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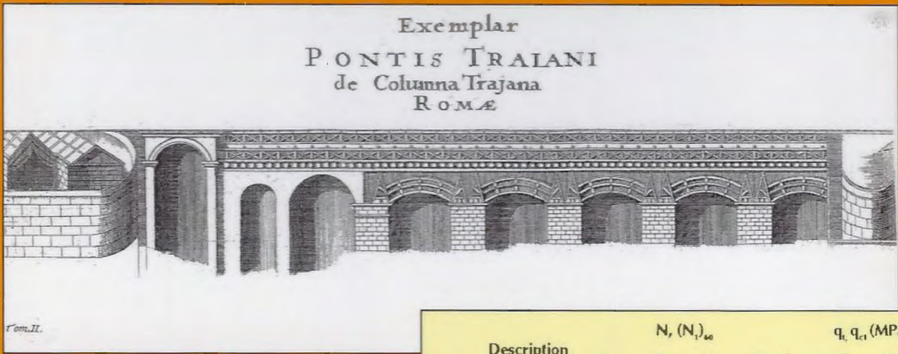
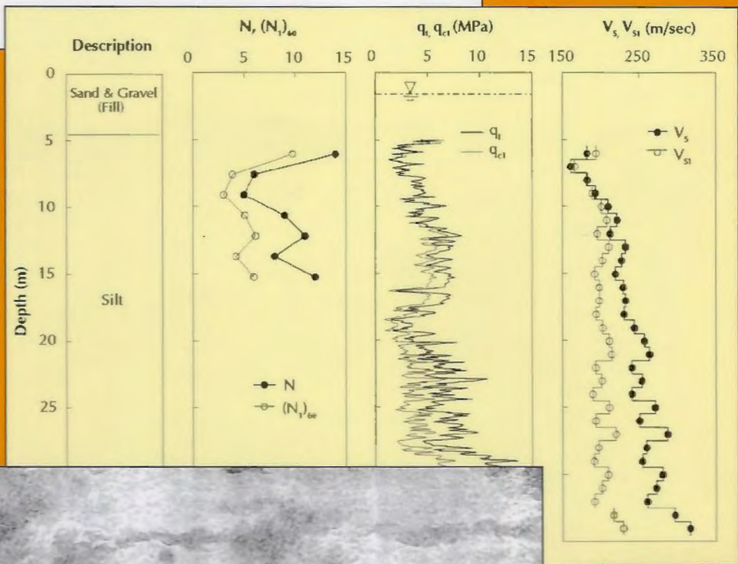
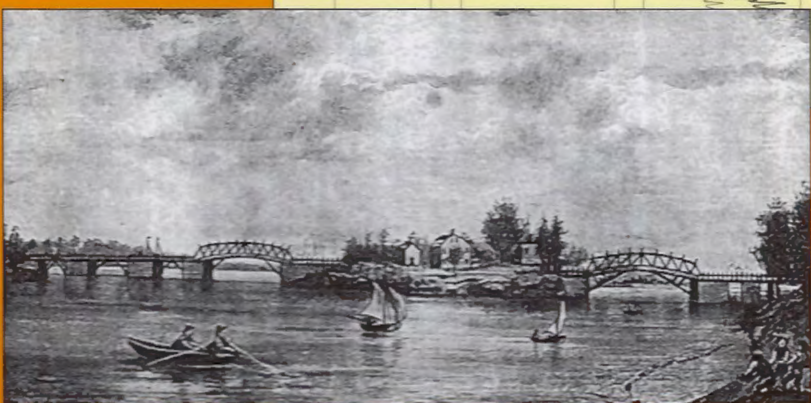


Evaluation of Liquefaction Potential at a Silt Site





Newburyport Bridge

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Evaluation of Liquefaction Potential at a Silt Site in Providence, Rhode Island

Given the fact that liquefaction potential depends on specific site conditions, it is necessary to perform such evaluations for any given project subject to risk of liquefaction.

A.S. BRADSHAW, R.A. GREEN & C.D.P. BAXTER

Assessing liquefaction potential in the Providence, Rhode Island, area is complicated by two factors:

- there are limited available ground motion records from large earthquakes in the region; and,
- much of the city is underlain by deep deposits of non-plastic silt, for which little is known about its cyclic resistance.

To provide insight on this issue, a deterministic evaluation of liquefaction potential was conducted at a site in Providence using a cyclic stress-based approach. The cyclic demand of the earthquake was evaluated by performing site response analyses using scaled intra-plate bedrock motions. The cyclic resistance of the silt was estimated using a soil-specific shear wave velocity-based correlation developed by the authors from an extensive laboratory testing program, as well as using existing standard penetration test (SPT) and cone penetration test (CPT) correlations.

Background

"Liquefaction" refers to the phenomenon that occurs when the soil skeleton of loose, saturated sand and/or non-plastic silt collapses and

