THE BRIDGE ON TRAJAN'S COLUMN IN ROME

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SUMMARY

The reliefs on Trajan's Column in Rome depicts major events of Emperor Trajan's two war campaigns against the Dacians. One of the reliefs shows the silhouette of a road bridge built before the second campaign. The bridge is widely recognised, described in encyclopedias [1, 2], books [3-8] and articles as the bridge over the Danube. In the author's opinion, the bridge near Drobeta has never been built, although it was designed by Apollodorus of Damascus and construction did start. Apollodorus supervised the construction of Trajan's Column. Being aware that the bridge over the Danube in the vicinity of Drobeta had never been built, he showed in the relief a bridge built to his design during Emperor Trajan's campaigns against the Dacians. However, the relief does not depict the bridge over the Danube.

Keywords: *Trajan's Column in Rome, bridge over the Danube.*

1. INTRODUCTION

The spiral bas-relief winding around the shaft of Trajan's Column in Rome depicts major events from Emperor Trajan's two military campaigns against the Dacians, in 101-102 and 105-106. One of the reliefs shows the silhouette of a road bridge built before the second campaign. The bridge is widely recognised, described in encyclopedias, books and articles as the bridge over the Danube, erected near the town of Drobeta (Turnu Severin). The span structure of the bridge portrayed in the relief consists of wooden arches resting on stone pillars (Fig. 1).

Scant historical records and ruins of supports confirm the existence of the bridge over the Danube near Drobeta. However, information on the bridge concerning its main dimensions – overall length, pillar height and width of the bridge – is diverse. For example, the bridge width reported by researchers to be between 13 and 19 m [6] seems grossly exaggerated, as permanent Roman urban bridges were of about 5-6 m in width [6]. There was no reason why a temporary bridge should be built in wartime conditions with a width three times that of a permanent bridge. The difficulties in determining the main dimensions of the bridge made it impossible to unequivocally reconstruct its appearance. It was commonly assumed that the image of the bridge shown in the relief presented the bridge over the Danube. However, the available information on the size of the structure does not confirm this assumption is right.

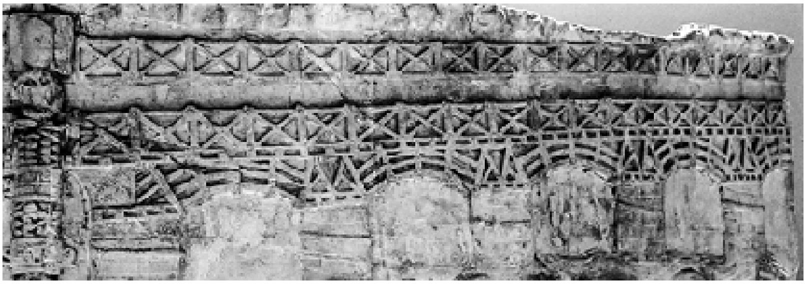

Fig. 1. The bridge as shown in the relief on Trajan's Column in Rome (photo by author).

2. COMPARISON OF THE BRIDGE OVER THE DANUBE WITH THE BRIDGE IN THE RELIEF ON TRAJAN'S COLUMN IN ROME

2.1. Characteristics of the bridge over the Danube according to Tudor

According to Cassius Dio (155-235), the bridge had 20 pillars. The spacing [between centres - J.R.] of the pillars (bridge dimensions were given in Greek feet - 1 Greek foot = 0.296 m) was 170 feet (50.32 m), with the span between pillars (clear span between pillars) of 120 feet (35.52 m). The pillars were 150 feet (44.40 m) in height and 60 feet (17.76 m) in width. The comparison of the centre-to-centre pillar spacing and the clear span between pillars shows that the pillar thickness was 170 - 120 = 50 feet (14.80 m). The length of the main spans of the bridge (between outermost pillar centres) was reported by Tudor to be 3570 feet (1,056.72 m).

