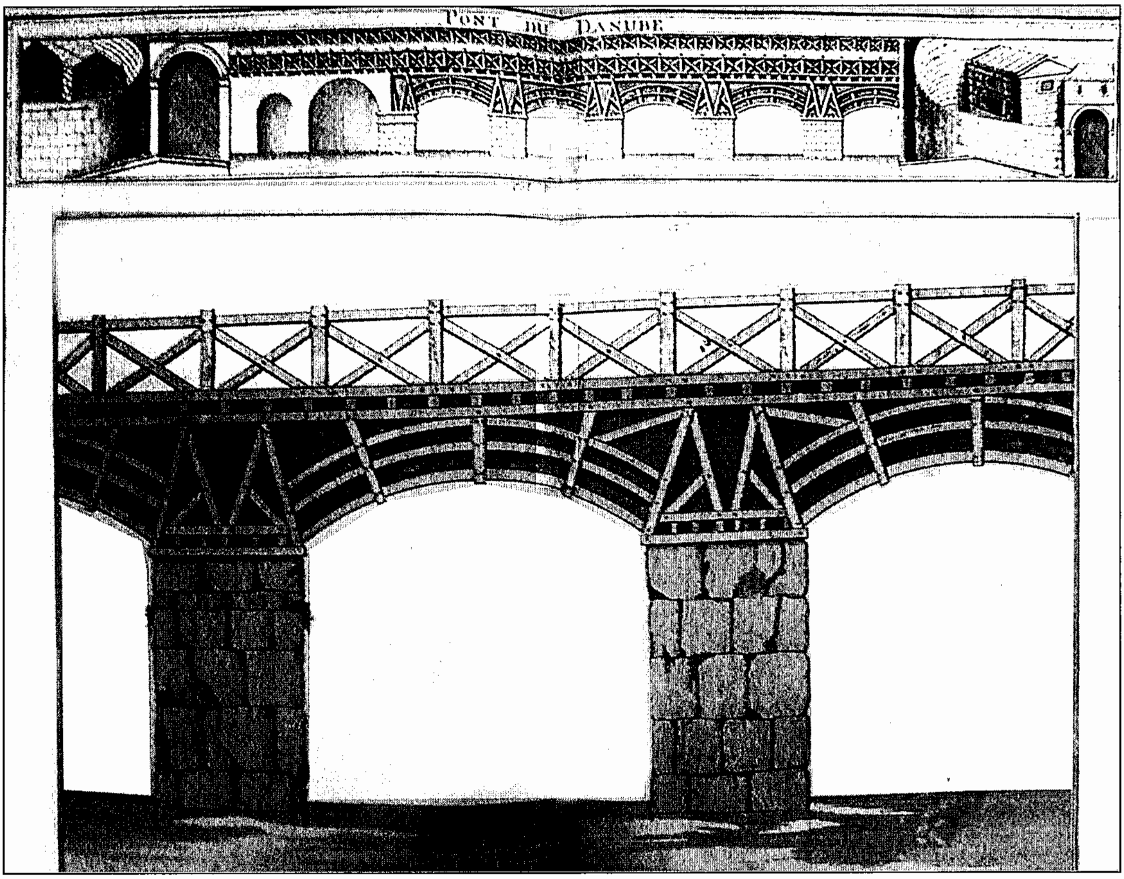

FIGURE 8. Montfaucon's bridge plan from 1722.

or 6.395 English feet.) He essayed a triangulation with a base line on the Romanian side, but due to lack of space he could not get a good value, and he indicated that General Savoie did not want to continue with that work. With his short base line he arrived at the 440-toise value. He obtained the 443-toise value by using a clear span between piers of 17.5 toise, a pier width of 3 toise and the number of spans and piers (for example, twenty-two arches and twenty-three piers). Based on a later, more exact triangulation, his estimates were on the low side.

Figure 9 is a cross-section taken through the abutment on the what is now the Serbian side of the river, what Marsigli called the Mysia abutment. He called the abutment on the Romanian side the Valachia. Figures 10 and 11 are sketches of the Serbian and Romanian (respectively) abutments as they existed at the time of Marsigli's visit.

Marsigli noted that Dio had the piers 150 pieds high, but he estimated that this height was only 42 pieds. He modified the plan in Montfaucon's book as shown in Figure 12.

Marsigli also considered how Apollodorus built the pier foundations in the Danube River, and along the lines of Tzetze proposed a caisson as shown in Figure 13. Evidently, the caisson, in Marsigli's opinion, was built up of three tiers of timber with wooden siding. Probably the piles were placed when the caisson was floated into place over the piles and sunk onto the piles. The inside of the caisson would be filled with stone or rubble until the finish stonework was installed on top of the filled caisson. Marsigli did not mention piles, but it is likely that piles were used to support the caisson and piers.

Nineteenth-Century Descriptions

There are few reports on the bridge from

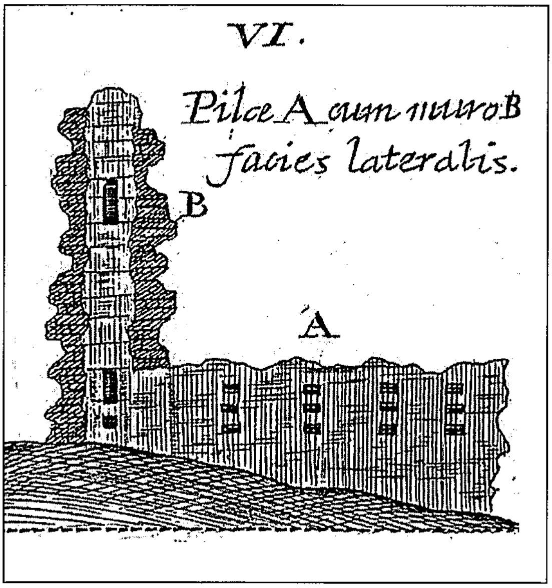

FIGURE 9. Cross-section of the Serbian abutment (by Marsigli).

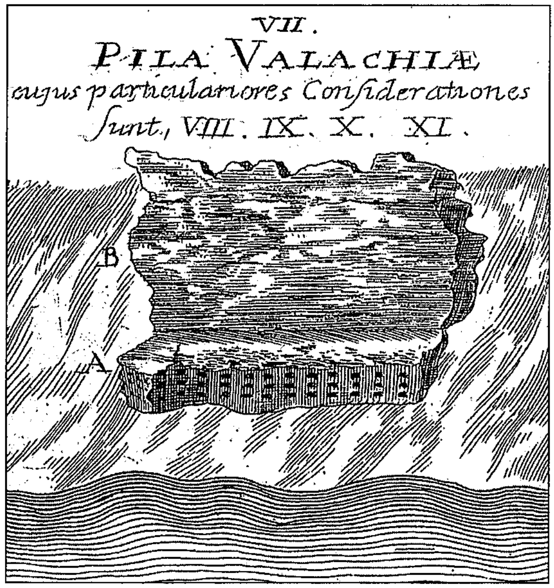

FIGURE 11. A view of the Romanian abutment (from Marsigli).

Marsigli until early in the nineteenth century. An early representation of the bridge was by the French engineer Rondelet in 1810, who praised the bridge (see Figure 14).[13] Rondelet's representation was very similar to that shown by Montfaucon's and on Trajan's Column. There was a slight difference in his framing on the piers with the Trajan's Column framing on the left pier and his improved framing, similar to Montfaucon's, on the right pier. Rondelet used curved segments for his arch with five radial posts (note that the outer posts were not exactly radial). His railing height and deck structure were also well out of scale and they more closely followed the image on Trajan's Column. Most nineteenth-century American books used Rondelet's image, or something very similar, when describing the bridge.

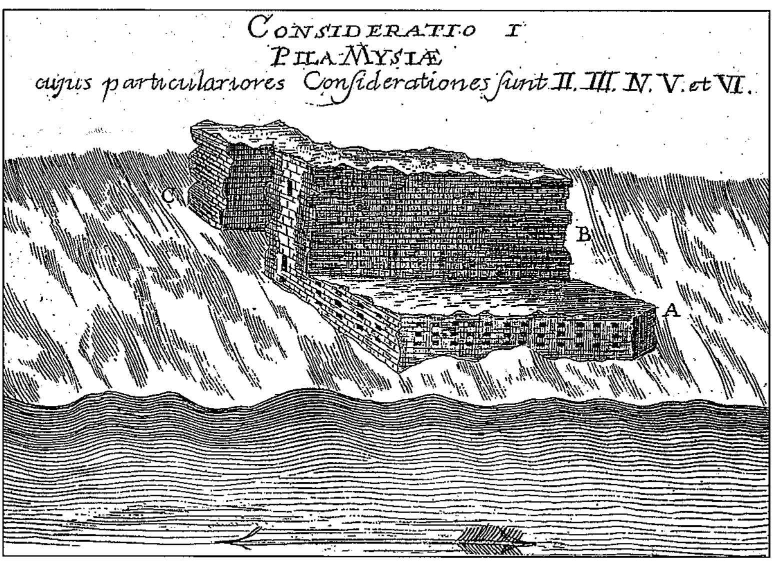

FIGURE 10. A view of the Serbian abutment (from Marsigli).

In 1858, the river was at one of its lowest levels ever, and the stubs of Trajan's Bridge piers were visible and measurable. A team of three — Imbrisevitch, Deuster and Popovici[8] — made a detailed survey of the river bottom, location and size of the sixteen visible piers and their nature of construction. The plan and profile of the bridge as given by Popovici is shown in Figure 15.[11] Three piers near mid-span were probably extant but covered by the island shown. The piers weathered consider-

FIGURE 12. Marsigli's version of Trajan's Bridge based on Trajan's Column.

ably over many years of ice and flood so the original dimensions were larger than those shown. In addition, the pointed icebreakers upstream had been completely worn away as had the pier stonework above the icebreakers. It is believed that the downstream faces were square and not pointed (since that type of design was a later practice). Popovici gave a uniform pier spacing of 21 toises (134 feet) — which is unlikely — and pier dimensions of 9 by 7.5 toises (57.5 by 48 feet). That being the case, he determined that the center-to-center pier spacing was 182.25 feet (compared to Dio's 170 feet, or if Dio or his translator were using French pieds, 181.2 feet) and the pier dimensions 57.5 feet (compared to Dio's 60 feet) by 47.9 feet. It is likely, given the wear over time, that the lower piers originally were approximately 60 feet wide (perpendicular to the river) by 50 feet wide with the icebreaker upstream extending more than 18 feet, for a total pier width of 81.2 feet. The bridge length from the top face of the abutment to the top face of the abutment was 577.2 toises (3,691.2 feet).

The water depth at the time of the survey was less than 1 toise (6.395 feet) and varied between 3 and 6 feet, with high water being 23 to 24 feet above the low water mark.

August Choisy, a well known French architect of the late nineteenth century, in his *L'Art de Batir chez Les Romains,* written in 1873, presented a typical pier and arch detail and framing for the bridge as shown in Figures 16 and 17.[14]

After citing Caesar's Bridge over the Rhine he discussed Trajan's Bridge, noting that it posed difficulties of another order. He indicated that the image on Trajan's Column was incorrect in having the arches stop at what appeared to be a radial and extended the arches down to the pier level. He then discussed

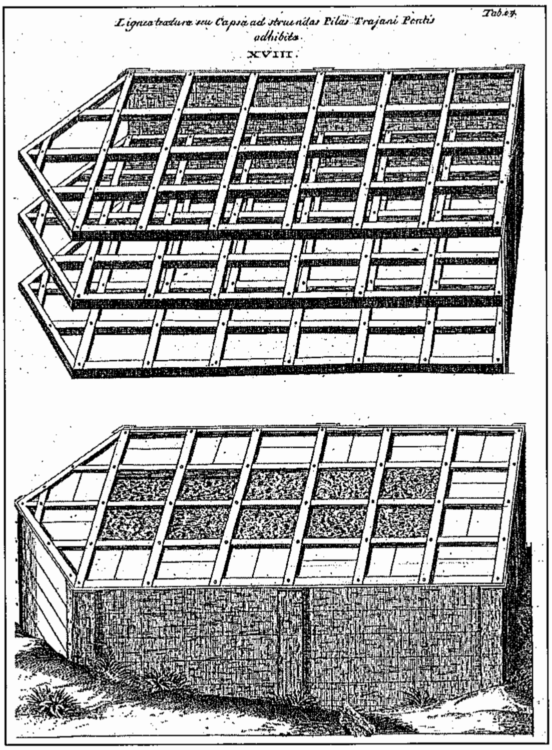

FIGURE 13. Marsigli's suggested pier caisson.

