

IGOR BJELIĆ
Institute of Archaeology
Belgrade, Serbia
E-mail: igor_bjelic@yahoo.com

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USE OF BUILDING MATERIALS DURING THE CONSTRUCTION OF TRAJAN'S BRIDGE ON THE DANUBE

ABSTRACT

Combining different building materials was not uncommon in Roman architecture. The use of various materials for the creation of the Trajan's Bridge on the former Danube Limes, that is wood, stone, brick and mortar, according to their characteristics, role in the construction, chosen construction methods, and pre-known behaviour of these materials over time, is one of the important features of the design of this building. The reasons for a deeper analysis of architect Apollodorus' solutions for the bridge regarding the achieved combinations of materials are the importance of the structure, the monumentality of its architecture, as well as the characteristics of the place where the bridge was built. The focus of this study will be on analyses of the bridge's masonry structures and, more precisely, the relationships between the building materials used for their construction. When studying the use of building materials, ancient writings were used, as well as analyses of the remains of the bridge in situ on the Danube banks of today's Serbia and Romania. The realised analyses point to new interpretations regarding the possible ways to span the spaces between the pillars on the riverbanks, and their connection to the choice of building materials.

KEYWORDS: BUILDING MATERIALS, CONSTRUCTION METHODS, MASONRY STRUCTURES, TRAJAN'S BRIDGE, ROMAN ARCHITECTURE, DANUBE LIMES.

INTRODUCTION

The remains of Trajan's Bridge are located in the riverbed and on the banks of the Danube river, where, on the left side of the river they are in the territory of today's Romania, and on the right side in the territory of the Republic of Serbia (Fig. 1). In Romania, they are today part of the urban fabric of the city of Drobeta – Turnu Severin, while on the Serbian side they are located 5 km from the small town of Kladovo, that is, 1.3 km east of the nearest settlement, Kostol.

On the initiative of Emperor Trajan, the bridge was designed by the architect Apollodorus, between 103 and 105, that is, between two Roman conquest campaigns in Dacia. On two occasions - in 1931 and in 1968, D. Tudor synthesised early

knowledge about the remains on the Romanian side (starting with the 1858 research conducted by Deustler, Imbrišević and Popovici and the 1907 research conducted by Duppereux)(Tudor 1974: 47). At the same time, he presented his analysis and new views on the architecture of the bridge. The remains of the bridge were investigated on the Serbian side in 1979 and soon after they were published by its researchers Milutin Garašanin and Miloje Vasić on behalf of the Institute of Archaeology in Belgrade (Fig. 1) (Гарашанин и Васић 1980). More recently, C. Crăciun and A. Sion, and I. Bjelić have carried out further analyses based on all previous research (Crăciun and Sion 2006; Bjelić 2020).

Regarding the construction of the bridge, we can differentiate two parts: One part was on the shore and, according to the relief on Trajan's Col-



Fig. 1. The archaeological site of Pontes with the remnants of Trajan's Bridge (photo-documentation of the Institute of Archaeology, Belgrade)

umn in Rome, it was completely built as a masonry construction. The other part was settled in the river bed as a masonry construction, while above it was the wooden supporting structure of the road of the bridge.

One of the major characteristics of Trajan's Bridge is the combination of several types of wooden and masonry constructions in different parts of the bridge. Wood had specific functions when combined with masonry constructions on this structure. It served as formwork for the foundations of the bridge pillars on the shore, as an integral part of the caissons for building the foundations of the pillars in the riverbed, and as a wooden "reinforcement" in the form of horizontal beams and driven piles. The main function of the interior of the bridge pillars was to ensure the equal settlement of mortar and aggregate masses within the supports and to enable the stable support of the masonry pillars on the riverbed. The wood also served as the supporting structure of the wooden platform i.e., the road of the bridge that spanned between the individual pillars.

Ancient writings, visual representations, as well as analyses of the bridge's investigated parts by previous Romanian and Serbian researchers represent the basis for this research, aimed at analysing the combination of wooden and masonry constructions (for older historical sources see: Гарашанин и Васић 1980: 9). One of the most important writings about the construction of the bridge itself, that of Apollodorus himself, has not been preserved. Instead, its construction is wit-

nessed by the texts of Dio Cassius, Procopius, and the poet Tsetses, some of which refer to the text of Apollodorus (On earlier literature and historical sources see: Гарашанин и Васић 1980: 8). In addition to written sources, there are also two important artistic sources: coins minted by the Roman Senate in 105 in honour of the construction of Trajan's Bridge and scenes on the metopes of Trajan's Column (scene XCVIII – XCIX and scene C – CI) (Vulpe 2002: 178 - 179). Previous researchers such as H. Dacovicu, M. Garašanin and M. Vasić already indicated the justification of the reliability of the pictorial sources on Trajan's Column (Гарашанин и Васић 1980: 9). At the same time, they pointed out that the representations of the bridge on coins are very stylised and simplified. In their opinion, the sculptors of Trajan's Column had a solid idea of the appearance of the bridge based on Trajan's writings (the emperor's comments on the Dacian Wars). At this point, we would add a new opinion to this one. Namely, the sculptors of Trajan's Column could equally have consulted Apollodorus himself. Apart from the fact that Apollodorus was the creator of the concept of the execution of Trajan's Bridge and the Column in Rome, let us add that the sculptors could have had the writings of the mentioned architect in front of them in addition to the emperor's comments. In support of the reliability of the depictions of the bridge on Trajan's Column in Rome, we also point to the fact that the depiction on the Column in Rome is a rare detailed representation of a wooden bridge in the Roman Empire.

BRIDGE CONSTRUCTION ON THE COAST

The geographical similarity of the two banks of the river, i.e., the symmetrical topography, made it possible for the approaches to the bridge to be designed in an almost identical way. The preserved remains of the masonry structures of the bridge on the Romanian and Serbian banks indicate identical designs, applied materials, and types of constructions at the two approach endings of the bridge. Previous comparisons of masonry structures on the two banks by Romanian researchers also point to this finding (Crăciun and Sion 2006: 373). The dimensions of the most accessible and best-preserved parts of the bridge, i.e., those on the banks, indicate an exceptional similarity in design: the length of the supporting structures of the embankment pillars (including the platforms at the end pillars on the river's edge) is 39.90m on the left bank, while the length on the right bank is 39.29m (Crăciun and Sion 2006: 375).