In 1858, measurements of the pillar ruins were taken when the water level in the river hit a record low. According to Popovici, the clear span between pillars measured (measurements were made in fathoms - 1 fathom = 5.84 Greek feet = 1.728 m) was 21 fathoms (122.6 feet; 36.29 m), pillar thickness was 7.5 fathoms (43.8 feet; 12.96 m), and its width was 9 fathoms (52.54 feet; 15.55 m). Oak beams were found in the pillar structure.

2.2. Analysis of the parameters of the bridge over the Danube

It would be unreasonable to rely on the bridge height reported by Dio as the pillar height [3]. Firstly, in arch bridges, the Romans usually used small elevation of the abutment above the mean water level [7]. Secondly, the surface features at the bridge crossing point did not necessitate the construction of supports that high. Thirdly, the greatest depth of the river at high water is about 8 m (according to Duperrex [3]). In the author's opinion, the height of the structure stated by Dio means the total height of the structure, from the foundation bottom to the highest point of the entrance gate portal. The portal is the end component of the abutment part of the bridge, a structure made of brick with arch spans.

In the author's opinion, wooden arches of bridge spans rested on 20 free-standing pillars clad with stone blocks and on 2 pillars adjoining brick abutments. Thus there were 22 pillars and 21 spans in total – Dio took into account only the free-standing pillars, and this number was quoted from him by all researchers as the number of all pillars of the bridge [3, 4, 6, 8].

Assuming that there were 22 pillars, there is a full consistency between the length of the main part of the bridge as stated by Tudor and the centre-to-centre pillar spacing as stated by Dio: 21 x 170 feet = 3570 feet.

It can be assumed that measurements were taken in 1858 with an accuracy of 0.5 fathoms, i.e. ± 0.25 fathoms. The measurements results were adjusted by 0.25 fathoms so as to get closer to the dimensions given by Dio. Tab. 1 compares the results of pillar measurements with the data provided by Dio.

Table 1. *Dimensions of the bridge over the Danube based on pillar measurements and historical sources.*

Bridge dimensions	**According to Dio**	**According to Popovici**		**Comparison**
	[foot]	**[fathom]**	**[foot]**	**[%]**
clear span between pillars	120	21.0 - 0.25	121.2	+1.0
pillar thickness	50	7.5 + 0.25	45.3	-9.4
pillar width	60	9.0 + 0.25	54.0	-10.0
centre-to-centre pillar spacing	170	28,5+0.25	167.9	-1.2

Both the centre-to-centre pillar spacing and the clear span between pillars correspond to the dimensions given by Dio with an accuracy of 1%. By contrast, measured pillar dimensions are about 10% smaller than those cited by historical sources. Pillar material losses are probably a consequence of erosion developed on two surfaces perpendicular to each other. A slightly greater loss of material in the width of a pillar is justified, as the head of the pillar is always additionally exposed to mechanical damage by ice floes and by tree trunks and other objects carried by high waters.

According to Duperrex [3], the pillars were triangle-shaped at the ends. This is in line with the Roman design principle of shaping the pillars of permanent bridges built over wide rivers. However, the shape of the ruins does not confirm that the pillars were triangle-tipped. Owing to the fact that the bridge was a temporary facility, it cannot be ruled out that the pillars were protected against the thrust of floating ice by wooden starlings which were destroyed over time.

2.3. Characteristics of the bridge in the relief on Trajan's Column

The reliefs on Trajan's Column in Rome depicts major events of Emperor Trajan's two war campaigns against the Dacians. The bridge depicted in the frieze was built to the design by the chief bridge builder under the reign of Trajan, Apollodorus of Damascus, a Hellenized Syrian, no doubt an excellent designer, who accompanied the emperor during his campaigns. It can be stated with a high degree of probability that in designing bridges he used the Greek foot and the pace (5 feet) as the basic units of linear measure.

The actual dimensions of the facility as depicted in the relief can be estimated only knowing the dimensions of elements which are constant for each structure. The height of the balustrade on the bridge is one such dimension.