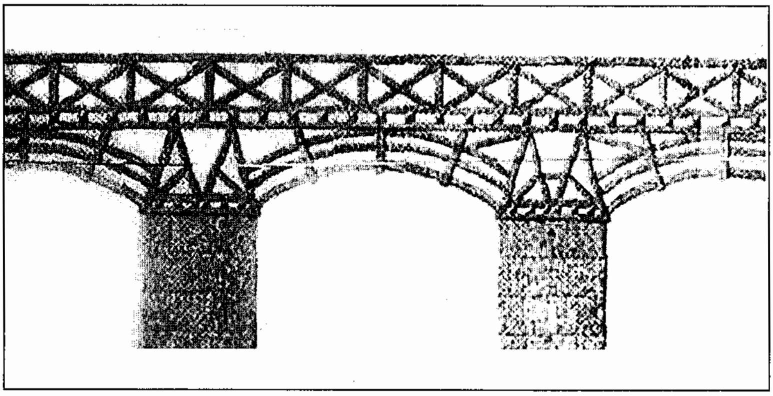

FIGURE 14. Trajan's Bridge as envisioned by Rondelet in 1810.

how, in his opinion, the arches were built with nine radials and illustrated the connection details for the arches and radials (see Figure 16). He closed his segment on the bridge by noting again that the image on Trajan's Column was vague and his interpretations had no way of being confirmed. He, however, based on his own intuition, built his arches with two members with curved segments and his radials out of three segments with the outer two segments broken at the arches and the middle member continuous. He had cross pieces between arches on the upper and lower arch segments to tie the entire woodwork together. He also added some small cleats to tie his pegged members together.

Twentieth-Century Depictions

In 1907, Edgard Duperrex published the most complete engineering analysis of Trajan's Bridge to that date.[15] He based his book on Marsigli's work and on the surveys by Imbrisevitch, Deuster and Popovici in 1858, as well as the historical record. Duperrex's drawings showed two stone arches on the end of the bridge and the wooden arched spans thereafter, with three ribs to the arch. The deck width appeared to be very narrow in comparison to the length of the piers.

Duperrex's image (see Figure 18) is perhaps the best representation of the bridge, but the opening in the gateway appears to be very narrow as does the width of the deck compared to the width of the piers. This image appeared on several stamps issued by Romania and a portion was placed on the crest of Romania showing the importance of the bridge to Romanians. Duperrex reviewed all previous records and drawings and came up with plans shown as Figures 19 and 20.[15]

He assumed a deck width of 15 meters (just less than 50 feet) and span lengths of 51 meters

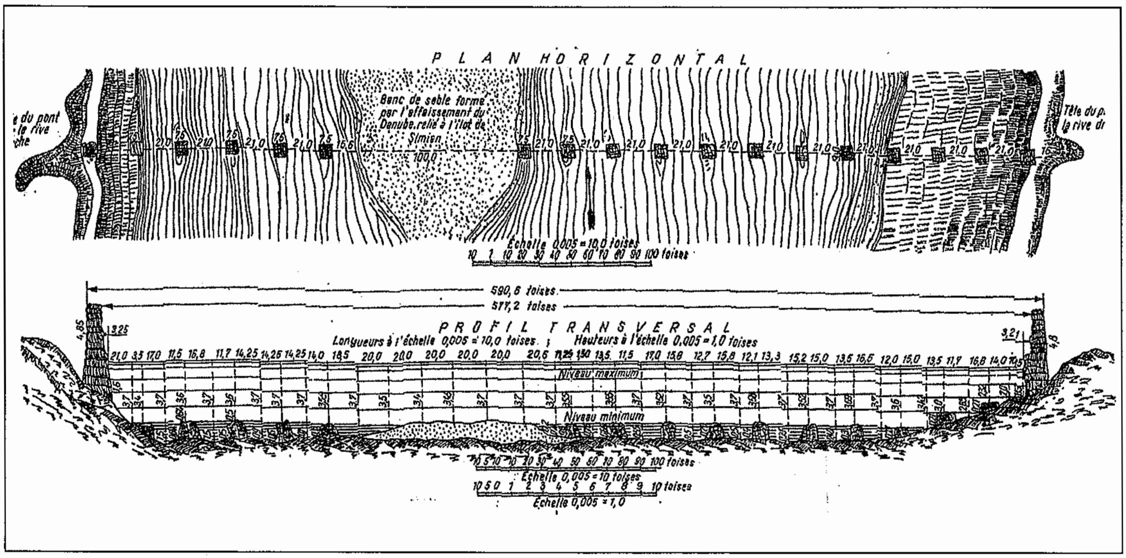

FIGURE 15. Popovici's plan and profile from 1858 (profile on 10 horizontal to 1 vertical).

(167.3 feet). His pier dimensions were 15 by 19 meters (49.22 by 62.3 feet), with triangular extensions both upstream and downstream with altitudes of 10 meters (32.8 feet), making the total pier length along the axis of the river 35 meters (114.8 feet). The height of framing from the top of pier masonry to the deck level was given as 9.5 meters (31.2 feet).

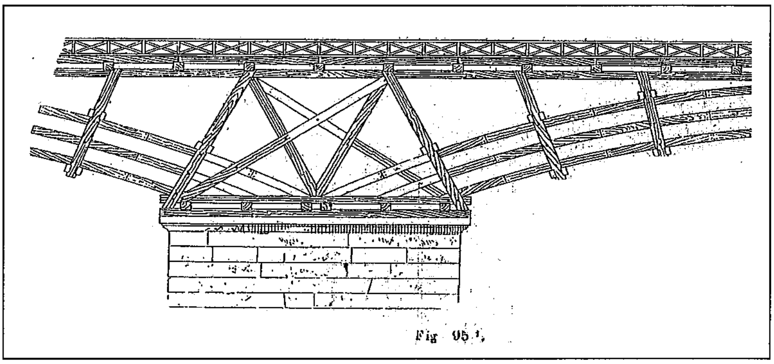

FIGURE 16. Choisy's framing.

In his cross-section, Duperrex showed eight lines of arches at a spacing of 2.03 meters (6.66 feet). His arch segments were separated by variable distances and were not concentric, from 1.5 meters (4.9 feet) at the peak to 3 meters (9.8 feet) at the piers. Perhaps for the first time by an engineer, he proposed a method of framing the bridge using laminated curved arch members as shown in Figure 21.

These arch members were made up of members 0.35 by 0.2 meters (1.15 by 0.656 feet) and were doweled together as shown in Figure 21. His eleven radials were twin 0.3 by 0.25 meters (0.98 by 0.82 feet) posts and were notched around the arch members. His longitudinal beams supported by the radials were 0.35 by 0.3 meters (1.15 by 0.98 feet). His cross beam sizes were not given, but from the scale shown can be calculated to be approximately 0.2 by 0.2 meters (0.656 by 0.656 feet) and were spaced 0.76 meters (2.5 feet) apart. Duperrex did not give a deck thickness, but with a beam spacing of 2.5 feet, it must have been at least 6 inches. He had some minor cross ties at the arches, but it is not clear how many or what size. He also added what appear to be small cleats tying the laminated arch segments and the twin radials together.

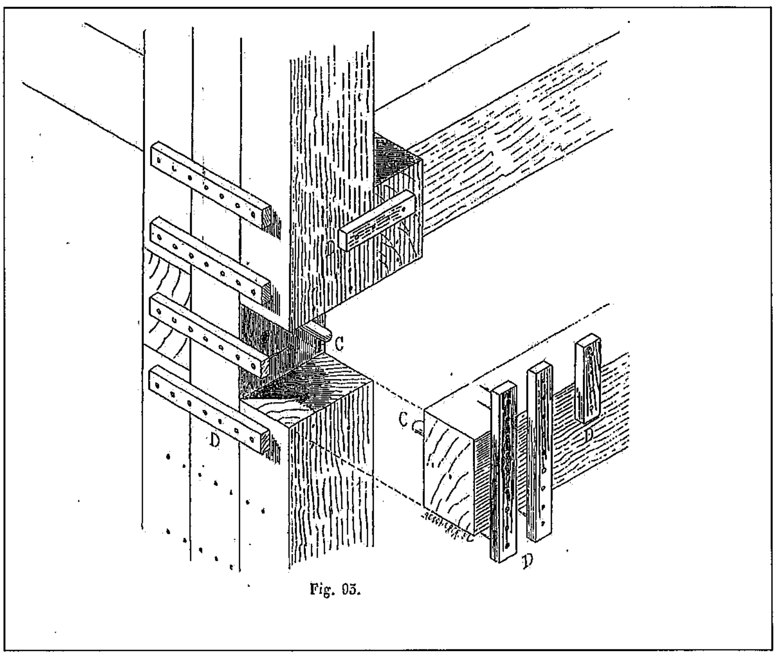

FIGURE 17. Choisy's framing.

In 1963, Piero Gazzola in his *Ponti Romani*, a catalog of Roman bridges (covering primarily masonry bridges), presented a model of the end span of Trajan's wooden bridge.[2] That model, as shown in Figure 22, is apparently based on Duperrex's proposed design.

Gazzola presented a model of a similar Roman bridge based on a description for a bridge across the Rhine at Mainz (see Figure 23).[2] This bridge had thirteen radials, with some additional struts running up from the center of the pier to a doubled top chord mem-

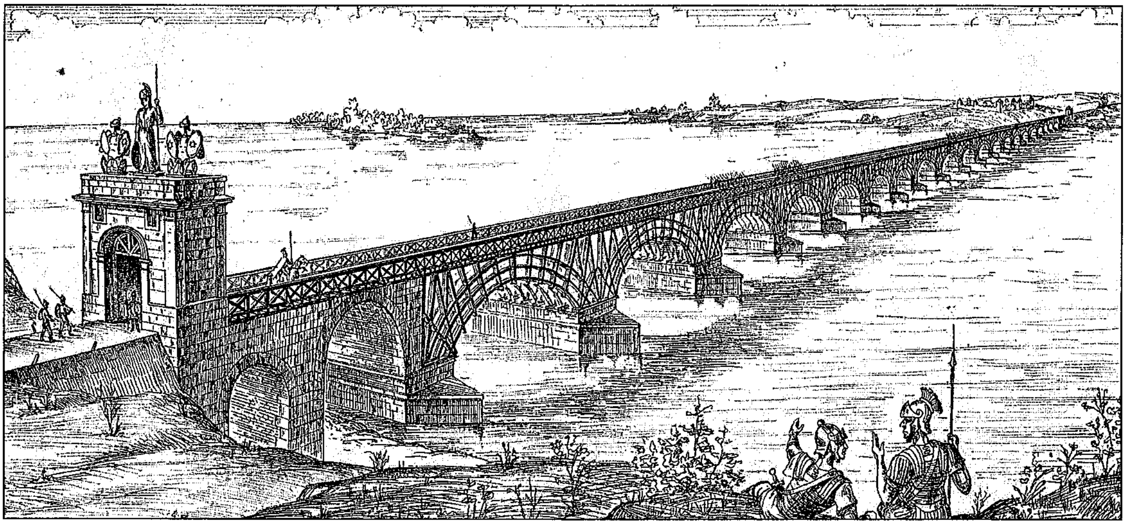

FIGURE 18. Duperrex's re-creation of Trajan's Bridge from 1907.