The dimensions of the other elements of the pillars on the Serbian and Romanian banks also indicate the similarity of the structures on both sides of the approach to the bridge (Table 1). However, by looking at the values in the Table 1, it can be noticed that the lengths of the centre parts of all four supports are closer to each other than the values of the total lengths of the supports. Taking into account the measurements of the central part of the first pillar on the Serbian bank, Craciun and Sion calculated that the length of 9.76 m most probably corresponded to the length of 38 pedes, which should have been

the length of the portal in its above-ground part (Crăciun and Sion 2006: 370).

The distances between the embankment pillars are different and range from 5.44 m between the first and second on the Serbian side to 6.52 m between the third and fourth pillar on the Romanian side (It is important to note here that the distance between the pillars, we primarily mean the distance between their central parts). The distances between the ends on the Romanian side are given according to the data of the Romanian authors (Crăciun and Sion 2006: 382). This information is important for considering the construction that bridged the space between the pillars on the bank, which we will see in the following text. All distances between individual pillars on one and the other side of the Danube are shown in Table 2.

Pillar foundations

Geotechnical tests of foundations carried out in 1983 by Romanian scientists indicated that the foundations lie on a bedrock made of clay and poorly cemented micaceous sands with marl intercalations. Blocks of crystalline schist and quartz were then placed over them, at a thickness of 30-50 cm, without bonding with mortar. Over these blocks, crystalline shale and quartz were used for masonry as well, bound with white mortar with the properties of modern hydraulic mortar (Crăciun and Sion 2006: 381).

Imprints of wooden planks for preparing the formwork of the foundations are most visible on the sides of the pillars (Fig. 2a). Since the remains

	Total length (m)	Total width (m)	The width of the central part (m)	The length of the central part of the pillar (m)	The length of the extension of the pillar (m)	The width of the extension of the pillar (m)
Pillar I – portal	16.66	6.36	4.76	9.76	3.60	5.50
Pillar II	14.12	4.75	2.36	9.40	2.38	4.13
Pillar III	13.95	4.15	2.38	9.40	2.30	4.15
Pillar IV (the platform part is not included)	13.42	4.95	2.95	10.10	2.85	4.95

Table 1. The values of the lengths of individual parts of Trajan's Bridge's masonry supports on the embankment (the attached values are based on the technical documentation of the Institute of Archaeology, Belgrade).

	I – II pillar	II – III pillar	III – IV pillar
Distance between middle parts of the pillars on the Serbian side (m)	5.44	6.23	6.52
Distance between middle parts of the pillars on the Romanian side (m)	5.50	5.75	6.60
Distance between ending parts of the pillars on the Serbian side (m)	4.31	4.71	4.31
Distance between ending parts of the pillars on the Romanian side (m)	4.40	4.00	4.13

Table 2. Distances between individual pillars on the Serbian and Romanian sides of the Danube river.