The balustrade on arch stone bridges was designed so that its height was strictly dependent on thickness, i.e. the lower the balustrade, the greater the thickness. A balustrade made of stone was roughly 1 foot in thickness and 3 feet in height [7]. The use of timber as balustrade material allowed its thickness to be reduced to about half a foot (0.15 m), whereas this made it necessary to increase its height for user safety reasons. Thus the balustrade height should be greater than 3 feet (0.89 m) but, for practical reasons, smaller than 5 feet (1.48 m). Thus it can be assumed that the height of the wooden balustrade used on bridges was 4 feet (1.18 m). The validity of this reasoning is confirmed by the fact that nowadays the standard balustrade height is 1.10 m.

The image of the bridge in the relief is rendered with a high degree of precision, preserving the dimensional proportions of the structural elements. Besides, it does not contain any element contrary to good engineering practice. This may indicate that it was made by an artist based on a technical drawing, and not a handmade sketch. Consequently, the bridge depicted in the relief can be treated as a true representation of a built structure. Assuming a height of 4 feet, the main dimensions of the bridge were determined on the basis of the bridge view in the relief. The dimensions are given in Tab. 2.

Table 2. *Dimensions of the bridge depicted in the relief according to the author.*

Bridge dimensions	Dimension [foot]
centre-to-centre pillar spacing	22.0
clear spacing of pillars	15.5
pillar thickness	6.5
rise of arch	3.5
arch span	15.5
arch radius	11.0
arch segment length	4.0
dimensions of largest facing stone blocks	5.0 × 2.0
centre-to-centre spacing of balustrade posts	6.0

In addition, the bridge pillars in the relief are not triangle-shaped at the ends.

2.4. Comparison of dimensions of the bridge over the Danube and in the relief on Trajan’s Column

Table 3 compares the dimensions of the bridge over the Danube with the dimensions of the bridge depicted in the relief on Trajan’s Column.

Table 3. Dimensions of the bridge over the Danube and that depicted in the relief on Trajan's Column

Bridge dimensions	Bridge over the Danube [foot]	Bridge in the relief [foot]	Dimension proportions [-]
centre-to-centre pillar spacing	170	22.0	7.7
clear spacing of pillars	120	15.5	7.7
pillar thickness	50	6.5	7.7

A comparison of the main dimensions of the bridge over the Danube with the dimensions of the bridge depicted in the relief shows that the individual structural elements of both facilities are proportional to each other.

3. ANALYSIS OF WHETHER THE BRIDGE IN THE RELIEF ON TRAJAN'S COLUM CAN BE THE BRIDGE OVER THE DANUBE

Assuming that the bridge in the relief represents the bridge over the Danube and that it is represented precisely, its dimensions would be proportional e.g. to the centre-to-centre pillar spacing of 170 feet. Some of its elements would then have the dimensions stated in Tab. 4.

Assuming that the thickness of stone blocks in the relief equals e.g. 1/5 of its length, the mass of a single stone in the facing of the pillar depicted in the relief would be more than 300 tonnes. Beam length of 9.0 m in an arch consisting of four elements is technically unjustified, and the balustrade height of 9.0 m is absurd from the utilitarian and technical point of view.

If we assume that the relief shows an image of the bridge over the Danube, then the artist:

- either made mistakes, but only with regard to: dimensions of facing stones, balustrade dimensions and division of the wooden superstructure into segments,
- or consciously presented only these elements in a distorted scale.

The artist's error is unlikely, as the construction of Trajan's Column proceeded under the supervision of Apollodorus, the builder of the bridge over the Danube.

Table 4. Dimensions of the bridge depicted in the relief as the bridge over the Danube.