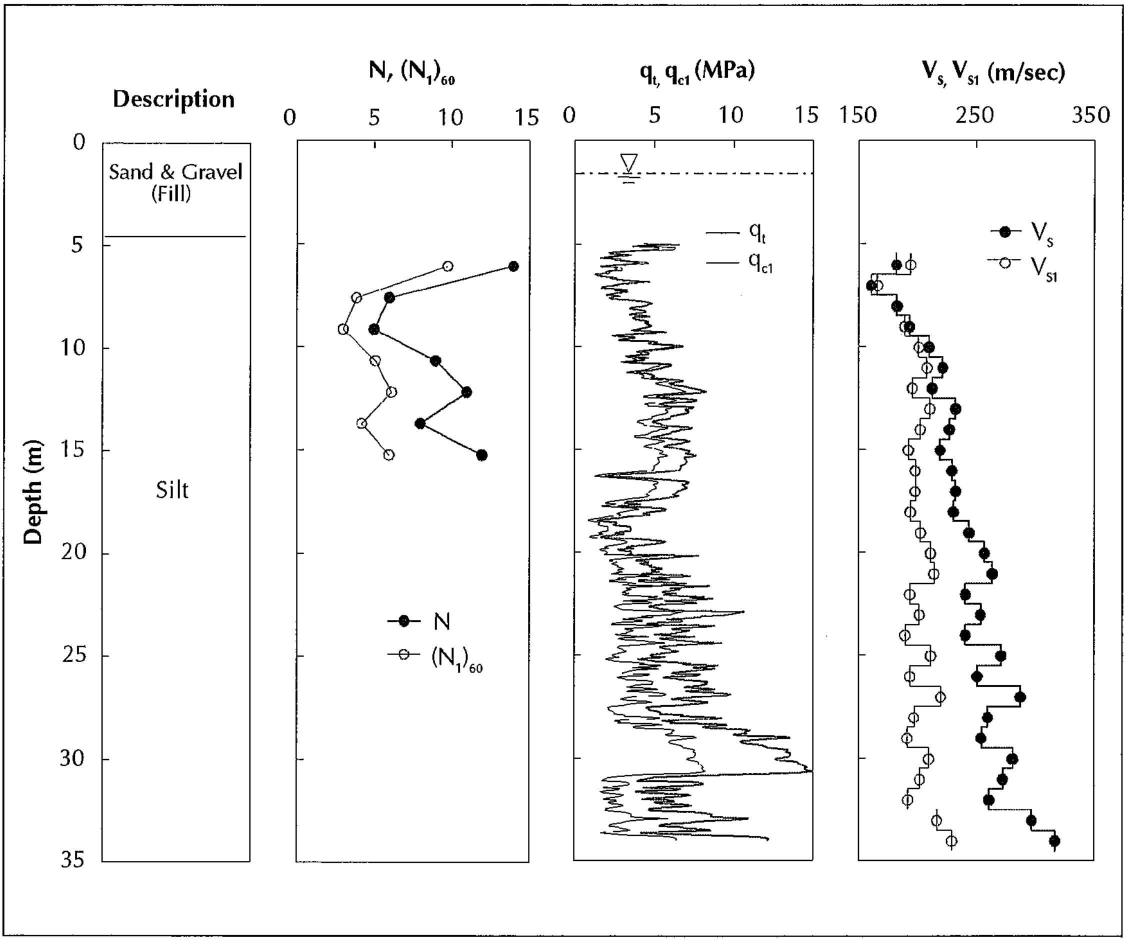

FIGURE 1. A representative geotechnical profile resulting from the site investigation.

there is a temporary transfer of overburden stress from the soil skeleton to the pore fluid. The collapse of the soil skeleton can be initiated in a variety of ways, one of which is earthquake shaking. There are numerous documented cases where earthquake-induced liquefaction led to the partial or complete loss of soil shear strength, resulting in building settlements, damage to utilities, and slope instabilities.[1]

The precise cause of earthquakes in the northeastern United States is uncertain. However, for earthquakes that are large enough to be of engineering interest, a generally accepted hypothesis is that they result from movements on ancient failed rift zones or passive margins, where the movements are driven by stresses transferred from the plate boundaries.[2,3] Because most seismic sources in stable continental regions (i.e., central and eastern United States) are not well defined, it is difficult to quantify the potential of such sources to generate future earthquakes.[4] However, some geologic studies have shown that prehistoric earthquakes in the Northeast have been large enough to cause liquefaction.[5-7] One study in Newburyport, Massachusetts, in particular uncovered two generations of buried liquefaction features, including sand dikes and sills, with the causative earthquake estimated to have a return period of approximately 4,000 years.[6]

In Rhode Island, the evaluation of liquefaction hazard is further complicated by the fact that most of the coastal areas, including Providence, are underlain by silt that is composed of approximately 95 percent fines. Assessing the cyclic resistance of the Providence silt is uncertain because the semi-empirical liquefaction evaluation procedures commonly used in practice were primarily developed using data from deposits containing less than 35 percent fines.[8] It is the combined difficulty of defining the design earthquake motions and the uncertainty in the cyclic resistance of the Providence silt that makes the assessment of liquefaction potential a challenging problem in this area.

Site Investigation & Soil Conditions

A geotechnical site investigation was performed at the site of a historic farmers' market in Providence, which included rotary wash borings with SPTs performed adjacent to seismic CPTs. The SPTs were accomplished using a standard split-spoon sampler with the inside liner removed. The efficiency of the donut hammer system was measured using a pile driving analyzer and ranged from 30 to 40 percent, with an average of 37 percent. Hammer efficiency measurements are critical for correcting the SPT blow counts to a standard efficiency of 60 percent for evaluating liquefaction resistance. Representative samples of silt were recovered between SPT intervals using a 7.5-centimeter diameter split-spoon sampler with a core catcher. These samples were reconstituted and used in a laboratory cyclic strength testing study.[9] Seismic CPTs included near-continuous measurements of tip resistance, sleeve resistance and pore water pressure. Shear wave travel time measurements were made "down-hole" and a shear wave velocity model was used to interpret the shear wave velocity profile at 1-meter depth intervals.

A representative profile of the soil conditions at the farmers' market including SPT blow counts (N), cone tip resistance corrected for pore pressure effects (q_t), and shear wave velocity (V_S) is shown in Figure 1. Values corrected to an overburden stress of 1 atmosphere (about 100 kPa) — *i.e.*, $(N_1)_{60}$, q_{c1N}, and V_{S1}) are also shown in this figure. The site consisted of approximately 4 to 10 meters of sand and gravel fill underlain by a thick layer of non-plastic silt. The water table was encountered at a depth of about 1.6 meters below the ground surface. The silt was deposited as glacial lake sediments during the last glacial retreat and is characterized by seasonal varves. Grain size analyses of bulk samples indicated that the silt was composed of about 95 percent fines (less than 0.075 millimeters), and Atterberg Limits could not be determined. The silt was therefore classified as a non-plastic silt (ML) according to the Unified Soil Classification System. Previous geotechnical explorations indicated that the silt was underlain by a very thin layer of till overlying bedrock.[10] The depth to bedrock ranged from about 36 to 61 meters below the ground surface and the rock consisted of a sandstone conglomerate.