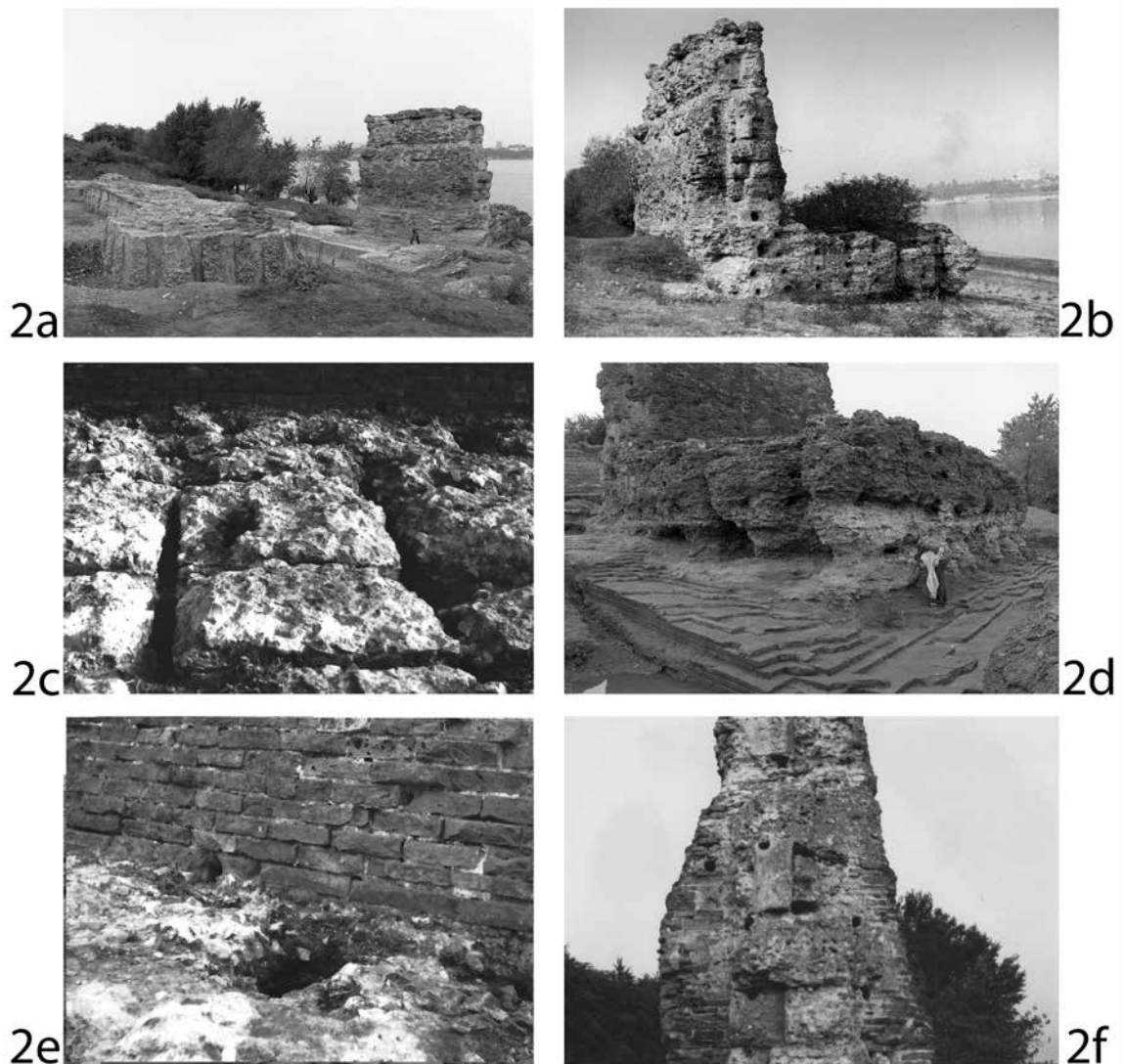


Fig. 2. a. Channels left as imprints from wooden planks of the formwork for the foundations of the first pillar in the foreground; b. The remnants of the fourth pillar of Trajan's Bridge; c. The imprints left from beams of the wooden grid system on the platform of the fourth pillar; d. Dense formation of stones and mortar tamped in the platform, with channels left from the horizontal wooden grid systems; e. a hollow left from a wooden post in the foreground of the platform and dense formation within the rows of bricks on the wall (opus testaceum); f. The only preserved ashlar and imprints from other missing ashlars on the side of fourth pillar; on their upper and bottom surfaces the channels left from wooden grids can be seen (photo-documentation of the Institute of Archaeology, Belgrade).

on the Romanian bank are very damaged pillars, no imprints of the formwork were registered. Therefore, on the Romanian side, there is no data on the size of the wooden formwork elements used for the foundations of the embankment pillars. On the Serbian side, there are clear prints of the vertical planks of the formwork on the faces of the foundations, which show the extent to which the *opus caementicium* was tamped and how the foundations were constructed. The fact that we can very clearly see these imprints from the planks shows that stones and lime mortar were tamped very strongly within the masses of the foundations. The method of execution of the formwork for the foundations of the bridge pillars was identical to that used for the foundations of the ramparts of the nearby Pontes castrum that protected the approach to the bridge. However, the main purpose of wooden boxes made up of planks and created for the execution of these foundations was in fact to prevent the collapse of the surrounding soil. Thanks to the clear imprints of the boards, the dimensions of their section, as well as other details, could be fully determined. The wood was cut into boards with a regular square section. The cross-section size of the wooden boards used in the foundation of the pillar with the portal (the first pillar) was 30 - 40 x 6 cm, for the second pillar it was 25 - 42 x 6 cm, and for the third pillar it was 45 x 6. We can also see the imprints in both directions: vertical and horizontal. The largest length of one horizontally placed board is 7.7m and it was registered on the southern face of the foundations of the third embankment pillar on the Serbian side. Lime mortar was poured inside the formwork formed in this way and larger stones (10-30cm) were hand-laid into it, and the whole mass was then tamped in order to achieve a compact foundation. During the tamping, the wooden formwork buckled and cracked, which was noted in several places on the foundations of the pillars on the bank (according to drawings and photos from the documentation of the Institute of Archaeology in Belgrade).

When it comes to the foundation of the platform along the fourth embankment pillar (Fig. 2b), within the space provided for the foundation, wooden posts were previously driven according to the modular system. With them, the future masonry construction of the foundation would be

tied to the river bed. Getting stones hand-laid into the mass of lime mortar was carried out in several steps, which were coordinated with the successful laying of grids made of wooden beams. A closer look at the masonry remains in the foundation part of the fourth pillar shows us the density of stones and mortar around it (Fig. 2d). We can also recognise the rows of stones tamped in the mass of lime mortar, and that the dynamic of this process was aligned with the setting of a wooden grid system. The fact that there are no voids between stones shows us how firmly the rows of stones were tamped within the masses of the bridge foundation. Also, we can see the classic Roman *caementa*, made up of larger stones (10 – 30 cm), which is different from today's modern concrete aggregate, which consists of different sizes of small stones. This procedure made it possible to make a solid mass for the foundation of each pillar, which could carry the masses of the above-ground parts of the masonry structure in the embankment part. The same procedure was certainly used during the building of the foundations of the pillars in the river bed, as we will see below.

On the surface of a pillar platform are channels left from the rotten wooden grid system (Fig. 2c, Fig. 3), as well as holes from wooden posts by which the foundation was fixed to the riverbank soil. Wooden posts were very often used in Roman architecture in western Europe (Ulrich 2008: 80; Lancaster and Ulrich 2014: 174).

According to Crăciun and Sion, the wooden post imprints left on the platform of the fourth embankment pillar on the Romanian side had a cross-section of 0.32 (0.26) x 0.24 (0.15) m, while on the platform at Pontes, four different cross-sections of posts were recorded: 0.32 x 0.23, 0.25 x 0.18, 0.30 x 0.19, 0.30 x 0.30 m (for the Romanian data see: Crăciun and Sion 2006: 384). One of the oak beams preserved in the Museum of the Iron Gates most likely had the function of a post (Tudor 1931: 22; Crăciun and Sion 2006: 384). According to the documentation of the Archaeological Institute in Belgrade, the wooden posts were not directly connected to the horizontal wooden grids that were placed inside the core mass of the platform of the fourth embankment pillar at a certain vertical distance.

Embankment pillars above ground level

The first embankment pillar on the approach to the bridge (with the portal) was rectangular in plan and longer than other pillars, which can also be seen in Table 1. The next two pillars in the above-ground part had the shape of the Latin letter I, while the fourth embankment pillar had a more complex plan shape. The first part of that pillar was in the form of a platform, while the second one was in the form of a tall pillar (Fig. 2b, Fig. 3). Even the construction details within the first part resemble details from the foundation of the pillars in the river bed, along with the wooden grid system and the inner core of masonry made up of stones hand-laid in lime mortar. Above the foundation boundary of that part, made from bricks, wall faces were executed by using stone blocks. The other part of the pillar had blocks only at its protruding ends. The wall part between these ends had faces made of brick with an inner core

of masonry made up of stones laid in lime mortar. Again, the remnants from a wooden grid system were registered.