Bridge element	Bridge in the relief [foot]	Bridge in the relief [m]
balustrade height	31	9.0
arch segment length	31	9.0
stone block length	39	11.5
stone block height	15	4.6

However, looking at the different scenes depicted in the reliefs, it can be noticed that the artist was using a distorted scale, but only in a specific convention. The idea was that, for instance, the dimensions of human figures in a particular group are proportional to each other, and the proportionality applies also to animals, e.g. to the horse mounted by a Roman in Scene XXXVI (scene numbering according to [9]) and objects (wooden beam carrier by a worker in Scene XVIII) included in the same group. Also the overall dimensions of buildings and their elements, such as: window openings, door openings, ashlars, maintain proportions, e.g. in Scene LXXIX. However, a building can be rendered in a distorted scale, e.g. in Scene LXXIX. Only this way was it possible to present the individual scenes without losing their vividness and preserving significant details (Scene LXXXI shows details of the soldier's uniform and the bird's eye view of the shape of defensive fortifications). Therefore, in the case of bridge depicted in the relief, which forms a separate fragment in Scene XCVIII relative to the group of figures, the application of a distorted scale to its elements is unlikely. Assuming that the bridge depicted in the relief is precisely represented (and, by all appearances, this is the case), it certainly is not the bridge over the Danube. If we assume that the relief shows the image of a bridge built by Apollodorus, but not the bridge over the Danube, then both bridges were built according to the same construction rules. It can be assumed that Apollodorus developed uniform design principles for bridges.

4. DESIGN PRINCIPLES FOR MILITARY BRIDGES DEVELOPED BY APOLLODORUS

The Romans mastered to perfection the art of building stone arch bridges. They were also familiar with the technique of making foundations on land and in water. It seems unlikely they used, in wartime conditions, design solutions other than arch-based. Bridges built during war campaigns undoubtedly were of a strategic/military nature. Owing to those specific purposes they should be constructed as quickly as possible. This condition could be satisfied when constructing the superstructure of the bridge from a light building material, uncomplicated to process, and widely available. The material meeting the above requirements was wood.

When building bridges over rivers during a wartime campaign, no engineering experiments are normally conducted. Instead, well-known and tested design solutions are applied. Thus Apollodorus replaced the stone arch with a much lighter, and by far easier-to-make, arch of wooden beams, adopting uniform design principles. Fig. 2 shows the principle of determining the main dimensions of a span depending on the pillar spacing.

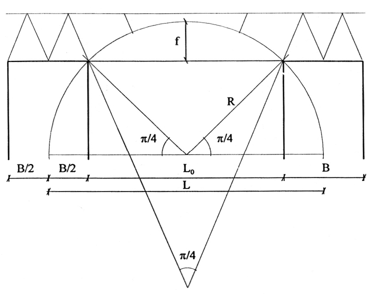

Fig. 2. *The principle of determining main dimensions of the span depending on the pillar spacing according to the author.*

Design principles according to the author [10]:

- the circular arc radius R of the arch equals a half of the centre-to-centre pillar spacing L,
- the arc of the arch rests on a straight angle,
- points of intersection of angle arms with a circle with radius R determine the clear span length L_0,
- pillar thickness B equals the difference between the centre-to-centre pillar spacing L and the clear span length L_0,
- the rise of arch f equals a half of pillar thickness B,
- the arc of the arch is divided into an even number of segments with an equal length,
- elements linking the deck to the arch are situated along the arc radius (perpendicular to the circle),
- the bottom arch beams form a polygon circumscribed around a circle with a radius R,
- all beams forming the arch are of the same length and spread with wedges at joints,
- the arch is fixed to the pillar structure.
- The division of the arc of the arch into an even number of segments makes it possible to apply a uniform structural design of the keystone. In addition, the arch structure is formed by interfacing arches of one-piece beams, which allows the required carriageway width to be obtained without changing the work method. It can be assumed that wooden arch structures were installed without erecting full scaffolding.
- Given this principle in designing bridges, each bridge was an exact replica of the model solution. They differed only in scale. Permanent structural elements which are independent of the span length, such as balustrade height and dimensions of stone blocks in pillars, were an exception. Also the number of spans and pillar height may differ, depending on the terrain conditions.
- If the above principle is assumed, the preliminary designing of a bridge was limited to:
- measurement of the width of the water table in the watercourse at medium water level, which is equal to the distance between centres of outermost pillars,
- division of the length of the main part of the bridge into spans, depending on the hydrological and hydraulic conditions,
- specification of the deck width.
- Other main dimensions of the bridge were pre-determined. Taking the above into consideration and based on the information that the centre-to-centre pillar spacing of the bridge over the Danube is 170 feet, the other dimensions are stated in Tab. 5.