Assessment of the Seismic Hazard

The first step in evaluating the liquefaction potential at a particular site is to assess the seismic hazard at the site. This study could be a regional hazard assessment based on building code provisions,[11,12] or a site-specific hazard analysis that is typically performed for important and/or hazardous facilities.[13] Ultimately, the results of a seismic hazard analysis are the design ground motions that are required for an analysis of liquefaction potential.

In lieu of performing a site-specific seismic hazard analysis, the design ground motions used herein are in general accord with current seismic design recommendations and standards for new buildings. The 2003 edition of the National Earthquake Hazard Reduction Program (NEHRP) provisions recommends seismic design motions having a 2 percent probability of exceedance in 50 years (*i.e.*, motions having an approximately 2,500-year return period).[14] This criterion was also adopted by the 2006 International Building Code (IBC).[15] The seismic hazard maps that accompany these building codes and additional information available from the United States Geological Survey (USGS) were used to determine the design ground motions at the study site. This approach is particularly attractive because the USGS provides online access to the seismic hazard data that were used to develop the seismic hazard maps that accompany the NEHRP and the ICC provisions.[16] A description of the procedures that were used to generate these map is given in Driscoll and Baise.[17] The hazard data can be accessed by entering the zip code or the latitude and longitude of the site of interest.

Methods Used to Evaluate Liquefaction Potential

Liquefaction potential was evaluated using a cyclic stress-based approach, which is commonly used in engineering practice.[8] The factor of safety against liquefaction is estimated at any depth in the soil profile from the following equation:

$$FS = CRR/CSR \quad (1)$$

Where:
CRR = cyclic resistance ratio of the soil; and
CSR = cyclic stress ratio induced in the soil by the earthquake.

Note that in using Equation 1 both CRR and CSR need to be evaluated for the same earthquake magnitude and initial stress conditions.

Cyclic Stress Ratio (CSR). The cyclic resistance correlations correspond to a magnitude 7.5 earthquake. Therefore, to be consistent with this magnitude, the CSR was calculated from the following expression:

$$CSR = 0.65 \cdot \frac{\tau_{max}}{\sigma'_{v0}} \cdot \frac{1}{MSF} \quad (2)$$

Where:
τ_{max} = maximum cyclic shear stress estimated at a given depth;
σ'_{v0} = initial effective overburden stress at a given depth; and
MSF = magnitude scaling factor.

The range for MSFs recommended by Youd *et al.* for M5.5 to M8.5 is shown in Figure 2.[8] For this study, an average of the recommended range was used and was extrapolated for M less than 5.5.

Site response analyses were performed using SHAKE91 to determine the maximum cyclic shear stress induced in the soil column.[18] The analysis required time histories of bedrock motion as inputs, along with a profile of soil stiffness and damping properties. The time histories were applied as outcrop motions at bedrock, which on average is at a depth of 49 meters below the ground surface. The small strain shear modulus (G_{max}) was computed from the shear wave velocity data obtained using the seismic cone (for example, see Figure 1) and estimated bulk density values. A bedrock shear wave velocity of 1,982 meters/second was used based on cross-hole seismic measurements made at a nearby site.[13] Shear modulus and damping properties as a function of strain were estimated at various depths using empirical relationships developed by Ishibashi and Zhang.[19]

One of the most important and challenging aspects of performing a site response analysis is selecting the input rock outcrop motions. It is common to generate synthetic motions that match a building code design spectrum or a uniform hazard spectrum (UHS) for the site of interest.[13,20] However, neither of these spectra is associated with a single earthquake scenario (i.e., a single magnitude, *M*, and site-to-source distance, *R*). Therefore, a limitation of this approach for evaluating liquefaction potential is the difficulty in determining an appropriate value of MSF to compute the CSR (see Equation 2).

As an alternative, the motions associated with one or more controlling earthquake scenarios can be used. These scenarios, called *modal events,* have the most significant contribution to the seismic hazard at the site. The *M* and *R* of the modal events can be determined from the deaggregation matrices for the 2,500-year UHS. The deaggregation matrices provide a breakdown of the percent contribution of a given earthquake scenario to each spectral acceleration defining the UHS. The deaggregation matrices can be obtained directly from the USGS website for spectral accelerations defining the 5 percent damped, 2,500-year UHS at periods of 0.0, 0.1, 0.2, 0.3, 0.5, 1.0 and 2.0 seconds.[16] As an example, the deaggregation matrices for 0.0- and 2.0-second spectral accelerations for Providence are plotted as histograms in Figures 3 and 4. As may be observed from these figures, the predominant modal event for the 0.0-second spectral accel-