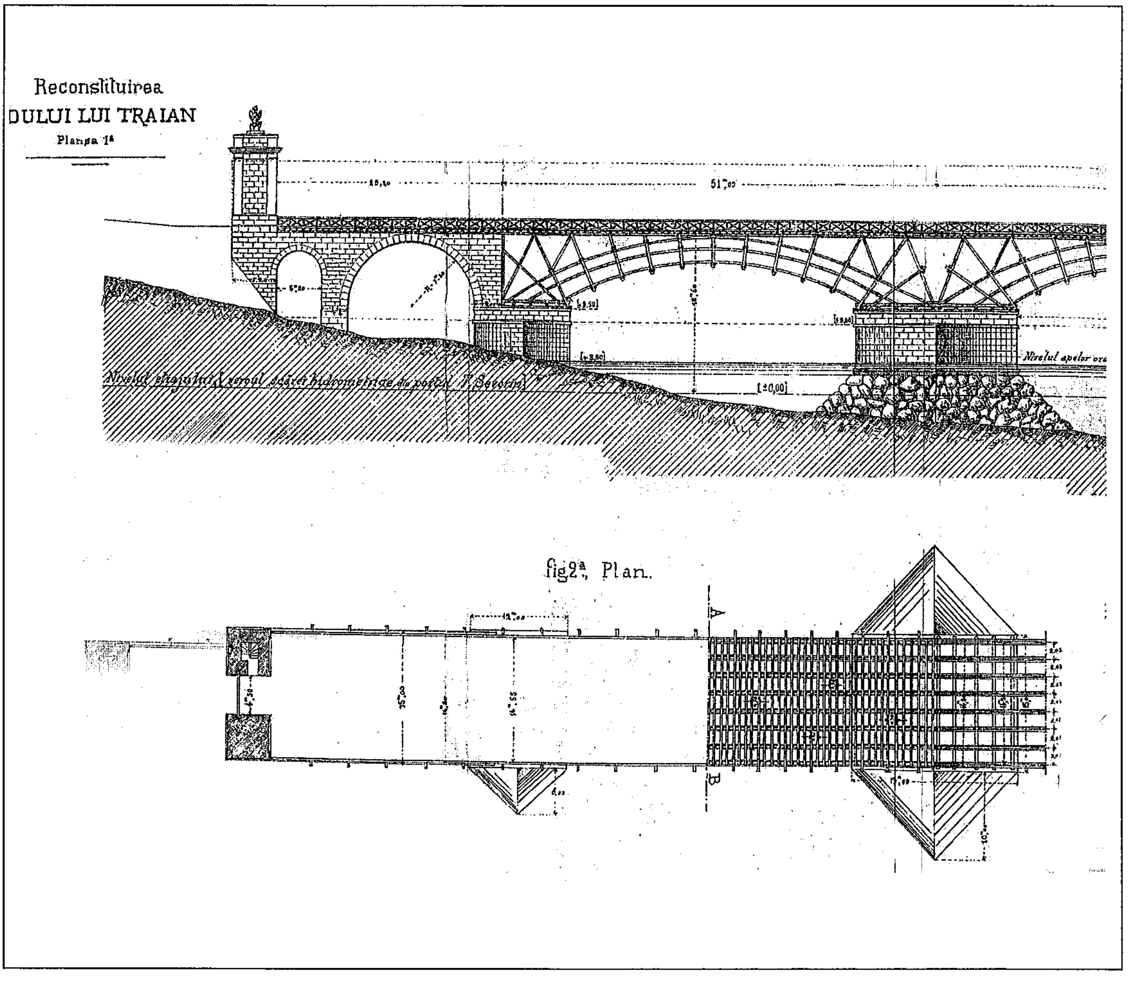

FIGURE 19. Duperrex's sketch of the end of bridge plan and profile.

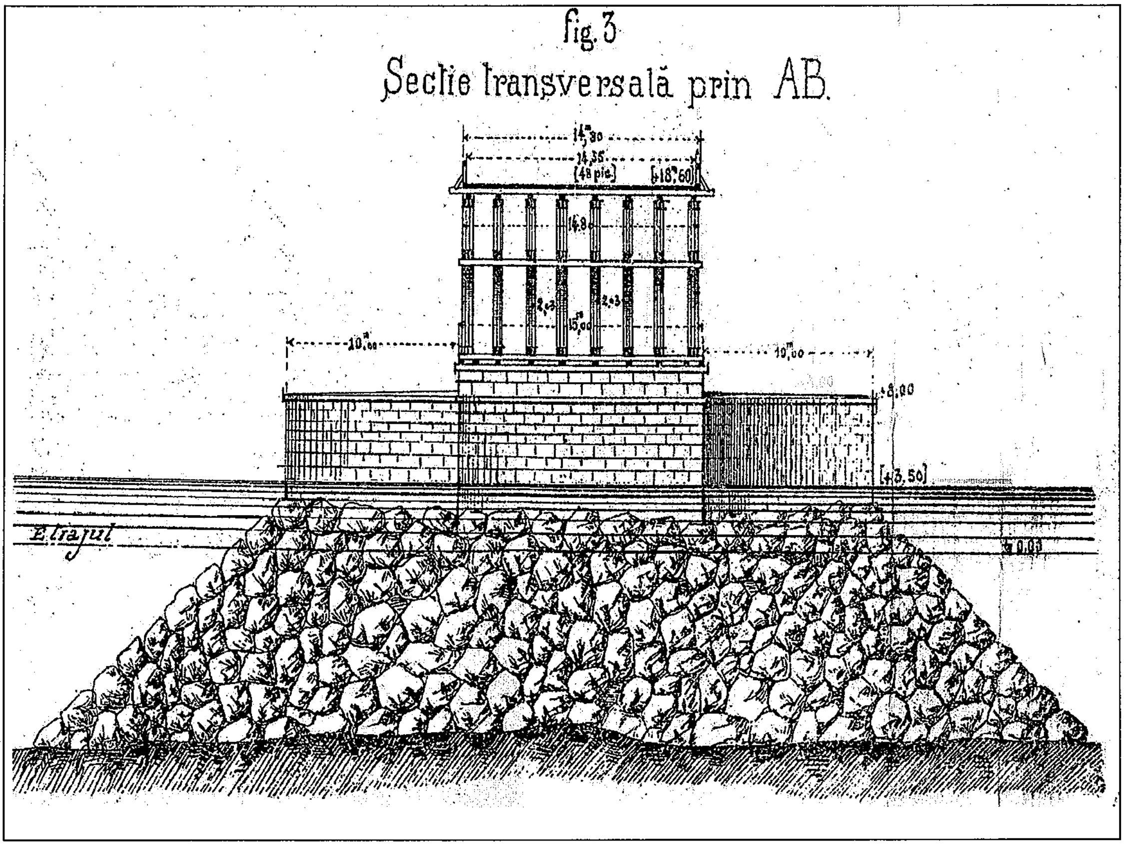

FIGURE 20. Duperrex's cross-section of the bridge.

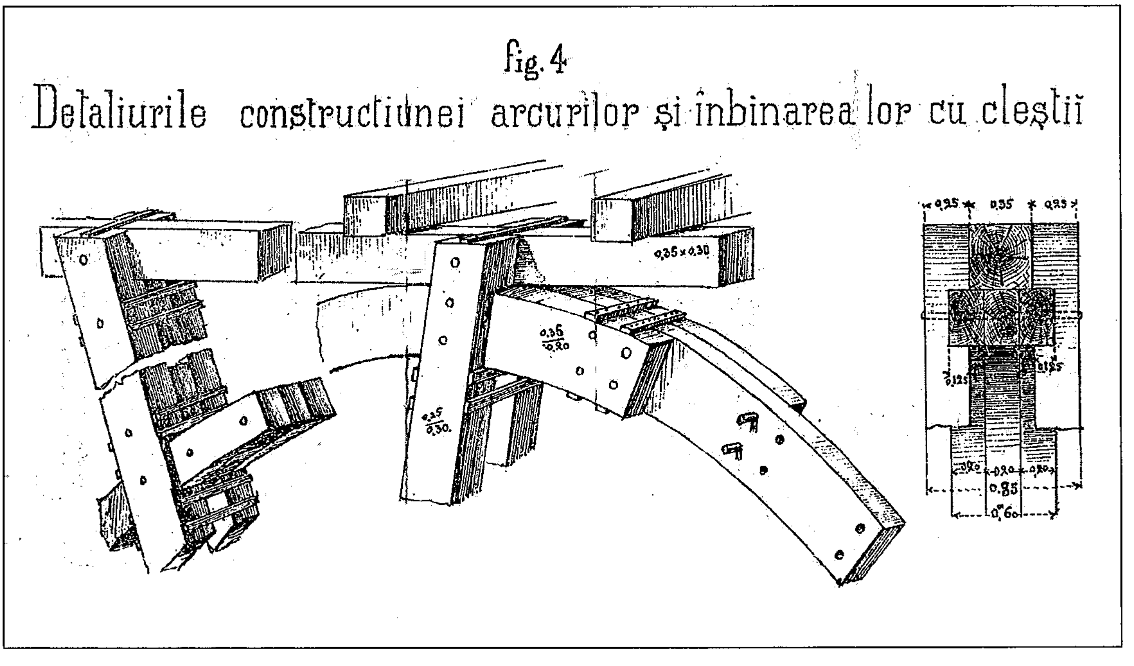

FIGURE 21. Duperrex's proposed framing for arches and radials.

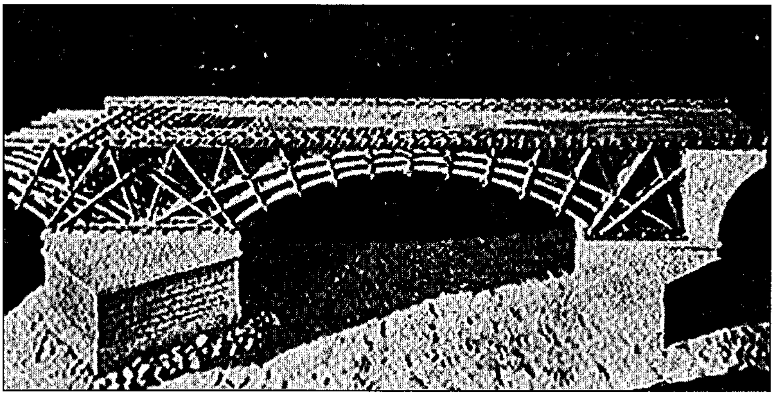

FIGURE 22. Gazzola's model of the bridge.

- Deck width — 14.55 meters (47 feet)
- Total length — 1134.90 meters (3,723 feet)
- Twenty piers each at 33 by 19 meters (109 by 62 feet)
- Depth of span on piers — 15.66 meters (51 feet)

ber. It appeared that the arches were set well back from the edge of the piers.

A model of Trajan's Bridge at the Iron Gates Museum, in Drobeta-Turnu Sevrin, shows the bridge in its entirety (see Figures 24 and 25). This model appears to be based on Duperrex's work. The person who built the model in Figures 24 and 25 had eleven radial posts lapping the three arches and extending up to the deck. In addition, there were many — apparently eight — parallel arch members. The piers were approximately square, with the ends pointed upstream. The deck width appeared to be reasonable, assuming a clear span of approximately 110 to 120 feet. The masonry arch spans at each end were similar to those shown on Trajan's Column.

The model was built to scale using the following assumed bridge dimensions:

These dimensions seem to be mostly based on a combination of Dio's commentary and the work of Duperrex, and not the latest work and research on the bridge. The model does show the arch segments extended to the masonry with top arches meeting at the center of the piers. To have the lower arch near the face of the pier and the top arch at the center of the pier would require that the arch segments be very far apart — similar to Duperrex, which is unlikely.

The model, the only one in the world built showing the entire bridge, is helpful in visualizing the magnitude of the project and how the masonry and wooden structures were built.

H. J. Hopkins in his *A Span of Bridges*, published in 1970, presented an approach to the bridge, as shown in Figure 26, but did not give any source.[16] He did comment, however, that the railing could have given the arches a significant stiffness and that the trussing was more effective than Palladio's 1,500 years later. Tudor showed a ramp from the bridge angling off to the right and probably downhill to the fort (see Figure 27). Hopkins's illustration may be of this ramp. The next arched wooden span with a clear span of 12 meters (39 feet) is

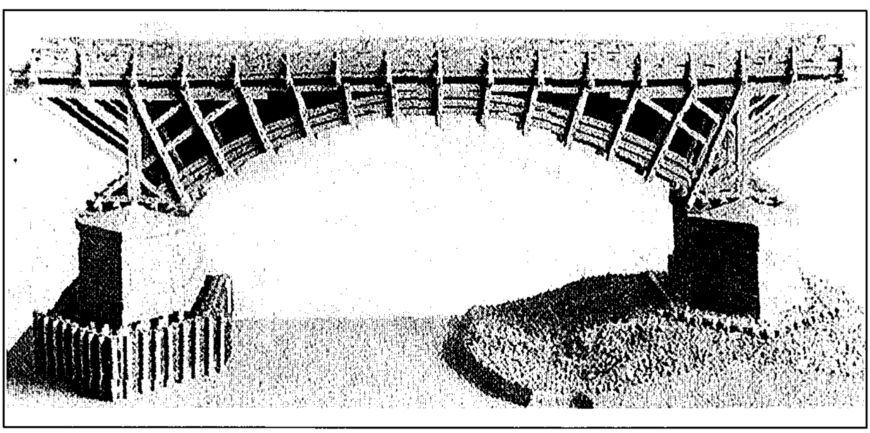

FIGURE 23. Model of a Roman bridge at Mainz that is similar to Trajan's Bridge.