Table 5. *Dimensions of the bridge over the Danube based on rules development by Apollodorus.*

Bridge element	Bridge over the Danube	
	[foot]	[pace]
clear spacing of pillars	120	24
pillar thickness	50	10
rise of arch	25	5
arch span	120	24
arch radius	85	17

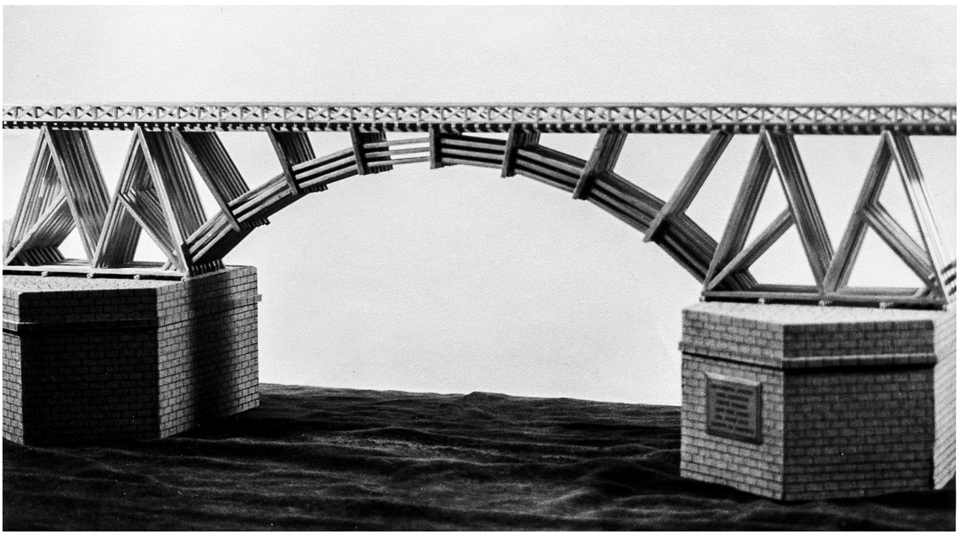

Fig. 3. *Span structure of the bridge over the Danube according to the author.*

The adoption of the above principles makes it possible to reconstruct the silhouette of the bridge span (Fig. 3). It can be assumed that the arches were made of beams with a cross-section area of 1 sq. foot, separated by wedges also 1 foot wide. Given this assumption, the carriageway of 6.0 m in width would be laid on 10 arches (6.0 m/(0.296 m × 2).

Attempts at reconstruction of the bridge on the Danube have been made by many researchers. In the author's opinion, the most successful reconstruction is that tackled by Duperrex [3] (Fig. 4). Its drawback is that the elevation of the span arch is too high relative to the principle adopted. In addition, the division of the arch into 10 segments is technically unjustified; a simple division of the angle into 10 equal parts using a compass and straight-edge is not possible.