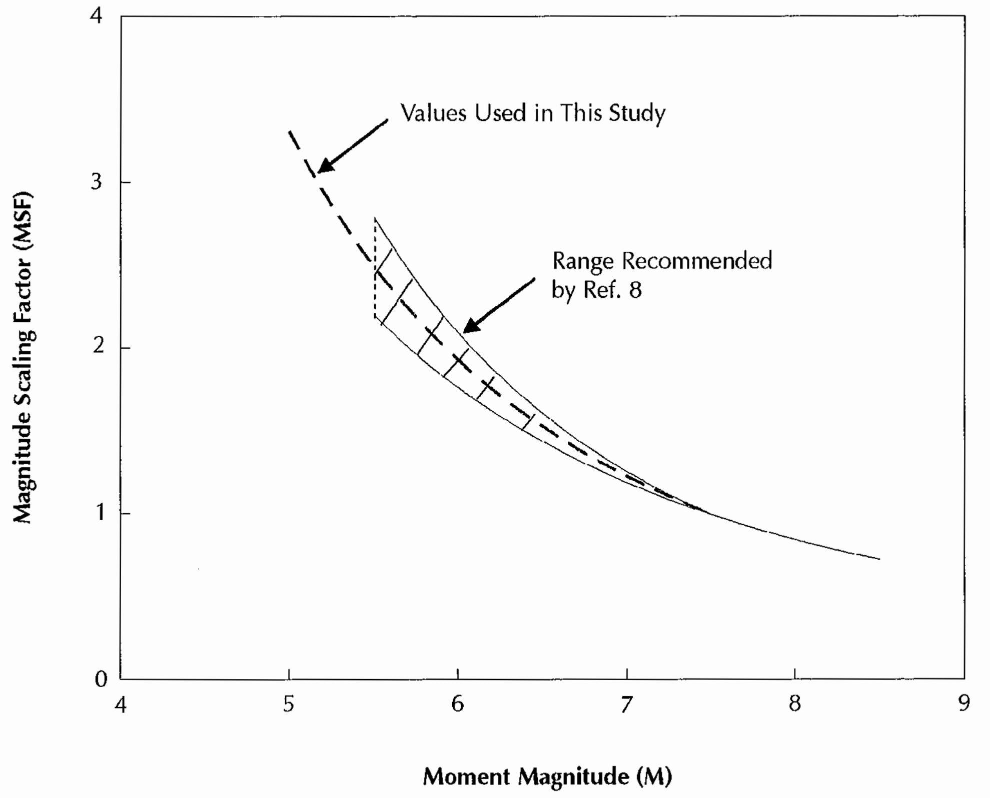

FIGURE 2. Magnitude scaling factors used in this study.

eration (*i.e.*, peak ground acceleration) is M of about 5 and R of about 15 kilometers. In contrast, the predominant modal event for the spectral acceleration corresponding to 2.0 seconds is M greater than 7 and R about 400 kilometers. Other modal events may be observed for both the peak ground acceleration and the 2.0-second spectral acceleration, but they are less pronounced than those identified.

For liquefaction evaluations, the modal events associated with the spectral accelerations at oscillator periods closest to the fundamental period of the site are of most interest. This is because motions corresponding to these events will induce the largest cyclic shear stresses in the soil column. A preliminary estimate of the fundamental period (T) can be made using the following equation:[21]

$$T = 4H/V_{S\,avg} \tag{3}$$

Where:

H = total thickness of the soil profile; and

$V_{S\,avg}$ = average shear wave velocity of the soil profile.

$V_{S\,avg}$ can be obtained by equating the travel time for a seismic wave to propagate from bedrock to the ground surface in the actual soil profile and an "equivalent" uniform profile:

$$V_{S\,avg} = \frac{H}{\sum_{i=1}^{m} \frac{h_i}{V_{Si}}} \tag{4}$$

Where:

h_i = thickness of sublayer i;

V_{Si} = shear wave velocity in sublayer i; and

m = total number of sublayers.

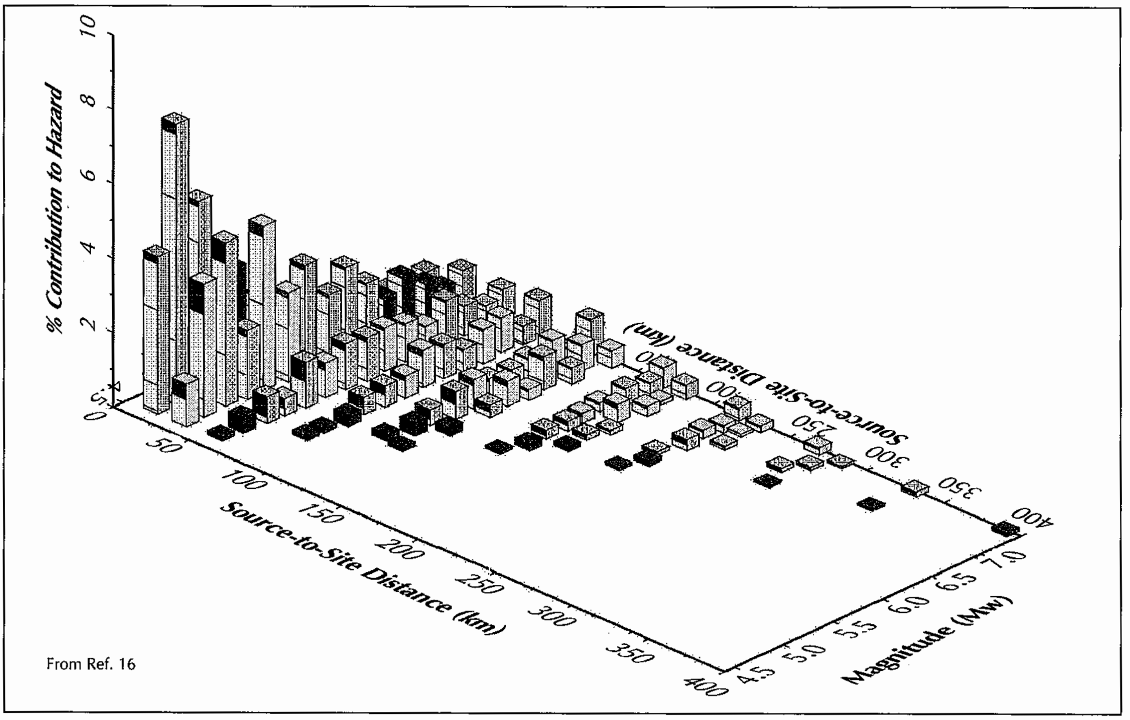

FIGURE 3. Deaggregation data for the study site for 2,500-year ground motions at a period of 0.0 seconds.