The facades of the above-ground parts of the pillars, were built of bricks on the longitudinal sides (*opus testaceum*) (Fig 2e). However, the protruding endings of pillars on both sides (western and eastern) were built of stone blocks (*opus quadratum*) firmly connected to the rest of the pillars with a wooden grid. The stone blocks (or their impressions) that were found on the remains of the pillars on which the portal stood had a length of 1.45 m and a width of 0.79 m (Fig. 2f). One of the few preserved stone blocks used to connect the central part of the pillar with its ends on the fourth embankment pillar has a cross-section width of 0.43 m and a height of 0.65 m. However, the impressions of other blocks on the same pillar indicate that the width could have been up to 1.15 m, while the height of the blocks was registered in the range of values from 0.61 to 0.83 m (according

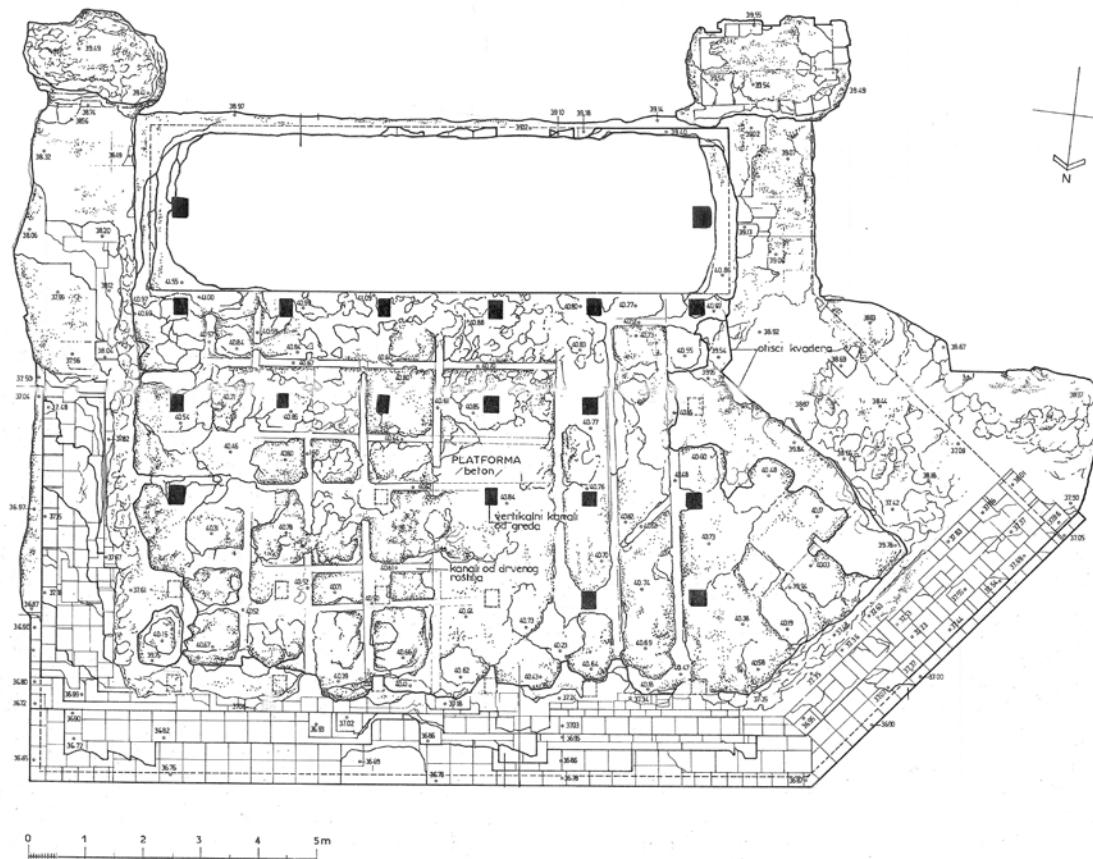


Fig. 3. Plan of the fourth pillar with its platform (technical documentation of the Institute of Archaeology, Belgrade and Petrović and Vasić 1980. Fig 5.)

to the technical documentation of the Institute of Archaeology in Belgrade). The imprints from the blocks were registered all along with the height of the pillar part of the pillar, as well as the voids and holes from the wooden grid system. Stone and bricks penetrate to different depths in the core filling mass of the masonry supports. The brickwork was done using large formats, especially in the area of the plinth. *Bipedales* and *sesquipedales* bricks were used, or bricks whose dimensions corresponded to the dimensions between the mentioned types, mostly 50 x 60 x 6 - 8 cm in size (Crăciun and Sion 2006: 383).

On the collapsed faces of the pillars, it is noticeable that the pouring and tamping of the *opus caementicium* were done in layers and were consistent with the installation of a wooden grid. The lower the compressive strength and uniformity of the mortar mixture, the greater would be the need for larger and more properly cut building units and vice versa (Vitti 2021: 3). For the ending parts of pillars on the bank, larger and accurately cut blocks were used, while the walls of the pillars between these ends were faced with layers of densely staggered bricks. In the cores of the pillars of Trajan's Bridge large pieces of irregularly shaped stone were used for the inside filling, firmly embedded in layers of lime mortar, and the combined settlement during the process of construction was controlled with a wooden grid.

At the western end of the platform, two important situations can be observed - there are no remains of wooden posts, and the network of wooden beams has a different orientation. This situation is present on both the Serbian and Romanian sides of the masonry structure¹. According to Crăciun and Sion researchers, the absence of remains of wooden posts at the western end indicates two possibilities. Based on the first, they could have been embedded deeper in the river bed, so that their top did not reach the surface of the platform as those in the eastern part. Based on the second possibility, the use of wooden posts could have been replaced by another type of construction, by which the platforms at their western

ends were fixed to the river bed (Crăciun and Sion 2006: 381). Concerning such possibilities, Crăciun and Sion assumed the existence of a modular system of 6 x 8 posts at the base of the platform (Crăciun and Sion 2006: 384). Additional rows of posts would be located, in that case, on the western and opposite eastern side of the platform. However, we cannot agree with this assumption since neither on the Serbian nor the Romanian side of the platform could we find material data that would confirm it. On the contrary, the state of preservation, or to be more precise, the damage of the platforms on both embankments of the Danube indicates the opposite - that there were as many piles as are visible on the surface of the platform near Pontes, that is, they were stacked in a modular system of 6 x 6 piles. This is primarily indicated by the better preservation of the remains on the Serbian side (Fig. 3).