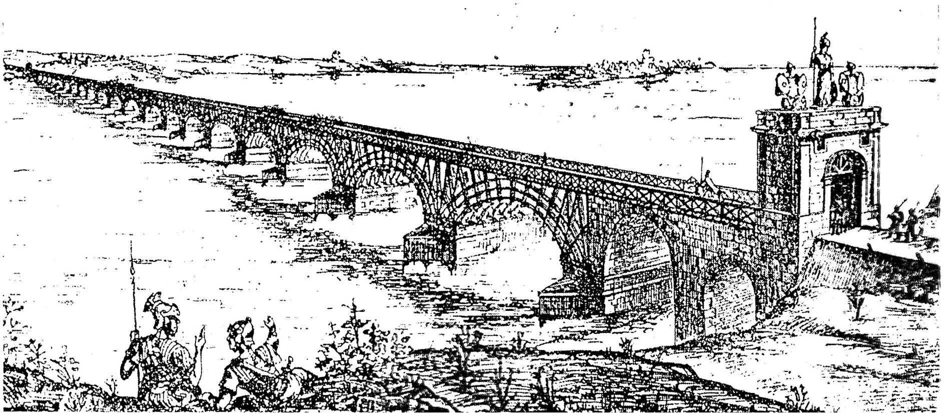

Fig. 4. Reconstruction of the bridge over the Danube according to Duperrex.

5. SUMMARY

I venture the hypothesis that the bridge depicted in the relief on Trajan's Column in Rome does not represent the bridge erected near Drobeta over the Danube. The silhouettes of the bridge as shown in the relief and the bridge reconstructed on the basis of historical sources, measurements of pillar ruins and Apollodorus' bridge design principles justify this hypothesis. The bridge silhouettes differ substantially. Fig. 5 shows a technical drawing of the bridge depicted in the relief, and Fig. 6 shows a drawing of the bridge over the Danube according to the author.

Moreover, I propose the hypothesis that the bridge over the Danube near Drobeta has never been built, although it was designed by Apollodorus and construction did start. The remains of supports testify to an attempt at building the bridge.

The construction of a bridge consisting of:

- 22 supports, each with a cross section of about 18 × 15 m and with a height of about 45 m,
- 21 spans, each with centre-to-centre spacing between supports of about 50 m,
- 10 triple arches per span (with carriageway width of about 6.0 m) of about 35 m,
- is technically infeasible. Quick construction of 22 concrete supports of about 45 m in height and 630 wooden arches spanning about 35 m is technically infeasible.

Apollodorus of Damascus, the designer of bridges in the times of Emperor Trajan, supervised the construction of Trajan's Column. Being aware that the bridge over the Danube in the vicinity of Drobeta had never been built, he showed in the relief a bridge built to his design during Emperor Trajan's campaigns against the Dacians. However, the relief does not depict the bridge over the Danube. In the author's opinion, the bridge portrayed in the relief on Trajan's Column may be located in Kamyanets-Podilsky in Ukraine [11].

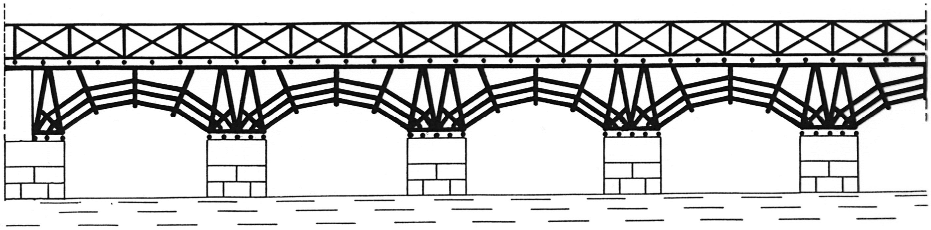

Fig. 5. Technical drawing of the bridge as shown in the relief on Trajan's Column in Rome according to the author.

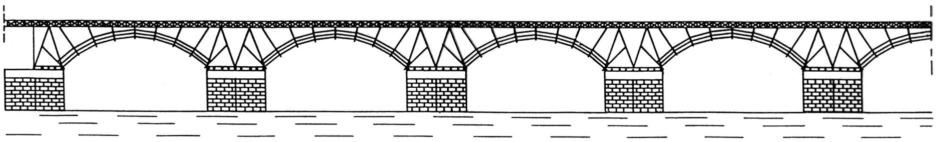

Fig. 6. Technical drawing of the bridge over the Danube according to the author.

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