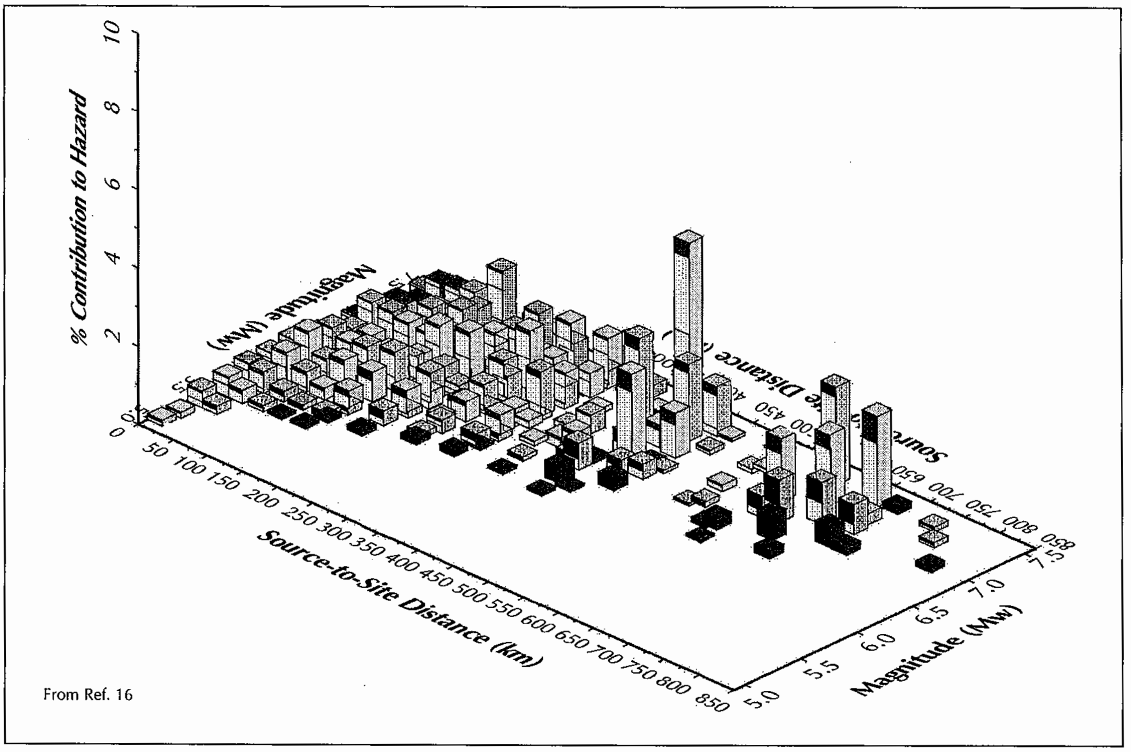

FIGURE 4. Deaggregation data for the study site for 2,500-year ground motions at a period of 2.0 seconds.

Using this equation, the fundamental period of the study site profile was determined to be approximately 0.85 seconds.

The closest oscillator periods for which the deaggregation matrices are provided by the USGS for the 5 percent damped, 2,500-year spectral accelerations are 0.5 and 1.0 seconds. Based on these matrices, two predominant modal events were identified:

- a small, local event with M approximately equal to 5.4 and R approximately equal to 15 kilometers; and,
- a large, distant event with M approximately equal to 7.4 and R approximately equal to 400 kilometers.

Having two predominant modal events corresponding to a small, local event and a large, distant event is characteristic of the seismic hazard in the central and eastern United States. Specific to Providence, the small, local event is associated with a background areal source used in the probabilistic seismic hazard analysis, and the large, distant event is associated with the Charlevoix Seismic Zone, which is located on the St. Lawrence River about 100 kilometers downstream (northeast) from Quebec City.

Obtaining earthquake records representative of these modal events is particularly difficult in the northeastern United States because there are limited recorded ground motions for earthquakes having M greater than or equal to 4.5. The only sizable events for which motions were recorded in this region were the 1988 M5.9 Saguenay earthquake and aftershocks, which occurred just south of Chicoutimi, Quebec, Canada, in a relatively aseismic region 75 kilometers north of the Charlevoix Seismic Zone. As a result, it is common practice in the Northeast to generate and use synthetic ground motions having characteristics representative of the modal events.

As an alternative to using synthetic motions, ground motion records from a database compiled by McGuire *et al.* were used.[22] McGuire *et al.* "scaled" motions recorded in active seismic regions (*i.e.*, inter-plate motions) using response spectral transfer functions that relate active seismic region motions to stable continental region motions (*i.e.*, intra-plate motions).[22] The transfer functions were based on a single-corner, point source model.[22-24] The use of scaled motions is preferred over synthetic ones because the former preserve many of the characteristics of the original recorded motions, particularly the distribution of energy over the time of shaking. An example of a scaled time history and associated response spectrum is shown in Figure 5.

TABLE 1.
Binned Scaled Rock Motions

Bin	M	R (km)
1	5-6	0-50
2	5-6	50-100
3	6-7	0-10
4	6-7	10-50
5	6-7	50-100
6	6-7	100-200
7	7+	0-10
8	7+	10-50
9	7+	50-100
10	7+	100-200

Note: M is defined using the moment magnitude scale and R as the closest distance to the fault.

McGuire *et al.* binned the scaled rock motions in their database according to magnitude (M) and site-to-source distance (R).[22] In general, motions recorded on profiles having an average shear wave velocity of the upper 30 meters (V_{S30m}) greater than 360 meters per second were classified as "rock motions." This criterion includes NEHRP site classes A, B, and C.[14] The motions were further subdivided into 10 M-R bins, each containing at least 30 records. These bins were as noted in Table 1.