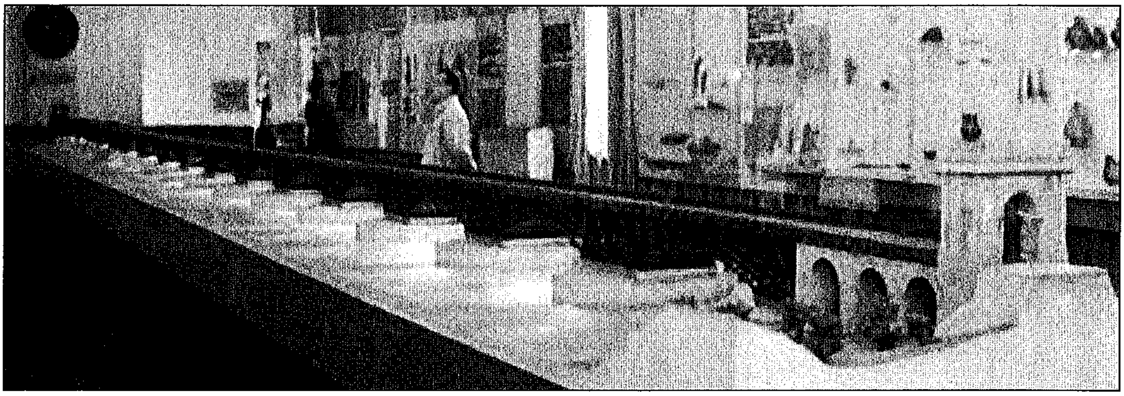

FIGURE 24. Model at the Iron Gates Museum, Drobeta, Romania.

assumed by most people to have been a masonry arch. His bridge proper would start to the left of his pier *Aa* and was 10.2 meters (33.5 feet) above the river level (see Figure 27).

In 1979, Garasanin and Vasic wrote a report in which they reviewed all previous work done on the bridge and measured and photographed remains of the bridge and Fort (Castellum) Pontes.[17] Their measurements of the abutment remains on the Serbian (easterly) side of the river were very detailed. A plan and an elevation view are shown in Figures 28 and 29. The plan in Figure 28 has been annotated by adding dimensions indicated to provide a comparison with Dio's narrative and to provide for dimensions to be used later in creating a new model of the bridge and its possible construction. The width of the roadway appeared therefore to be between 30 and 33.5 feet and was most likely approximately 32 feet. The platform dimension of 29 feet along the axis of the bridge indicated that a full river pier would be twice that, or 58 feet, which is close to Dio's stated 60 feet. The spacing of the arches, which were six in number, was about 6.33 feet. The function of the fourth row of holes from the back (to the right) of the abutment is not clear. The back three rows most

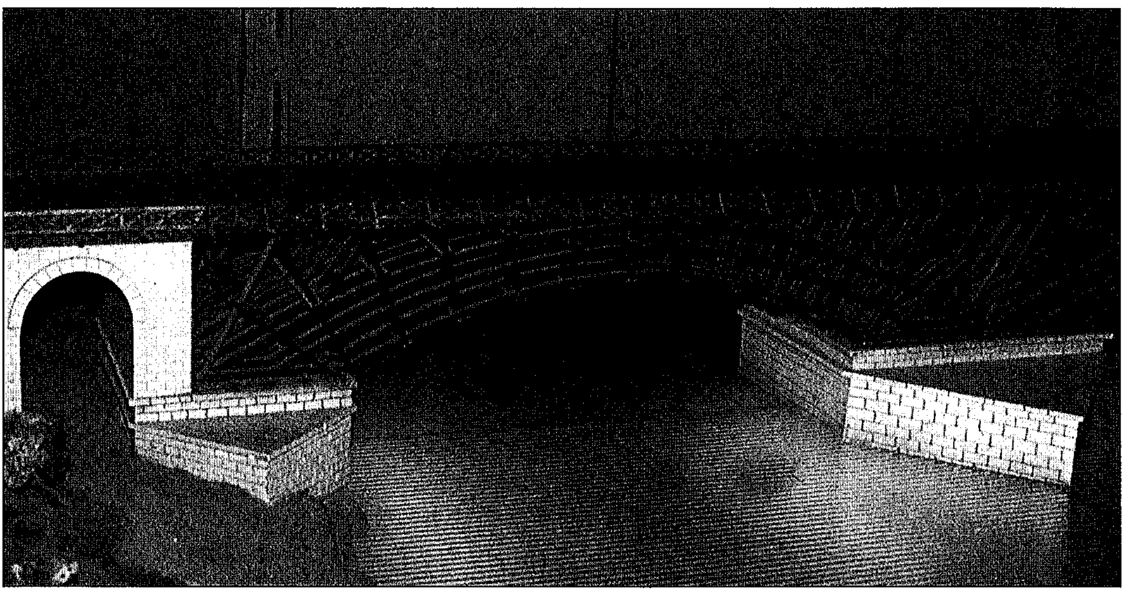

FIGURE 25. Close-up of a typical span from model at the Iron Gates Museum. It has eleven radial posts with several end struts.

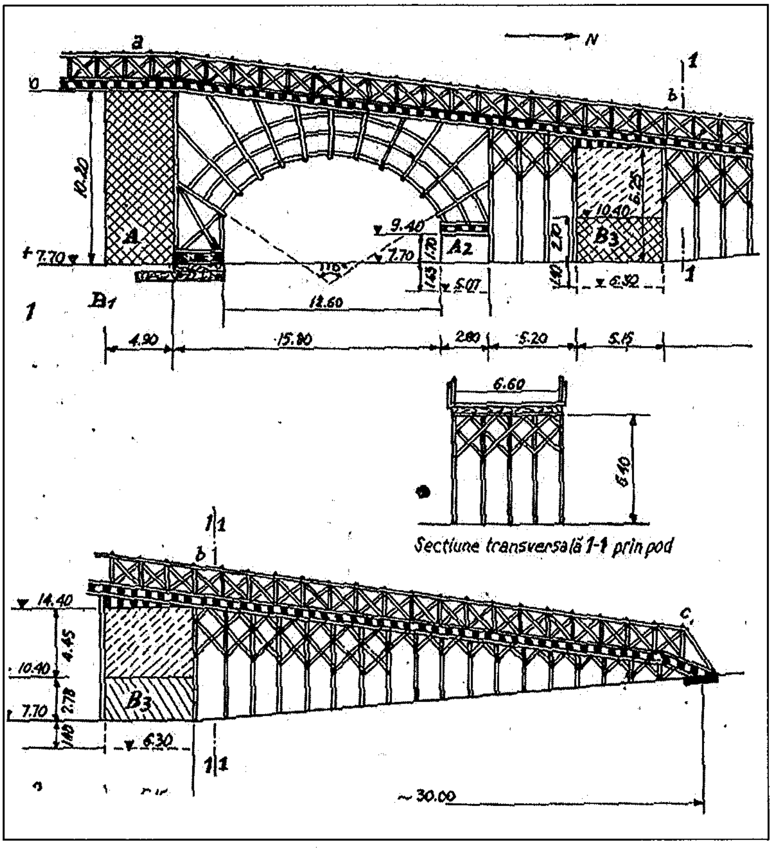

FIGURE 26. Hopkins's version of an approach to the bridge.

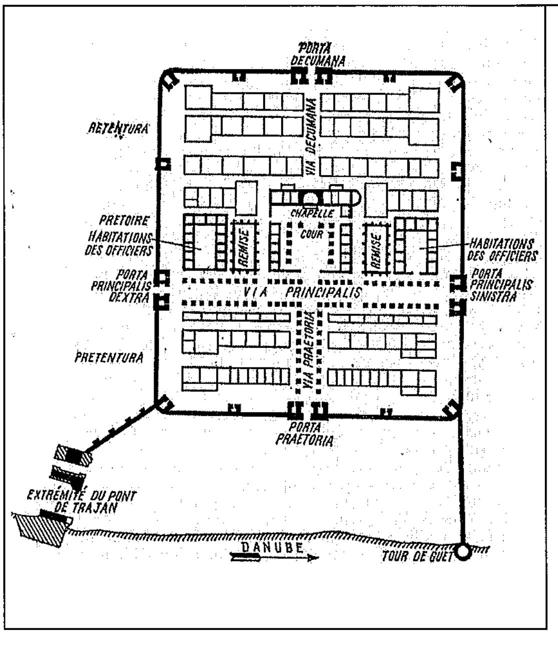

FIGURE 27. An approach to the bridge as envisioned by Tudor.

likely were for posts that supported the ends of the three arch segments or their projections back to the masonry.

The 32-foot width of the deck was much greater than the 20 feet suggested by others, but well less than that implied by Trajan's Column. If it was necessary to have chariot or wagon traffic in both directions, as well as troop passage at the same time, the 32-foot width would seem more likely. In addition, it appeared that Trajan knew he was creating a masterwork and may have wanted a width to match the bridge length and, therefore, created one of the widest bridges in the Roman Empire. The elevation view indicated a width of back wall of his abutment of just less than 10 feet. These two views tended to verify, more than any other commentaries or plans, that Dio was correct in most of his dimensions. The height from the river to the top of the stonework was 51.1 feet above water level, which is much more likely than the 150 feet indicated by Dio. If it is assumed that the abutment width were one half the river pier and that the icebreakers were at a 45-degree angle, the width of the lower portion of the pier would have been just less than 58 feet and the total length along the river axis would have been 56.2 feet. The upper pier would have been just less than 5 feet high and 48.21 by 33.5 feet.

It should be noted that these dimensions were significantly different than those suggested by Popovici in 1858 — 7.5 by 9s toise (48 by 57.5 feet), not including the icebreaker triangle. They appear, however, to be more reliable.

Colin O'Connor in his book, *Roman Bridges*, prepared a sketch of the arch spans based on

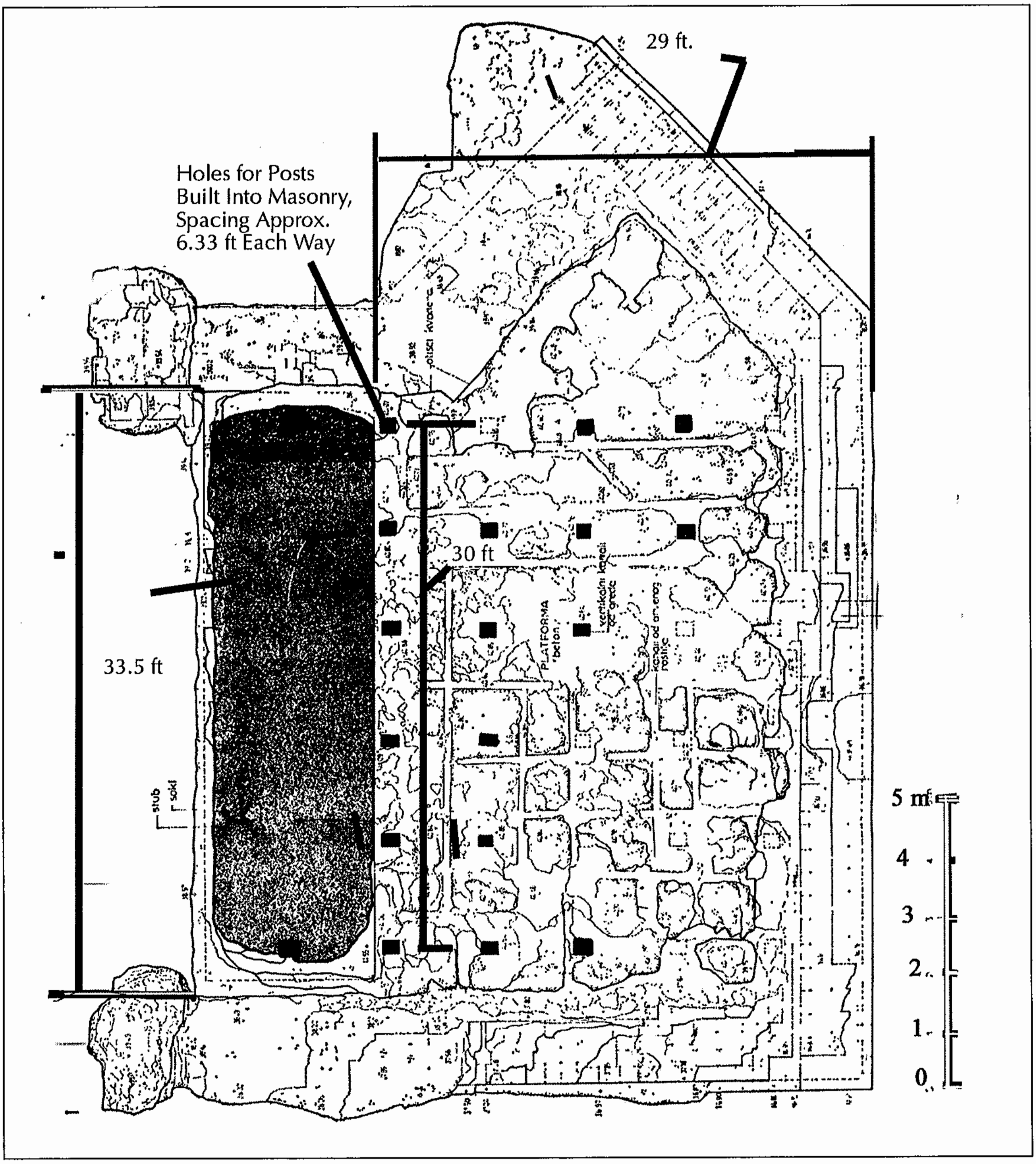

FIGURE 28. Garasanin and Vasic's plan modified with notes.

earlier descriptions and his knowledge of other Roman bridges.[18] The sketch is shown in Figure 30. He assumed that the clear span of the arch work was around 110 feet (170 feet center to center of pier minus the 60-foot width of pier). O'Connor assumed a deck width of only 20 feet and three rows of arches.