The wooden grid system at the western projecting end of the fourth pillar platform has a different orientation than that of the rest of the platform surface (Fig. 3). The possibility that there are posts buried deeper in the river bed at the western end cannot, however, be ruled out, but at least one part of them would be visible on the damaged parts of the platform on the Serbian side. Even if such posts do exist, there was a particular reason for them not to appear in the western triangular projecting zone at the western end of the platform, nor 2 m west of the eastern edge of the platform.

There is another interesting detail in the depiction of Trajan's Bridge on the Column in Rome. Namely, if we adopt the thesis of the previous researchers about the reliability of that representation, we notice that the wooden platform with its longitudinal and transverse supporting beams crosses the level where the tops of the arches are located above the embankment structure of the bridge. In that case, the connection of the masonry arches with the wooden platform above the bridge can be viewed from a different perspective. Namely, taking into account that the average distance between the central parts of the embankment pillars was from 5.44 to 6.52 m, we notice that such a span was sufficient to be bridged with stronger wooden beams such as those used to form the supporting structure in the part above the riverbed. Using the representation of the bridge on Trajan's Column, two variants of the construction

¹ For an insight into the preservation state of the remains on the Romanian side, see in: Crăciun and Sion 2006. 381. The state of preservation on the Serbian side is visible at the base of the platform depicted in the Fig.1 of this paper (photo documentation of the Institute of Archaeology Belgrade).

that bridged the spans between the pillars on the bank can be assumed. In either of those variants, it is indisputable that there were arches between the protruding endings of these pillars. According to the first variant, as assumed by earlier researchers such as Dupperex, Tudor, and S. Gušić, the spans between the middle parts of the embankment pillars would have been covered by barrel vaults (Fig. 4a) (Gušić 2015: 77, with older bibliography). According to another variant, between the pillars of the bridge on the banks, in the width between their arches, there was a wooden structure made of oak beams (Fig. 4b).

Apart from the depiction of Trajan's Bridge on the Column in Rome, the last conclusion is indicated by a few more details on the bridge construction itself (Fig. 4b). We have already indicated that the values of the length of the middle parts of the bridge's embankment pillars are closer to each other than the values of the total length of the masonry pillars. To be precise, this is the length of each middle part on the first three embankment pillars whose facades were built of bricks. In contrast, the total length of the pillar with the portal differs from the second and third pillars, while the length of the former also differs to some extent from the total length of the fourth embankment pillar (excluding the platform, of course). This would mean that the length of the aforementioned middle parts was more suitable for determining the equal width of the road on the bridge over all the embankment pillars. The same width is covered by the area of the grid system on the platform of the fourth embankment pillar, which is defined by longitudinal and transverse wooden beams, as well as vertically driven posts.

In this sense, the absence of wooden posts at the western end of the platform, which would have secured it to the river bed, can also be observed. Namely, at this point, we would assume that the wooden posts could also have had the function of additionally strengthening the connection of the wooden platforms for the arch supports with the structure of the masonry construction of the bridge. This is supported by the fact that all the imprints of the wooden posts were visible on the surface of the masonry platform of the fourth embankment pillar on the Serbian side, which indicates that they pierced its surface. Since *opus caementicium* did not pass over posts on the platform

surface, this could only have been done for a special reason. According to the technical recordings and photographs at the Institute of Archaeology in Belgrade, they were not tied with a horizontal wooden grid system (Fig. 3), so the only other type of structure with which they would be tied is a wooden platform for carrying the wooden arch supports of the bridge. This view fits with the previous one regarding the possible width of the road on Trajan's Bridge (Fig. 4b).

PILLAR SUPPORTS IN THE RIVERBED

Studying Deuster's drawings from 1858, Dupperex reconstructed the shape of the masonry platforms in the river (Tudor 1931: 24). According to him, they were rounded rectangles with two equilateral triangles attached to the shorter sides. The tops of those triangles were directed upstream and downstream and had the function of facilitating the flow of the river so that during this process the creation of river sandbanks did not occur. It is interesting that on the platform next to the embankment pillar on the Romanian and Serbian banks, there are no triangular protruding endings on their eastern parts. However, Crăciun and Sion do not rule out the existence of such protruding parts to the east on pillars in the river bed (Crăciun and Sion 2006: 384).

Using Dio Cassius's statement, these pillars were reconstructed by Dupperex to be 18-19 m (60 ft) wide (Tudor 1931: 25). The method of the foundation of the bridge pillars in the riverbed is very similar to that indicated by Vitruvius in his comments on the method of the foundation of the perimeter walls near seaports a century before the building of Trajan's Bridge. Considering the similarity and importance of his descriptions concerning the construction of the foundations of Trajan's Bridge, they are reproduced here in full. (Crăciun and Sion 2006:381; Vitruvije 2009: V, XII, 3 – 6.):

3. Then, in the place previously determined, a cofferdam, with its sides formed of oaken stakes with ties between them, is to be driven down into the water and firmly propped there; then, the lower surface inside, under the water, must be levelled off and dredged, working from beams laid across; and finally, concrete from the mortar trough—the stuff having been mixed as prescribed above—must be heaped up until the empty space which was within