For each of the predominant modal events identified above, six representative time histories were selected from the McGuire *et al.* database.[22] The records for the large, distant event (*i.e.*, M approximately 7.4 and R approximately 400 kilometers) were taken from Bin 10 (see Table 1). Additional scaling was then applied

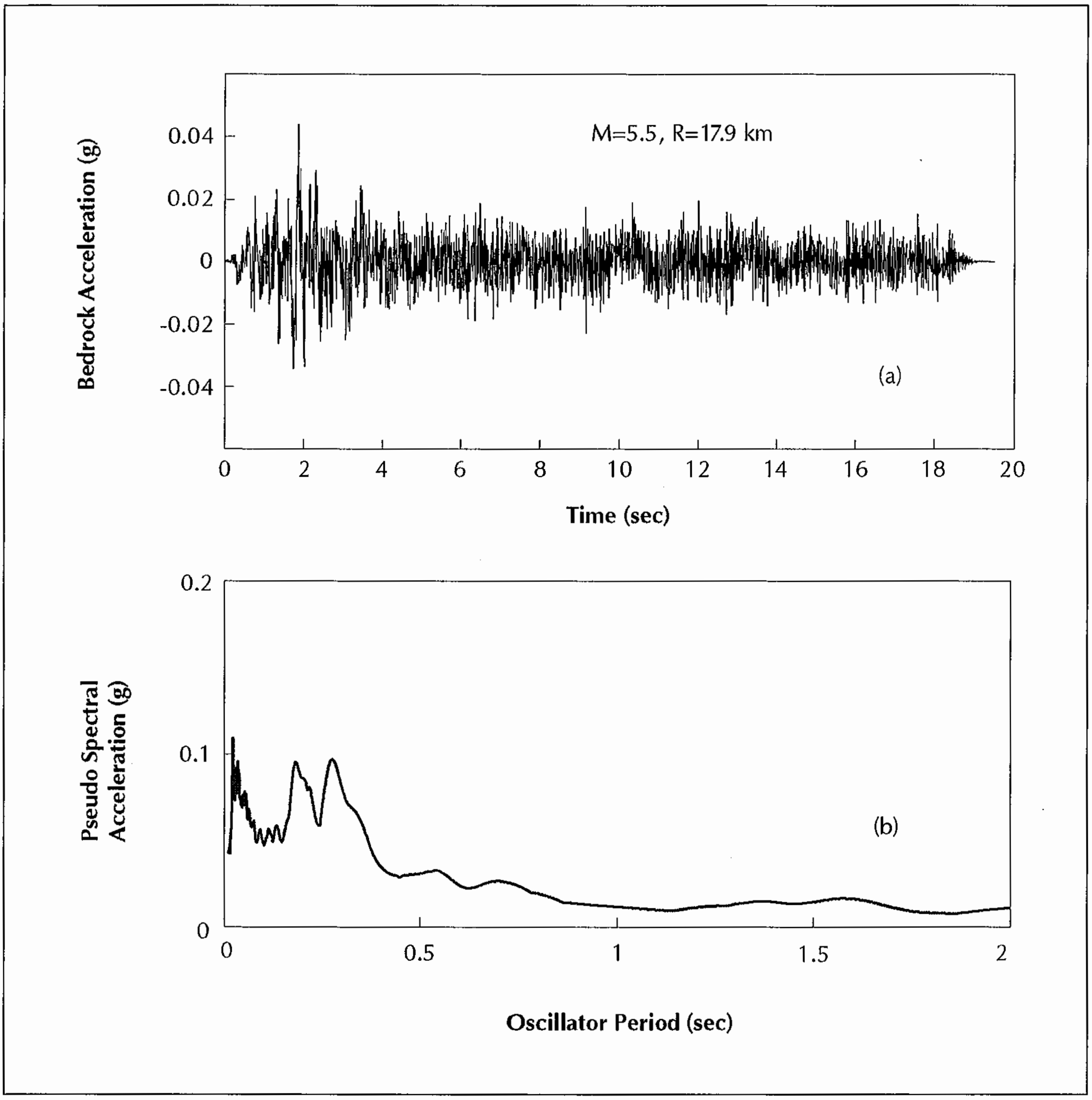

FIGURE 5. An example of a) scaled bedrock time history used in the site response analyses and b) the corresponding 5 percent damped response spectrum.

to these records to account for differences in the site-to-source distances. The scaling approach used was the same as that used by McGuire *et al.* to initially scale the motions. Although there are other studies in which the amplitude of recorded motions were scaled to match the 2,500-year spectral acceleration at a specific oscillator period, this scaling was not done since the basis for this additional amplitude scaling is questionable. The approach used herein is a straight deterministic analysis where the earthquake scenarios used in the analysis corresponded to the predominant modal events from the deaggregation of the probabilistic seismic hazard.

The twelve selected records were used in the site response analyses to compute the CSR induced in the soil profile as a function of depth. The median CSR profiles for each modal event are shown in Figure 6. As shown in this figure, the CSR profile for the smaller, local event is significantly higher than that for the larger, distant event, although both CSR profiles are relatively low.