Based on some assumed timber sizes, he calculated that the strength of the timber was sufficient, assuming that there would have been lateral support at the quarter points of the arches and connections between the members of the segmental arch. His design analysis was perhaps the first published account by a civil engineer since Duperrex.

The builders of the models shown previously have many more radial posts than shown on Trajan's Column or on O'Connor's

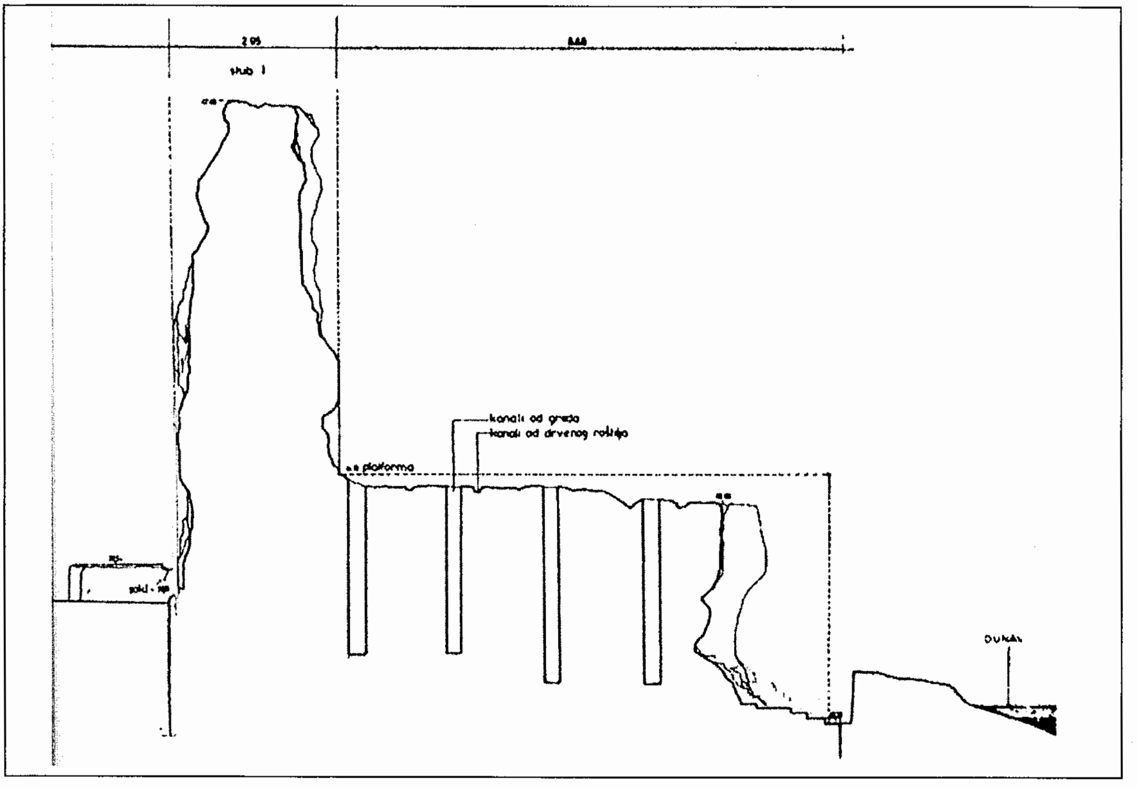

FIGURE 29. Elevation view of westerly abutment, by Garasanin and Vasic.

representation. These models are more likely to represent Trajan's Bridge since thirteen posts would yield many more deck supports and result in shorter arch segments with more provisions to brace the segments from buckling under the compressive load. In addition, deck stringers would have to have been shorter, or made continuous over several struts and, therefore, stiffer. There would, of course, have been more joints, which could possibly have weakened the arch from bad connections. Like many wooden bridge

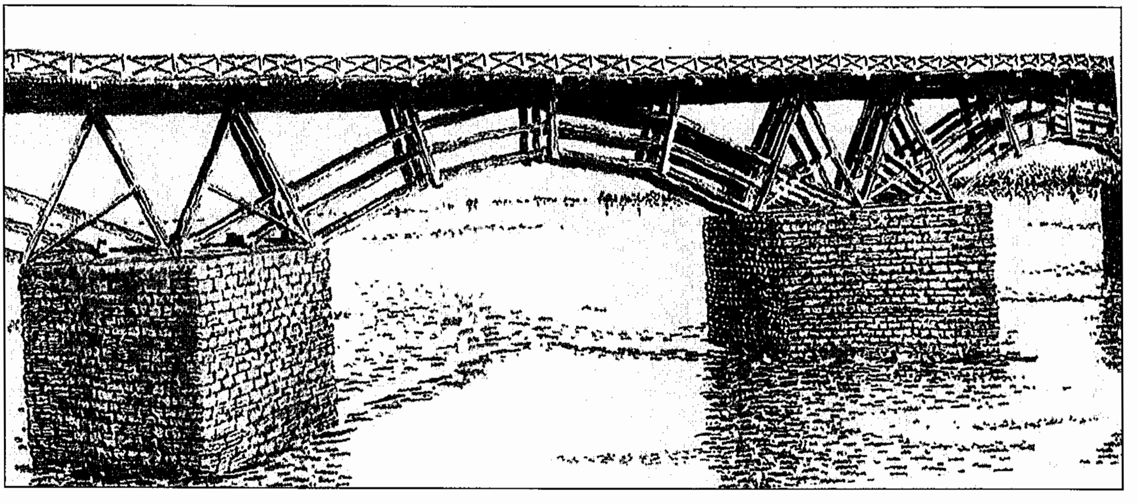

FIGURE 30. O'Connor's sketch of typical span.

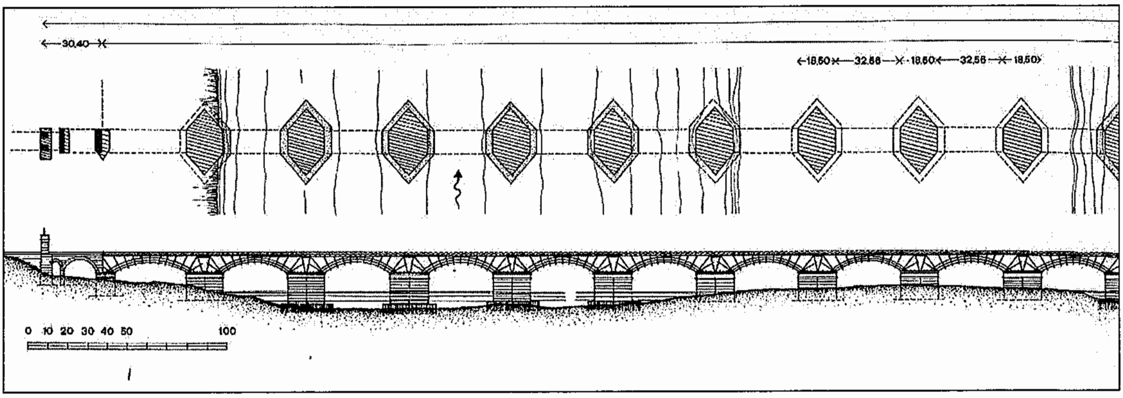

FIGURE 31. Galliazzo's vision of the bridge.

builders after Apollodorus, the bridge, as built, may have indicated points where it was weak and, therefore, additional radial struts were added until the bridge performed to their needs.

Galliazzo, in his book, *I Ponti Romani*, published in 1994, presented versions of the bridge indicating a center-to-center span length of 51.06 meters (167 feet) and a clear space between piers of 32.56 meters (106 feet) (see Figures 31 through 33).[19] He had eleven radials with cross beams under the lower arch and tied into the radials. He believed that the arches were curved, rather than a series of straight members. He also had some significant timber framing on top of his piers, apparently to serve as a base for the arches and possibly to resist the arches lateral forces (see Figure 33). This method resulted in a timber piece separating the ends of adjacent arch members. He, like many, had the arches resting near the edges of the piers and abutments. Galliazzo did, however, extend his arch members to the pier level with the last radial not supporting the ends of the arch members as implied on Trajan's Column.

Twenty-First-Century Descriptions & Studies

In the summer of 2003, Gordona Karovic and M. Nenadovic conducted a multibeam sonar exploration of the river bottom between the two existing abutments to determine the location and/or existence of river piers.[20] They prepared a contour map of the river bottom for a short distance (100 meters [328 feet]) upstream and downstream from the bridge line. They also determined the distance from face of abutment to face of abutment was 1,079.5 meters (3,541 feet). Table 1

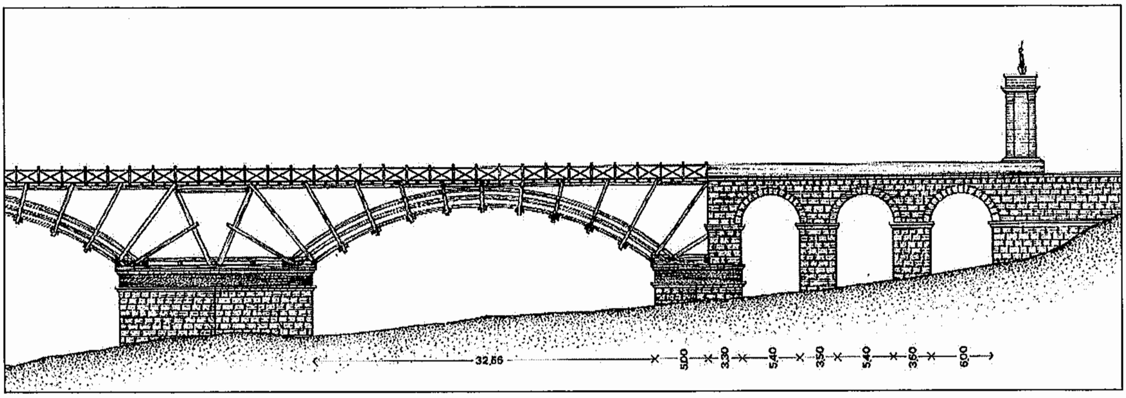

FIGURE 32. Galliazzo's version of the bridge showing the masonry approach on the Serbian side of river.

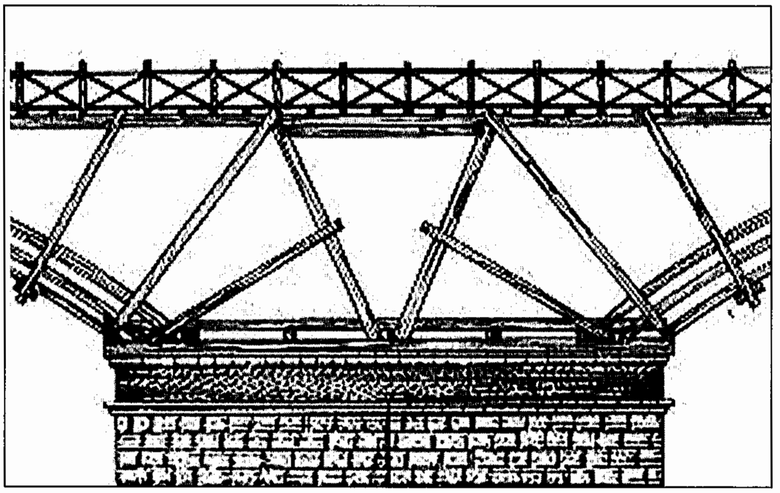

FIGURE 33. Close-up of framing on a pier (from Galliazzo).