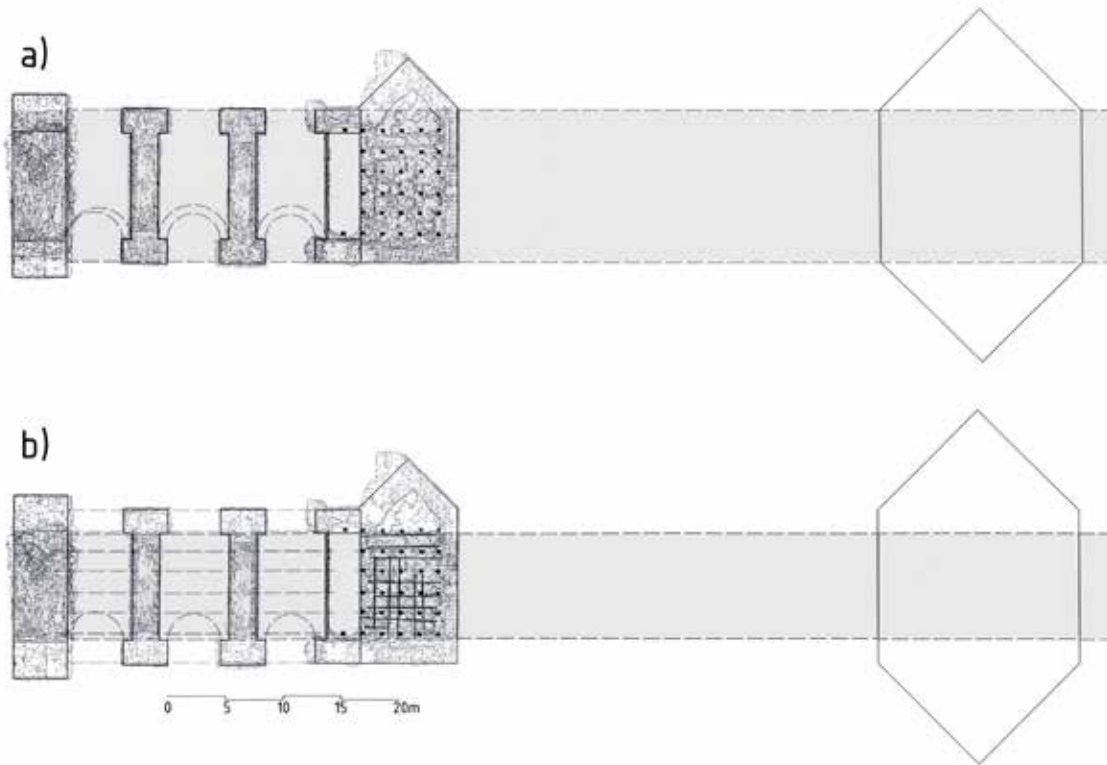


Fig. 4. Two solutions for spanning the spaces between pillars on the bank of the Danube: a. Variant with arches and vaults between middle parts – the width of the walking platform on the bridge is adjusted to the overall length of the second and third pillars; b. Variant with arches on the pillar ends and wooden beams between middle parts – the width of the walking platform on the bridge is adjusted to the length of middle parts of all pillars (technical documentation of the Institute of Archaeology, Belgrade, modified by I. Bjelić).

the cofferdam is filled up by the wall. This, however, is possessed as a gift of nature by such places as have been described above. [...]

5. But in places where this powder (volcanic ash) is not found, the following method must be employed. A cofferdam with double sides, composed of charred stakes fastened together with ties, should be constructed in the appointed place, and clay in wicker baskets made of swamp rushes should be packed in among the props. After this has been well packed down and filled in as closely as possible, set up your water screws, wheels, and drums, and let the space now bounded by the enclosure be emptied and dried. Then, dig out the bottom within the enclosure. If it proves to be of earth, it must be cleared out and dried till you come to the solid bottom and for a space wider than the wall which is to be built upon it, and then filled in with masonry consisting of rubble, lime, and sand.

6. But if the place proves to be soft, the bottom must be staked with piles made of charred alder or olive wood, and then filled in with charcoal as

has been prescribed in the case of the foundations of theatres and the city wall. Finally, build the wall of dimension stone, with the bond stones as long as possible, so that particularly the stones in the middle may be held together by the joints. Then, fill the inside of the wall with broken stone or masonry. It will thus be possible for even a tower to be built upon it.

Although the example of the construction of the foundation of the bridge in Mainz indicates the possibility of placing one row of planks that limit the volume of the foundation from the outside, the description of the destruction of the foundation on the Romanian side of the river speaks in favour of placing two concentric rows of planks for each pillar in the Danube riverbed (Tudor 1931: 22; Crăciun and Sion 2006: 380). At the same time, this description coincides with that mentioned by Vitruvius (*cofferdam with double sides*).

Based on the aforementioned Vitruvius' statements, as well as the recorded remains of caissons in the river, the statements of Dion Cassius and Tsetses about the use of caissons for the construc-

tion of pillars in the river bed can be confirmed (Каровић и Ђорђевић 2004: 64-67; Karović, Mihailović and Vučković. 2008: 288, note 2; On earlier literature and historical sources see: Гарашанин и Васић 1980: 8). According to the same source, the caissons were 120 feet (36 m) long and 80 feet (24 m) wide. Dupperex, however, warned that the height of the caissons in the deepest places of the Danube river bed, in that case, was significant (before the formation of the Đerdap II hydroelectric power station, the depth of the Danube at that location was about 7-8 m) (Tudor 1931: 33). If it is taken into account that each of the caissons for the pillars was 36 m wide and that, according to the aforementioned ancient writings, the distance between the pillars in the river bed was 56.70 m, then it follows that the width of the river bed at that location was narrowed by about 370 m by the construction of the bridge. This means that the width of the river bed was also reduced by about a third of its value, so the force of the river that flowed past the pillars had to be greater.

Based on Procopius' statements, it is also known that the course of the river was divided into two parts to lower the river level and build supports in the river bed (On earlier literature, historical sources, and Procopius's insight into Apollodor's writings see: Гарашанин и Васић 1980: 8). According to Tudor's interpretations, Apollodorus, therefore, had the opportunity to build at least 4 or 5 pillars on the dry part of the river bed (out of a total of 20 pillars that the bridge had in that part of the river bed) (Tudor 1931: 30 - 32). During the construction of the caissons of the other pillars towards the middle of the river bed, the depth of the river had to be lowered to at least 5-6 m, which is still high for the installation of the caissons recommended by Vitruvius. Even so, the pillar caissons that remained in the water had to be built on land. According to Tudor's hypothesis, which has survived until now as the only possible one, the caissons would then have been anchored at a certain distance and gradually filled with stone and wood to sink to the bottom. The caissons, according to Vitruvius' recommendations, would certainly have been laid so that their planks were facing each other, between which clay was then packed. Thus, a more suitable environment would be created in the interior of the caisson for the construction of the masonry structure of the

bridge support. The rest of the water from the interior of the caissons was probably extracted by using an Archimedes' screw, which Vitruvius mentioned in this context above. After that, wooden posts were set in a grid system. A firm lime mortar was tamped within the empty interior of the caissons, so the wooden posts and beam grid system along with the boundary of caissons strengthened the foundations to the ground.