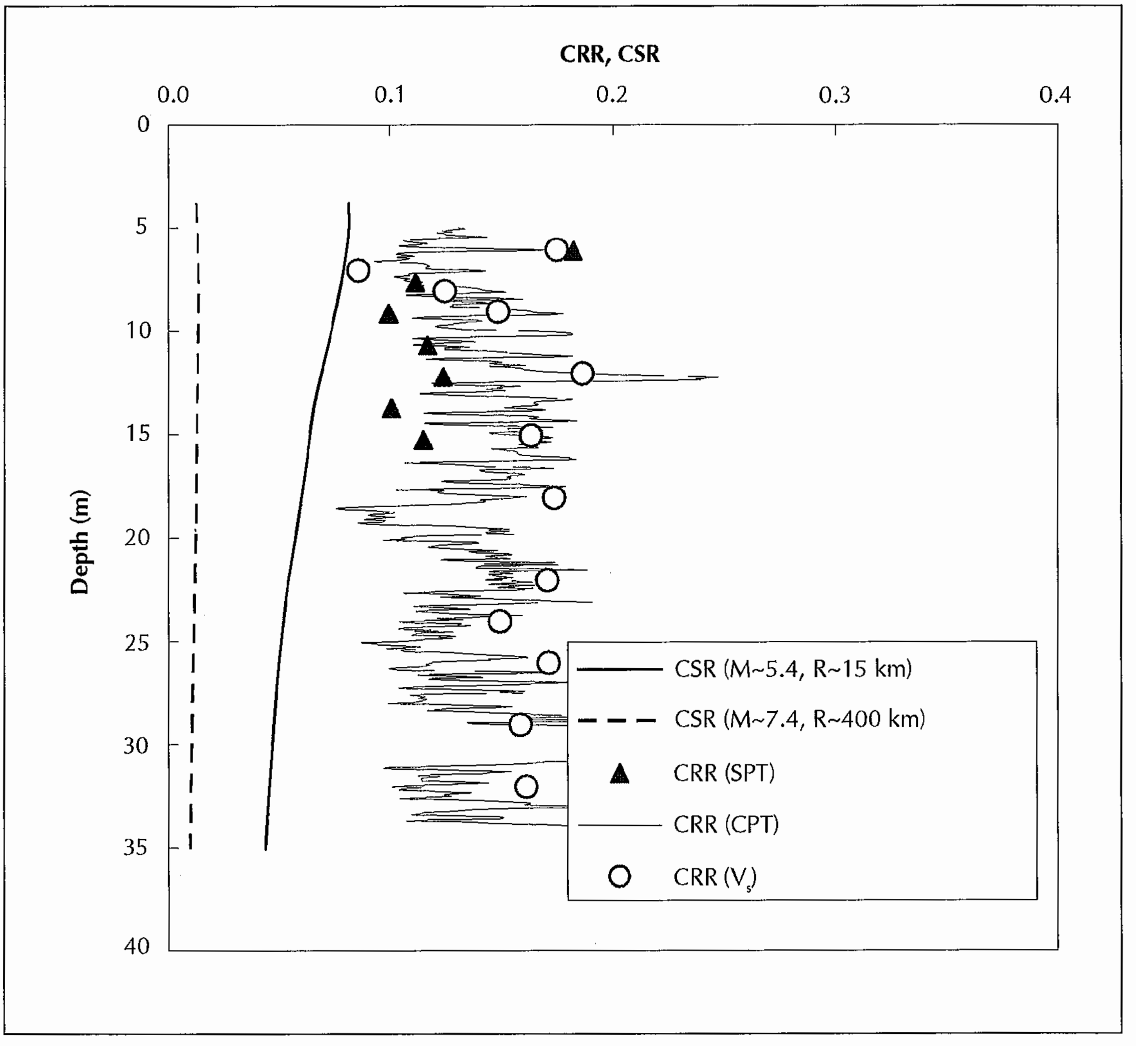

FIGURE 6. CSR profiles for a small magnitude, local event and a large magnitude, distant event and CRRs estimated using the SPT-, CPT- and VS-based methods.

Cyclic Resistance Ratio (CRR). To avoid problems associated with sample disturbance, the trend since the early 1980s has been to use in-situ test-based correlations to estimate cyclic resistance of soils.[25] Correlations with three different types of in-situ tests were used to estimate cyclic resistance at the site including the SPT, CPT and shear wave velocity (V_S). The former two were existing correlations, while the latter was developed specifically for the silt encountered at the study site.

The SPT-based approach was initially proposed independently by Seed and Idriss,[26] and independently by Whitman.[27] The current standard-of-practice is described in Youd *et al.*[8] and utilizes the data and correlations of Seed *et al.* with some modifications.[28] Cyclic resistance is correlated to $(N_1)_{60}$, defined as the blow count corrected to an effective overburden stress of 1 atmosphere (approximately 100 kPa) and a hammer efficiency of 60 percent. Since the majority of the soils used to develop the CRR correlation contained less than 35 percent fines, there is some uncertainty in using the existing correlations with the pure non-plastic silts commonly encountered in the Providence area.[29] However, the CRR profile for the site was computed using the $(N_1)_{60}$ values and the recommended fines corrections down to a depth of about 15 meters and is plotted in Figures 6. As