Due to river deposits drifting in the bank region of the riverbed, the remains of the first two pillars, visible in 1982, cannot be noticed. Of the third and the fourth pillar only contours are discernable under the sand, namely the structure from broken stone in mortar. Such intense river deposits drifting is the result of dredging which has been carried out in recent years a few kilometres downstream, at the area around Kladovo,

gives bridge length values from a range of studies. Karovic and Nenadovic reported:

In the length of 320 meters [1,050 feet] towards the middle of the river, from the construction of embankment used for protection of the remains of the bridge located on land on the right, Serbian bank, visual diving prospection was also carried out. as well as of the fact that the remains of the Trajan's Bridge today are situated in the lake formed between two hydroelectric power plants. The fifth and sixth pillar are situated in the section where the river main current is strong, and therefore drifting is minimal. At the depths between 8 and 8.5 meters [26 and 28 feet] the preserved remains of these two pillars rise from the river bottom to the height of 80 centimeters [31.5 inches]. The remaining four pillars in the direction of the Romanian bank, the positions of which were defined by hydrographic measuring, allow us to conclude that the level of preservation at the river bottom surface is considerably smaller than on previous pillars. At this route section underwater survey and video recording have not been carried out.[20]

TABLE 1.
Calculated Lengths of Trajan's Bridge

Study (Ref.)	Length (ft)	Length (m)
Marsigli (12)	2,758	841
Duperrex* (15)	3,517	1,072
	3,505	1,068
Singer (21)	3,510	1,070
Gazzola (2)	3,609	1,100
Paget (22)	3,900	1,189
O'Connor (18)	3,510	1,071
Karovic & Nenadovic (20)	3,541	1,079

Notes: The other estimates vary widely with some probably based upon various written bridge descriptions. Some of these estimates may include the masonry arches at either end of the bridge. It is not possible from the accounts given, although Paget being the longest, probably includes the end masonry. *Duperrex undertook two triangulations.

Approximating the location of the piers by the closed contours that would have formed around the piers (moving from the Serbian shore), it appeared the center to center of piers was closer to 180 feet rather than the 170 feet called for by Dio. These dimensions also coincided well with Popovici's values in 1858. Due to the muddy character of the river, Karovic and Nenadovic were not able to complete dives to photograph stubs of the piers or perform measurements locally. It is clear, however, where the piers were located and their spacing, especially the fourth to

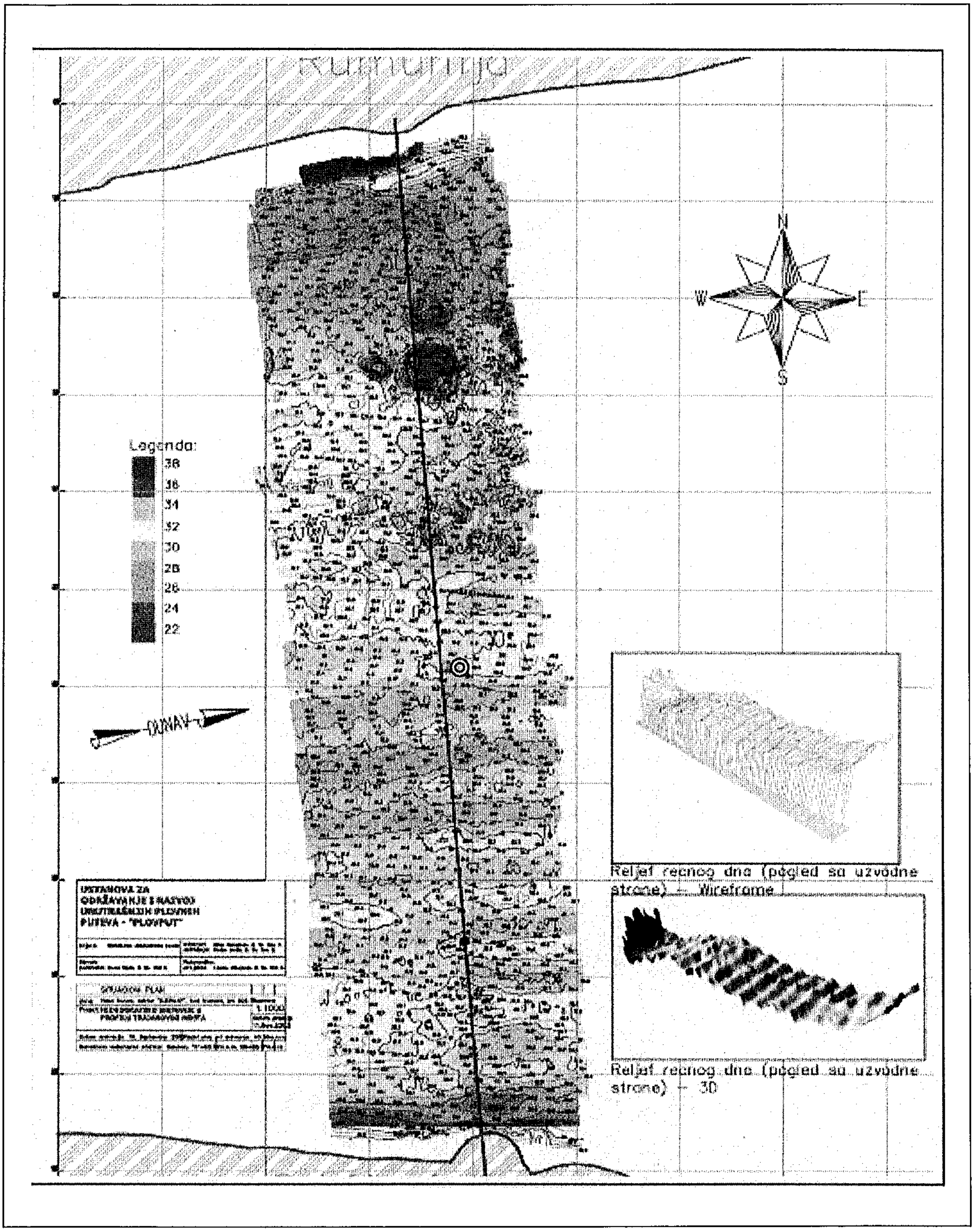

FIGURE 34. A contour map of the riverbed by Karovic and Nenadovic.

eighth piers from Serbia. Using this span length and the total length of 3,600 feet resulted in twenty spaces, or nineteen piers plus the two abutment/piers. Some accounts called for twenty-one piers, which would be true if the abutments were counted as piers. Popovici indicated that there were nineteen piers, with three missing at midstream.[11]

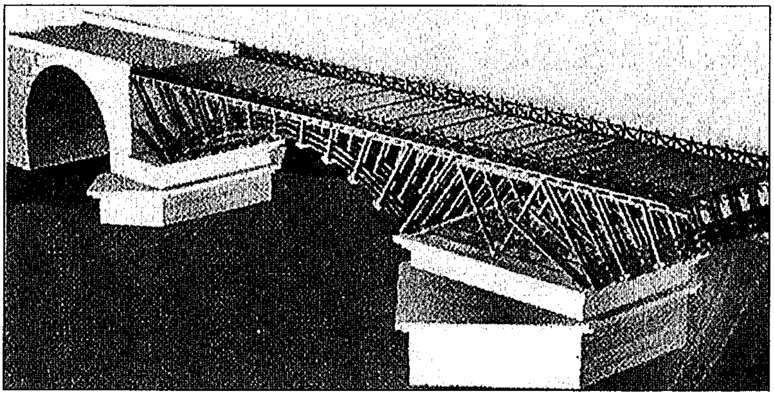

FIGURE 35. CAD model of the bridge by Ceraldi and Ermolli.

Kirovac and Nenadovic planned on continuing their exploration of the site in the future. Their work to date, however, has confirmed the existence of many of the piers and their uniform spacing on a straight line from abutment to abutment. Their information, coupled with the work of Popovici in 1858, Duperrex in 1907, Tudor from the 1930s to the 1970s, and Garasanin and Vasic in 1979 makes it possible to suggest a plan for the construction of the bridge based on all this information.

Ceraldi and Ermolli, in a recent paper, built a computer-aided design (CAD) model of the bridge as proposed by Galliazzo (see Figure 35).[23] The model did not show the ends of the arches being set onto and resisted by timbers anchored to the masonry. The model also was inconsistent as to how it handled diagonal struts on the pier and abutment surfaces. Based on this model, Ceraldi and Ermolli analyzed the structure with various methods to connect the radials and the arch members, and ran model tests on segments of the structure to determine the best way to make these connections. They concluded that the structural system needed a high degree of fixity between the arch segments, and this fixity could have been attained by adding transverse timbers between the arches tied to the radials and by blocking the ends of the arch segments into place.

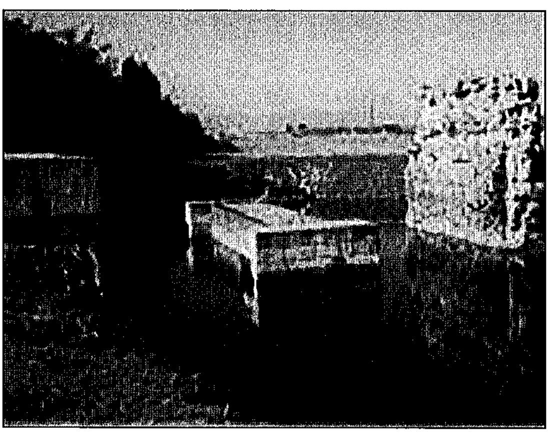

FIGURE 36. Abutment on the Romanian side of river showing remains of the end of the main bridge (on right) and foundation for the flanking masonry arches.

Current Bridge Site Conditions

A dam, Djerkap I, was built upstream from the bridge site in 1969 and Djerkap II was built approximately 44 miles downstream of the bridge site in 1984. The lower dam raised the water level at the bridge site and this higher water level, combined with dredging on the Romanian side, increased the depth of water to upwards of 59 feet, with shallower water on the Serbian side of the river. To protect the remains of the bridge, an earthen berm was placed around the abutment on the Romanian side (see Figures 36 and 37) and a concrete

FIGURE 37. Romanian abutment encased in fill.

TABLE 2.
Dimensions for a Suggested Plan for Trajan's Bridge

Dimension	Length (ft)	Based On
Span	180*	Refs. 11 & 20
Number of Spans (River Piers)	19-20	Ref. 11
Width of Deck	32	Ref. 17
Height of Structure on Pier & Abutment	29.85	Ref. 15
Height of Deck Above River Level	51.18	Ref. 15
Pier (Icebreaker) Width	57.5	Ref. 17
Pier (Icebreaker) Depth	56.25	Ref. 17
Pier Structure	49.5 X 52.25	Ref. 17

Note: *Distance from center to center of piers.

wall was built around the abutment on the Serbian side (see Figure 38).

A Suggested Plan for the Bridge

After reviewing all of the historical studies on Trajan's Bridge, the information can be synthesized and a plan developed based on the dimensions shown in Table 2.

The number of radials necessary depended on how the bridge was framed and the timber size available that could have been worked into required dimensions. O'Connor followed the Trajan Column pattern with four radials and three sets of arches while the Mainz Model called for thirteen radials and the model at the Iron Gates Museum showed eleven. Galliazzo, as well as Ceraldi and Ermolli, also assumed eleven radials. If eleven radials were used, the lengths of the top chord between supports would be just less than 20 feet, which is reasonable. There are six rows of arch members set 6.33 feet apart. The center-to-center spacing of the three arch ribs would be 4.31 feet, yielding a distance of approximately 6 feet between the springing points of each arch segment, which matches the holes in the existing abutment. The three radii (used to determine the straight line segments of the arches) are approximated as 188.50, 184.19 and 179.87 feet. For purposes of the sketch, all arch members are drawn as 12 by 12 inches, as are the top chord members. The radial posts are twin 4- by 12-inch planks and the cross beams, spanning the 6.33-foot spaces, are drawn as 8- by 8-inch timbers. The stringers are also drawn as 8- by 8-inch members and are spaced at 2 feet on center. A deck thickness of 4 inches is shown. The cross braces are drawn as 8 inches by 3.33 feet, and probably would be built up of two members spiked to the radials. The railing would have then been placed on the deck surface, assuming 6-inch square posts set 6 feet on center with a height of 3.5 feet. The railing would be set back from the edges of the deck with kickers to provide lateral support. The posts set into the masonry to resist the lateral thrust of the arch members are drawn as 12- by 12-inch by 6-foot long timbers set 6.25 feet apart laterally and 6 feet apart longitudinally.

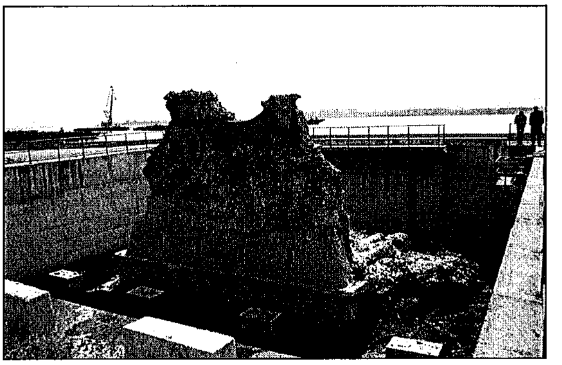

FIGURE 38. Abutment on the Serbian side of river.