When it comes to the structure and appearance of the masonry pillars in the river, Tudor's reference to the testimonies of people who participated in the demolition of the pillars in the river bed on the Romanian side in 1909 is significant. According to them, at first, they encountered broken stone connected by "concrete" and horizontal layers of bricks. Next came horizontal rows of large hewn stone blocks connected with mortar. The blocks had different shaped blocks with channels on their upper surface. Inside the channel, wooden ties were found that connected two rows of blocks to each other (Tudor 1931: 27).

The placement of the wooden grid systems had to be coordinated with the placement of stone blocks along the edge of the masonry supports in the river bed. One of the best indicators of the method of combining blocks with wooden beams are the preserved blocks from the destroyed pillars on the Romanian side of the riverbed. After their destruction, the blocks were transferred to the yard of the river fleet command building in Drobeta - Turnu Severin. These blocks were technically recorded and published by Tudor, whose drawings we use here on this occasion (Fig. 5) (Tudor 1931: Fig. 8). The blocks were 110-140 cm long and 42 cm to 75 cm wide, depending on the position. Their height is between 56 and 60 cm (Tudor 1931: 27). On their top and bottom surfaces, carved channels, 7 - 8 cm wide and deep, are noticeable in different formations. According to their dimensions and the appearance of the channel, such hewn blocks correspond to those that can be seen on the fourth embankment pillar on the Serbian side of the river. The angles and position at which these channels are orientated and placed are adapted to the geometry of the blocks themselves and their place in the plan of the masonry river pillar. Some intersections of these channels were made at an angle of 90°, while others were at an angle of 135° (90° + 45°). In these

channels, there were wooden beams that connected the core of one pillar with the blocks of its stone faces. Placing wooden grid systems in the interior of the masonry supports allowed the mass of stone and mortar to settle equally within the mass of the core. Finally, using a strongly tamped mass of mortar and stone, the compact core structure of these supports was formed, which is indicated by the fact that the remains of masonry supports in the riverbed have survived to this day.

The same method used for the wooden grid systems and posts in the masonry core of the platforms of the fourth embankment pillar was also used for the execution of the masonry supports of the bridge in the river bed. Major Imbrišević's report also points to the existence of pilots near the river pillars (Tudor 1971: 202; Crăciun and Sion 2006: 382). It is obvious that Apollodorus counted on several factors to ensure the stability of the

masonry pillars of the bridge. The monumental masses of masonry supports were formed, strong enough to resist the force of the river, the humidity of the surrounding landscape, and temperature changes, and strong enough to carry the monumental wooden arches of the bridge's supporting structure.

Above that kind of prepared foundation, the wooden structure of the bridge was constructed. The kind of radial and concentric structure that we can see in the depiction of the bridge on Trajan's Column in Rome was probably most similar to the constructions of wooden scaffolding for the execution of the masonry arches on the aqueduct of Pont du Gard in France. Similar constructions were reinvented during the 18th century in France and Great Britain (for more information on these structures see: Bjelić 2020, with bibliography).

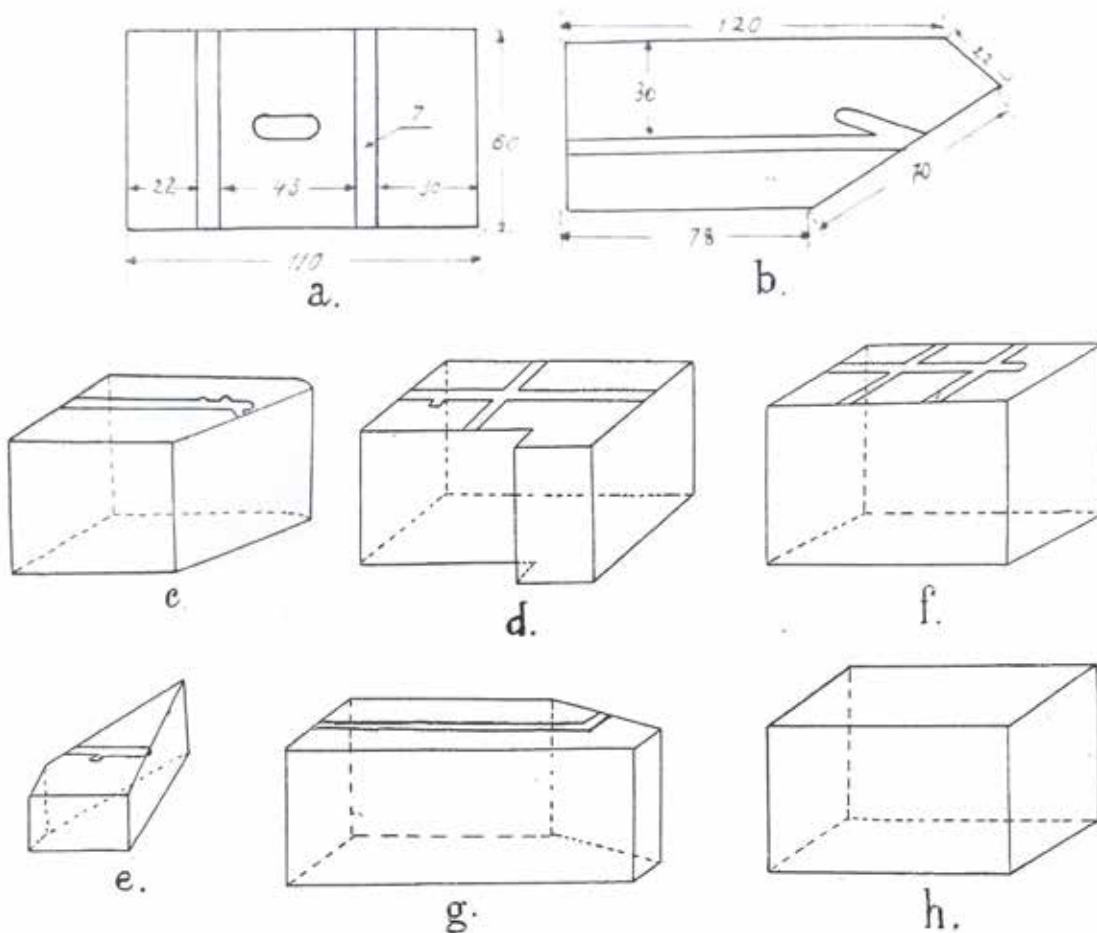


Fig. 5. Ashlars from the pillars of Trajan's Bridge in the Danube riverbed. On their surfaces, the carved channels for wooden beams can be seen (according to Tudor 1931, Fig. 8).