The pier is based on the work of Garasanin and Vasic (see Figure 39).[17] Its width of 57.5 feet is close to the 60 feet called for by Dio. The 57.5- by 56.25-foot extent of the main pier, not counting the icebreaker, is close to the 9 by 7.5 toises (47.96 by 57.55 feet) given by Popovici. If the proposed plan were accepted, it would appear that the piers have lost approximately 5 feet off each side as well as the entire triangular icebreaker. It also assumes that there were no triangular extensions on the down-

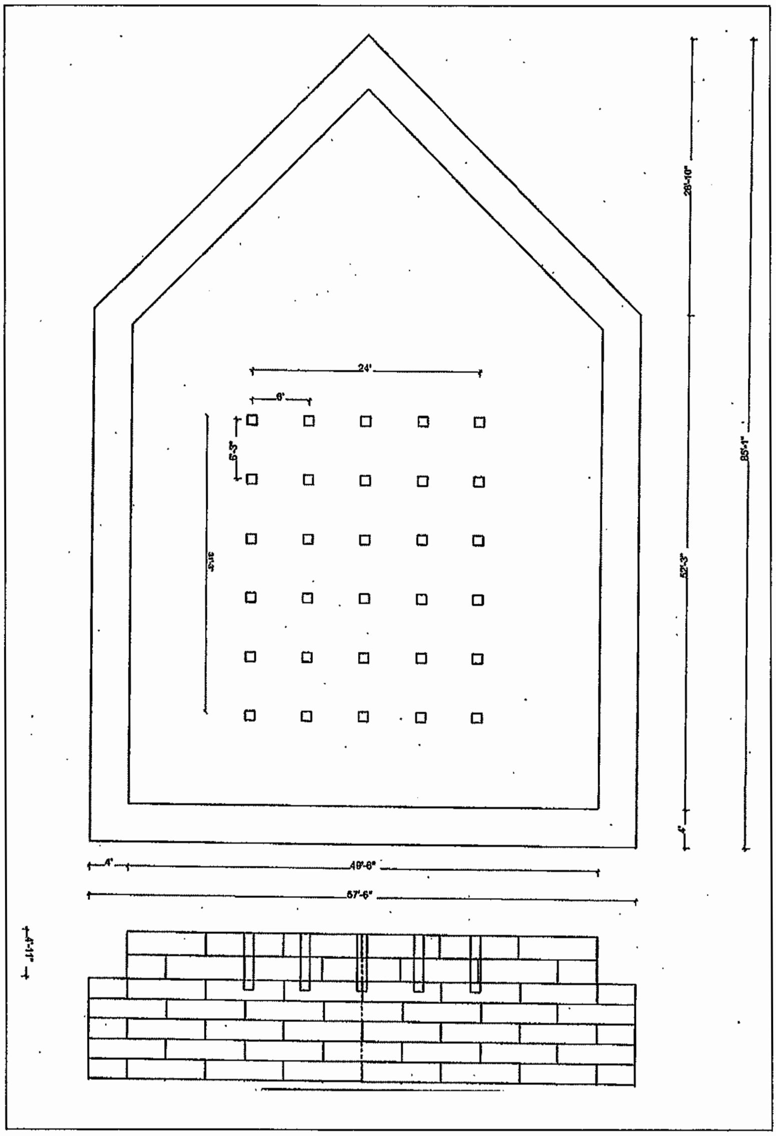

FIGURE 39. Suggested typical pier.

stream side of the pier as indicated by Galliazzo and others. The pattern of the holes in the masonry are shown based on the hole pattern in the abutment shown by Garasanin and Vasic.

The main structural difference from this model and others that have been presented is how the arches are supported on the horizontal pier surfaces. Many writers have apparently taken the image on Trajan's Column and assumed that the radial running from the base of the lower arch member supported the other two arch members as a bending member. Based on the measurements made on the existing abutment, this proposed means of construction does not appear to be the case and the last radial would have acted like all the other radials in supporting the top chord and deck of the structure, and the arch members would have continued past the last radial to the pier surface. Another significant difference is that the arches do not set on the edges of the piers but are set well back on them, with the highest arch member from adjacent spans abutting the same post built into the masonry at the center line of the pier. From a structural standpoint, this solution would be a better way to transfer load from the arches to the masonry. In addition, with the bearing points of the arches well back on the pier surface, there is less chance of the wooden members being destroyed in a flood or the lower arch losing its support in the event of the outer stonework shifting or settling.

In order to laterally stabilize the long slender arches, some type of cross bracing was necessary. A close look at the image on the coin shown in Figure 1 reveals that diagonal bracing existed under the lowest arch member on the left underside of the bridge. This type of bracing would have helped keep the members parallel but would not have helped in keeping them in a vertical plane. Diagonal "X" bracing between the triple arches would have provided this stability but would have been difficult to place. A simpler method would have been to have straight timbers running transversely between the ribs and spiked to the arches.

Ceraldi and Ermolli ran model tests using this assumption and found deformations of the model were greatly reduced with this type bracing (see Figure 40).[23]

This configuration provides a connection between the radials and arch members. If cross-timbers were wedged into place, it would have resulted in a very stiff assemblage of timbers. Galliazzo showed the bottom cross-timbers only in his proposed model of the bridge.[19] Using the adage of "keep it simple stupid," it is believed that this solution would have been the easiest solution to the lateral stability problem. It is likely that Apollodorus experimented with various means of providing cross bracing on other bridges he built using a similar plan. It is unlikely that he would have determined to use a bridge of this span length and number without first having built one as a test case. It is possible that the bridge across the Rhine at Mainz was built prior to the larger Trajan's Bridge and therefore served as a model for its construction. Based on these considerations, the proposed model is shown with cross bracing as suggested by Ceraldi and Ermolli. It is also likely that Apollodorus nailed retainer blocks onto the cross bracing to lock the arch members in place. This method has not been shown elsewhere, but it seems like an obvious and simple solution to retain the arch members in plane.

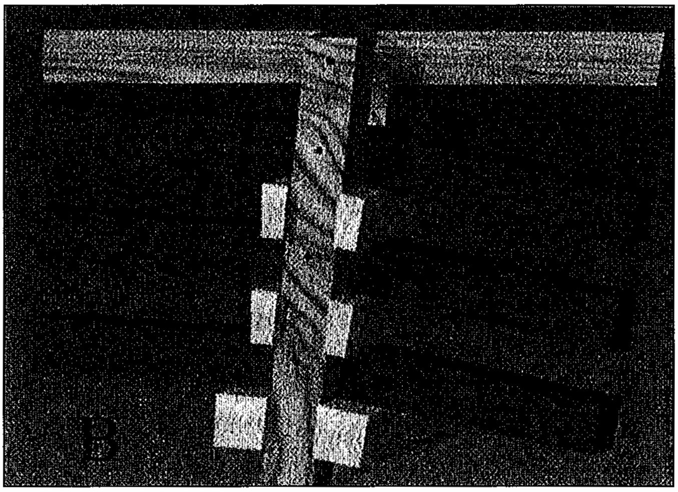

FIGURE 40. Ceraldi and Ermolli's structural model.

Figures 41 through 43 show possible construction details and are based on historical records, evidence found at the site and an understanding of how the Romans used and connected wood in centering structures for masonry arches. For the purposes of these drawings, it was also assumed that the arches were segmental and not curved.

With a proposed bridge plan in place, the next item to be studied is how the bridge was built. What did the Roman's know about materials and construction and when did they know it? The work of Vitruvius, *Ten Books of Architecture*, written around 65 is the best, and possibly the only work, that survives describing the methods and materials used by the Romans to construct their buildings, and, to a certain degree, their bridges.[24]

How Was the Bridge Built?

To understand how Romans built this bridge, it is necessary to know what materials they used as well as what tools they developed or copied from engineers of countries that they

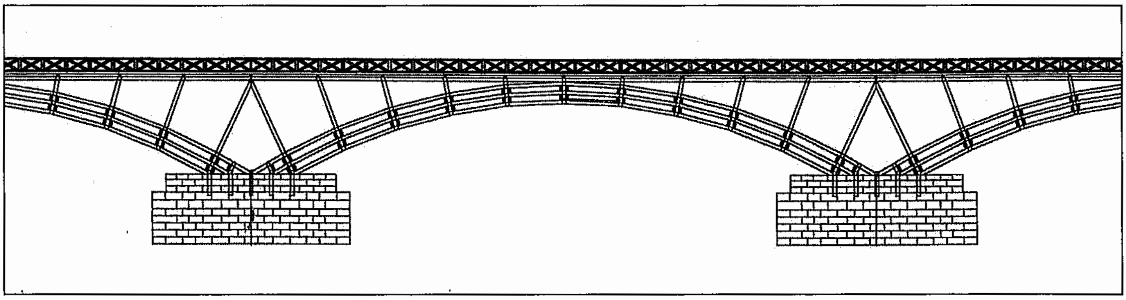

FIGURE 41. Typical possible span framing.

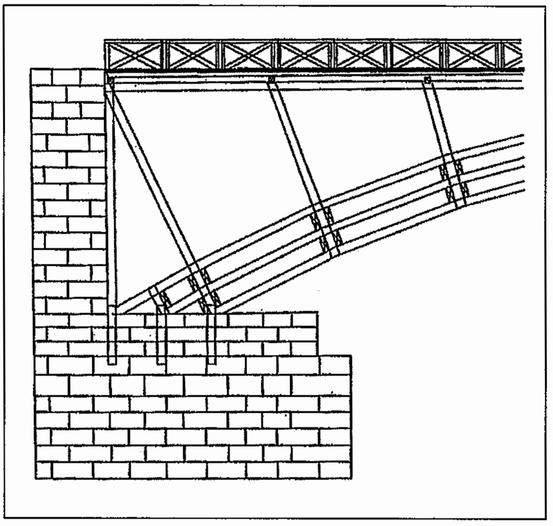

FIGURE 42. A detail at the ends of arch members on the abutment surface.

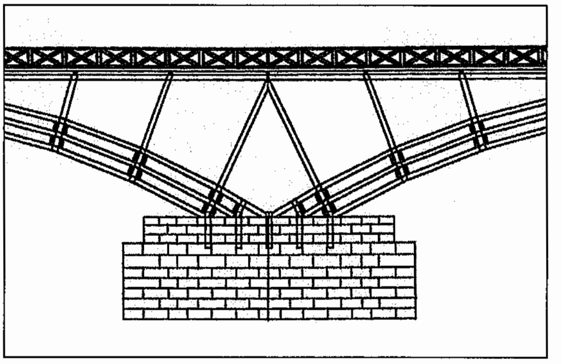

FIGURE 43. Possible pier framing detail.

conquered, such as Greece. By 100, there is no doubt they had tools and workmen to quarry, shape and move large blocks of stone both for bridge work and for buildings. They had tools to shape large timbers and place them in major structures. They connected timbers either by wooden pegs or wrought iron rods placed in holes, with the ends bent over washers to hold members in place. They also used mortise and tenon with wooden pegs to connect members together.

From at least the time of Caesar, as shown by his Rhine Bridge, they were able to place foundations in relatively deep and fast-moving rivers. In many locations, their foundations were placed on wooden piles driven into river bottoms with a wood mat on top of the piles and stonework for the piers placed on the mats. The Roman pile driver used to place piling in rivers or lakes has been proposed by Galliazzo (see Figure 44).[19] He suggested that the pile driver was mounted on a raft that was positioned into place and anchored while the piles were being driven.

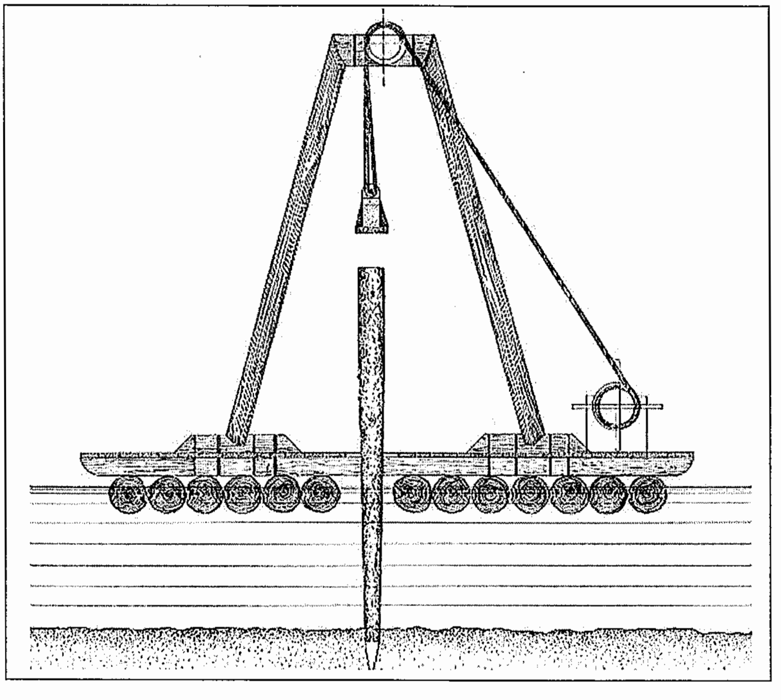

FIGURE 44. Galliazzo's proposed Roman pile driver.