CONCLUSIONS

The study of the use of different materials in the construction of Trajan's Bridge indicates that without the analysis of ancient writings one cannot get a clearer picture of the former appearance of the bridge and ancient construction methods due to the pronounced damage of its remains. Writings such as Tsetses, Dio Cassius, Procopius, and Vitruvius enable us to get a clearer picture of the use of these materials during the construction of Trajan's Bridge.

Field data is certainly the most important in terms of specific methods of using different materials. In the case of Trajan's Bridge, it is particularly significant if elements of these materials are preserved in situ, but equally important are the imprints of specific elements in the *opus caementicium*. Imprints of wooden elements on part of the foundations indicate the way in which the foundation was formed and the degree to which mortar and stone were compacted, to achieve the best possible bond between these two materials. The analysis of the special positions of individual elements and materials on the embankment part of the bridge construction indicates the need to reconsider certain interpretations about the method of spanning the spaces between the pillars in this space. The method of spanning between the pillars in the river bed and the analysis of the dimensions of individual elements on the embankment parts of the structure indicates that the spaces between the embankment pillars did not have to be covered with barrel vaults, but with wooden beams. The aforementioned conclusion would also affect the speed of execution of the entire structure, which is characteristic of the entire structure of Trajan's Bridge.

In the example of Trajan's Bridge, we see a variety of construction methods. This is the result of the combination of different materials used during building in different environments (the parts of the construction exposed to water and those parts exposed to the air and soil). In the end, we can say that most of the processes undertaken during the construction of the bridge were devoted to the stability and durability of the structure. Bearing in mind that Romans did not know about static calculations and that their approach to the equilibrium of building structures was empirical, we can rec-

ognise that all the combinations of materials used during the construction of the masonry parts of Trajan's Bridge were devoted to most of the aspects of its security known to its builders. The wooden construction could not, of course, last long above the surface of the river, and there is a good probability that the Romans destroyed it themselves during the retreat from Dacia. However, the fact that masonry parts of the bridge remaining in the river bed and on the Danube banks of Romania and Serbia survived for such a long time speaks in favour of the idea that the supporting structure of the bridge must have been planned as thoroughly as Roman engineering could provide.

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REZIME

**UPOTREBA GRAĐEVINSKIH
MATERIJALA TOKOM
IZGRADNJE TRAJANOVOG
MOSTA NA DUNAVU**

KLJUČNE REČI: GRAĐEVINSKI MATERIJALI, METODE KONSTRUKCIJA, ZIDANE STRUKTURE, TRAJANOV MOST, RIMSKA ARHITEKTURA, DUNAVSKI LIMES.

Posle prvog rimskog osvajanja Dakije, car Trajan je svom arhitekti Apolodoru dao izazovan zadatak da projektuje i izgradi najveći poznati most u antičkom svetu, dužine preko 1.000 metara, koji je premostio jednu od najvećih evropskih reka - Dunav. Brzina izgradnje mosta, koju je car morao zahtevati, nametnula je korišćenje više različitih metoda konstrukcija koje su se odnosile na konkretne elemente mosta.

Prateći umetničke i istorijske izvore, *in situ* ostatke i analogije u ostalim delovima Rimskog carstva, u ovom radu su izvršeni pokušaji definisanja izgleda konstrukcije mosta. Nju čine tri dela: deo mosta na obali reke, deo noseće konstrukcije u koritu reke i deo mosta preko površine Dunava. Dok je poslednji deo bio isključivo od drveta, a deo u vodi bio zidan, za izgled obalnog dela su moguće dve varijante, prema kojima je on mogao biti u celosti zidan ili izveden u kombinaciji zidane strukture i drvene konstrukcije.

In situ ostaci na obalnim delovima mosta pokazuju specifične metode izgradnje ovog dela konstrukcije. Na delu stubaca u visini temelja reg-

istrovani su jasni otisci dasaka, koji pokazuju u kojoj meri je *opus caementicium* bio nabijen i kako su temelji građeni. Lica podužnih strana nadzemnih delova stubova, zidana su od opeke. Bočna lica nadzemnih delova stubaca zidana su kamenim blokovima čvrsto povezanim sa ostatkom stubova drvenim rešetkama.

Opravdanje upotrebe napred navedenih različitih građevinskih materijala možemo potražiti u ispitivanju Apolodorove potrebe za brzom izgradnjom mosta. Na danas sačuvanom stupcu kome pak nedostaje lice uočljivo je da je nalivanje i nabijanje *opus caementicium*-a vršeno slojevito i u skladu sa periodičnim postavljanjem drvenih rešetki u ulozi armature. Za unutrašnju ispunu stubaca mosta korišćeni su komadi kamena nepravilnog oblika dobro uronjeni u slojeve krečnog maltera, dok je ravnomerno sleganje u procesu izgradnje kontrolisano drvenom rešetkom.

Sve intervencije rimskih inženjera korišćene pri izgradnji zidanih stubaca Trajanovog mosta pokazuju da je njihov pristup bio empirijski, posvećen većini njima poznatih aspekata sigurnosti konstrukcija. Istovremeno, kombinovanje različitih građevinskih materijala za konstrukciju mosta bilo je verovatno uslovljeno potrebnom brzinom izgradnje, ali i okolnim prirodnim uslovima, odnosno dostupnošću i karakteristikama upotrebljenih materijala.

* * *

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