The first step in constructing the piers was to drive piles into the river bottom and cut off the pile tops at the appropriate elevations (see Figures 45 and 46). They apparently drove piles on very close spacing. This finding was based on examining the remains of bridge piers that could be seen when the river was at low levels. There is also archeological evidence that they built piers inside of cofferdams made by driving two rings of piles around the proposed pier and filling the space between them with clay to create a relatively watertight wall (see Figure 45). They used Archimedes screws, or slaves with buckets, to lift the water out of the inside of the cofferdam. Piles were cut off at the required depth and a mat or grid of timbers or concrete-filled stonework would have then been placed on the piles and then cut-and-shaped stonework would have been placed on top of that. The stones would have been carried to pier sites by boats. A crane, built of timbers and using block and tackles, would have lifted the stone from the boat and placed it on the foundation. All stone would have been cut to size prior to being taken to the site so that individual stones would fit in place. Given that Trajan and Apollodorus had an unlimited number of slaves and legionnaires to work on the bridge, it is likely that many piers were placed concurrently, supported by a vast army of men cutting the stone at quarries and delivering it by wagon and boat to the pier sites.

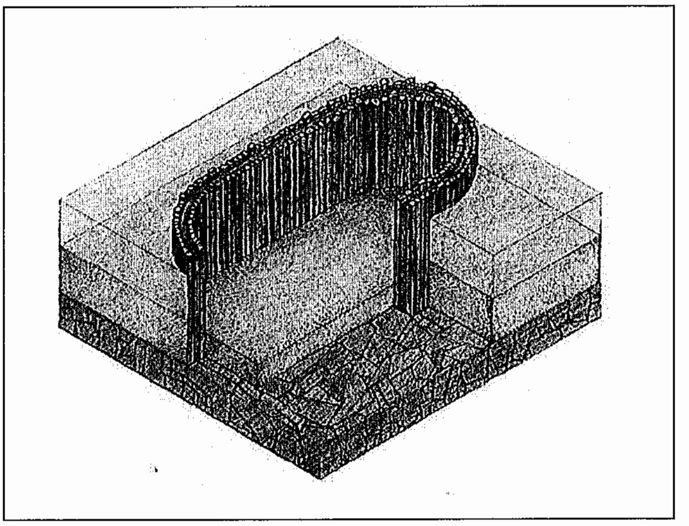

FIGURE 45. A Roman cofferdam.

The Mainz model shows the cofferdam, a pile foundation that is apparently topped with a stone and concrete cap with stonework placed on top of the cap (see Figure 23). An example of a similar bridge abutment along Hadrian's Wall in England is shown in Figure 47.[18] Remains of Hadrian's Wall are shown at the top center of the figure. The quality of the stonework on the abutment is clear, with alternating courses, headers and stretchers of stone and cut stone at the angle points in the pier. It appears that most of the top two courses of stonework had been removed over time, as well as some of the first visible course at the left of the image. The missing stones in the first course appear to be underlain by at least one additional course. Unfortunately, no excavation has been undertaken to determine if the abutment was founded on piles. In addition, it is not clear how many courses of stonework were placed to support the pier. J. C. Bruce, in his *Handbook of the Roman Wall,* believed that the bridge at this site was similar to Trajan's Bridge over the Danube.[25] It cannot be determined from Figure 47 whether the hole pattern found on the existing pier at the Danube was repeated at this site. The use of iron rods to tie the face stone together to resist the action of ice is clear in the course shown. It is likely that the outer stones of most courses, especially the lower courses, were also tied together by the same type of iron bars.

It is also likely that scaffolding, or a dock constructed of pile-supported wood members, was erected outside the cofferdam upon which cranes were built and boats delivering the stonework were docked. The cranes would have placed precut stone in place, with the stonework being delivered in sequence to

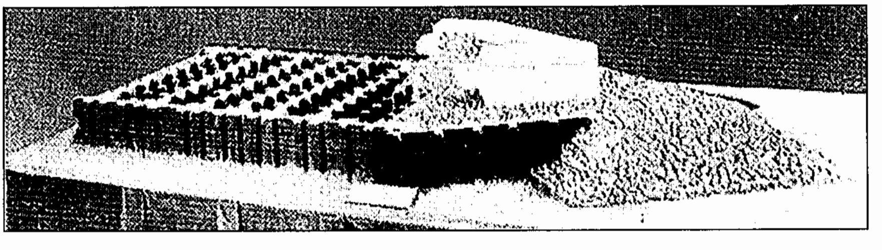

FIGURE 46. Model of a Roman foundation uncovered at Mainz.

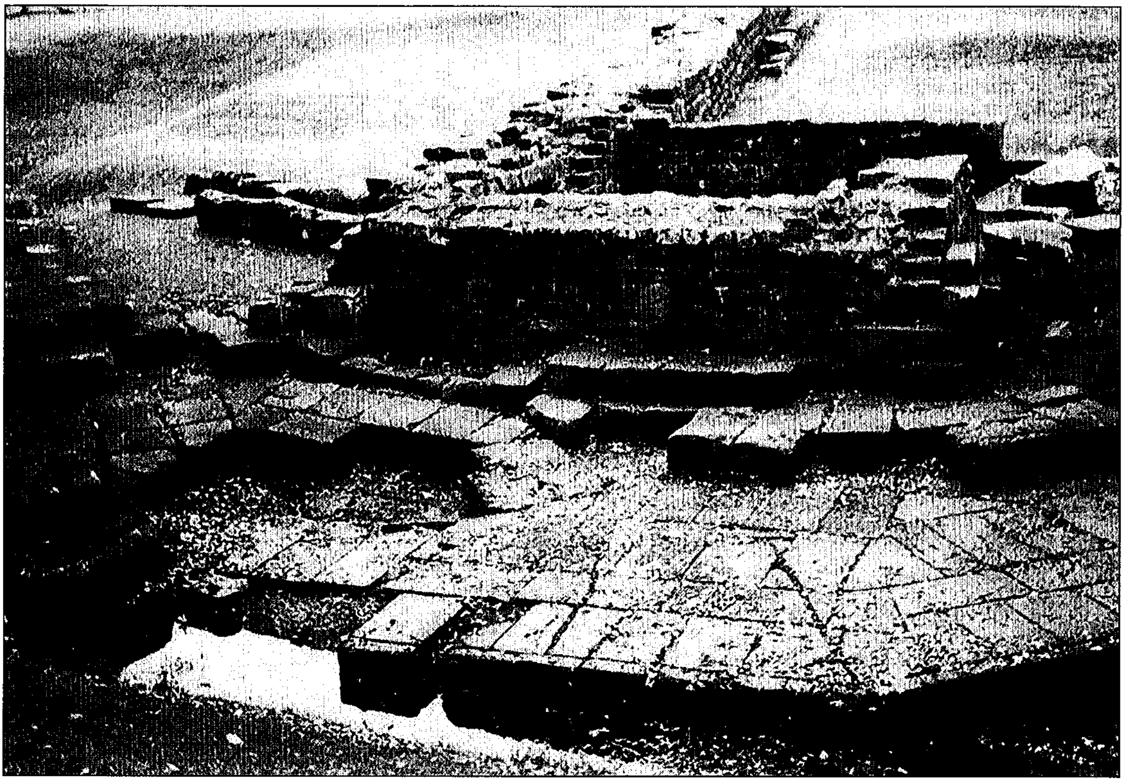

FIGURE 47. Bridge foundation from Hadrian's Wall at Chesters, England, from O'Connor (Ref. 18).

ensure that each lift was completed prior to the commencement of the upper lifts. The stonework may have been laid dry or concrete placed in the joints to tie the whole work together. From illustrations such as Figure 46 and the two abutment/piers at the Danube site, it is likely that the stonework was laid dry. The iron bars tying the exterior stones together were placed in a manner similar to that shown on the Hadrian Bridge for each lift of stonework.

Once the piers and abutments were in place, the next step was placing six lines of segmental arch members and tying them together with cross braces and possibly underdeck cross bracing as shown on the Roman coin (see Figure 1).

Once the piers had been completed, or were being completed on a progressive pattern probably starting at the Roman-controlled Serbian side of the river, the wooden arch structure would, or could, follow. In constructing buildings, or on bridgework, Romans typically built wooden scaffolding bearing on the walls or piers. This staging was done for short spans and masonry arches. With a 120-foot clear opening, constructing the supporting structure would have been as time consuming as constructing the permanent structure. For this reason, it is likely that they built a falsework of piles in the river and timber framing up to the lower arch member. This falsework would have been built from rafts using pile-driving machines mounted on them and anchored into place to resist river currents in the same manner as for pile driving for the bridge piers. With the falsework in place, the timber — which was precut, drilled and mortised and tenoned in a nearby field — would have been delivered to the site and assembled on the falsework. As the arches were placed, the radial posts would have been connected to each arch. With the radials in place, the arches would have been plumbed and aligned, and cross braces would have been placed. The scaffolding extended up to the upper chords, allowing the top chords to be attached to the radials. With the top chords in place, the cross beams, one at each radial, would have been placed and connected to the top chords. With the cross beams in place, the stringers could have been started from the shore, resting on the cross beams. Then the decking followed to serve as a working platform.

The method of connecting all the timber is not known with certainty, but it is likely that for the "monumental" bridge that Trajan was building they used the best technology that they had available to make the connections. Timbers would have been squeezed together with a vise of some type and square wrought-iron rods inserted into predrilled holes. Iron washers were placed over the ends of the rods and the ends of the rods were bent to form hooks. It is possible that some nailing was used, but it is known that the Romans at this time had not developed the threaded bolt, even though they used all types of screws in wood for their cranes and war machines. Apollodorus probably knew his bridge would have been able to support larger loading if he made the joints in his arch members as fixed as possible so that the arches acted as continuous members rather than a series of pin-connected members. He could have accomplished this means of providing greater support by having the ends of the arch members mortised and tenoned with the radial posts (shown on the drawings as 4- by 12-inch planking serving as connecting plates). Twin radial members would have probably been connected with four rods per intersection, two on each side of the arch joint. With good control of the fabrication of woodwork and the construction of falsework (which would have been removed when the span was completed), which would have leapfrogged ahead to be rebuilt at the next span to be framed, it would have been possible with the unlimited manpower available to build the bridge in the two-year period as indicated by Dio. The most demanding part of the project, of course, was building the piers in the relatively deep, fast-moving waters of the Danube.

It is assumed that the masonry arches at each end of the bridge were built concurrently with the river piers and abutments. With the bridge being completed on a span-by-span basis, it would have been possible to use its surface to supply workers with materials in a more efficient manner. Given Trajan's plan to invade Dacia as soon as possible, it is likely that Apollodorus was instructed to advance construction of the bridge using all possible labor and material available. If expediency were the case, it would have been likely that multiple piers and multiple wooden arches were placed concurrently. As the bridge came closer to the Dacian bank of the Danube, the Romans probably began construction of a fort to protect the bridge from attack and destruction.

Summary

Trajan's Bridge, as many writers from Dio on noted, was a remarkable structure built over a turbulent river in the proximity of an enemy force. The development of triple segmental arches to support spans upwards of 180 feet was a unique solution to the bridging of such a wide river. Trajan apparently made the decision that a wooden bridge similar to Caesar's over the Rhine or another bridge of boats was not in keeping with his image or his legionnaires as conquerors of much of the known world. Apollodorus realized that using short span wooden beams on stone piers would have required an excessive number of piers, and the bridge could not have been built in the time frame set for him by Trajan. His solution to cut down on the number of piers and lengthen his wooden structures led him to the wooden arch solution as described.

ACKNOWLEDGEMENTS — *The author relied on many European engineers and writers to prepare this article. Much of their work was in Italian, Greek, Latin, Romanian or French. With the help of translators and the use of illustrations, it was possible to create the bridge's history for American readers and to develop a proposed plan for the bridge and its piers.*

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