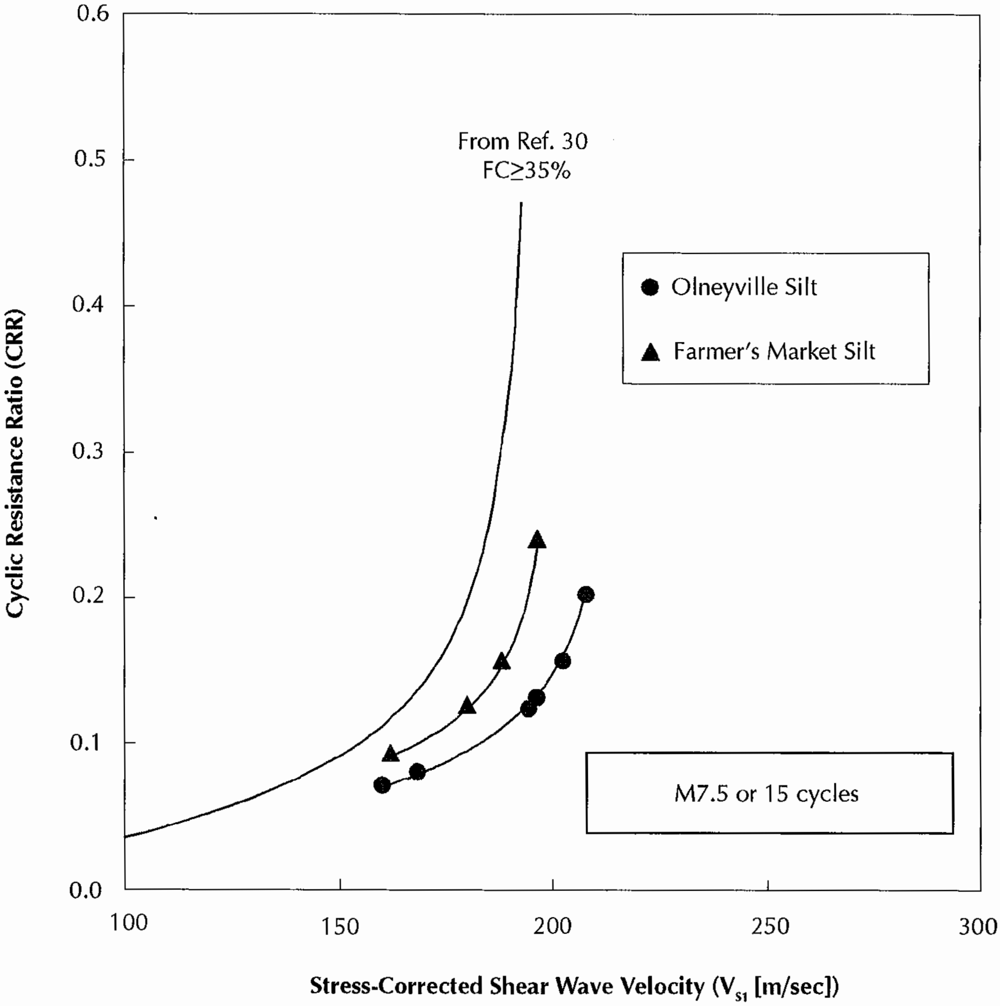

FIGURE 7. Shear wave velocity-based cyclic resistance correlations developed for two Providence silts, including silt recovered from the Farmers' Market site (after Ref. 9). The field based correlation developed by Andrus and Stokoe (Ref. 31) is also shown.

shown in Figure 6, the CRR at a depth of 6 meters is approximately 0.18 and then drops to approximately 0.1 at greater depths.

The procedure developed by Robertson and Wride forms the current standard of practice for evaluating liquefaction potential using CPT.[8,30] This approach correlates CRR with cone tip resistance normalized (q_{c1N}) to an effective overburden stress of 1 atmosphere (about 100 kPa). Like the SPT-based procedure, the cyclic resistance correlation was developed from case histories in relatively clean sands containing less than about 35 percent fines, and its applicability for the Providence silt is uncertain. Using q_{c1N} values for the study site (see Figure 1) and the recommended fines corrections, the CRR profile for the site was computed down to a depth of about 34 meters and is plotted in Figure 6. As shown in that figure, the CRR for the profile varies between about 0.1 to about 0.19 for the depths analyzed.

The current state-of-practice for evaluating liquefaction resistance using shear wave velocity field data was developed by Andrus and Stokoe,[31] and is also described in Youd *et al.*[8] The correlation relates CRR to shear wave velocity (V_{S1}) normalized to an effective overburden stress of 1 atmosphere. Recently, Baxter *et al.* developed similar correlations from an extensive laboratory study of two Providence silts, including silt obtained from the Farmers' Market site.[9] These two new correlations are shown in Figure 7. Cyclic triaxial tests were performed on both reconstituted[32] and block samples of the silt, where the V_S of the samples was measured using bender elements that were incorporated into the triaxial apparatus.[9] The difference between the two laboratory curves shown in Figure 7 further supports previous research in sands that has suggested that CRR-V_{S1} correlations are soil specific. Also note that the use of Andrus and Stokoe's field-based correlation for fines content (FC) greater than or equal to 35 percent would overestimate the CRR of the Providence silts.

The CRR-V_{S1} correlation developed for the Farmers' Market silt, shown in Figure 7, was used to calculate the CRR profile down to a depth of about 33 meters and is plotted in Figure 6. Note that the majority of the V_{S1} values for the profile (see Figure 1) fell within the range of the CRR correlation shown in Figure 7. As shown in Figure 6, the CRR for the profile reaches a low of approximately 0.09 at a depth of about 7 meters and then progressively increases over the next 3 meters, reaching a relatively constant value of about 0.16 for greater depths.

Discussion of Results

There is some uncertainty when using the SPT- and CPT-based CRR correlations for silt because these correlations were developed primarily from soils having fines contents less than 35 percent. The soil-specific V_S correlation is most representative of the in-situ strength of the silt at the study site, and was used as a baseline for a comparison of SPT- and CPT-based methods.[33] As shown in Figure 6, there is good agreement between the CRR values predicted by the CPT and soil-specific V_S correlations. In contrast, the SPT-based correlation consistently predicted the lowest CRRs. This occurrence is most likely due to the higher uncertainty of the SPT method itself,[34,35] with the increased scatter in the SPT data resulting in a more conservative placement of the cyclic resistance curve.

Figure 6 also illustrates some of the benefits of using CPT to evaluate liquefaction resistance. First, an almost continuous profile of CRR is obtained, which allows improved characterization of thin strata. Also, unlike SPT, CPT is entirely automated and, thus, less subject to human error that inherently leads to lower uncertainty in the results. However, from experience at other sites, both SPT and CPT may give erroneously high resistances in soil containing gravel; in which case the V_S-based procedure is a viable alternative for estimating cyclic resistance.

Liquefaction is predicted at depths where the CSR is greater than or equal to the CRR resulting in a factor of safety less than or equal to unity (see Equation 1). As shown in Figure 6, the factor of safety against liquefaction is significantly greater than one for the CSR profile computed for the large, distant earthquake. For the small local event, the factor of safety is also greater than one at all depths evaluated, although it is close to one at a depth of approximately 7 meters when the CRR is estimated using the soil-specific V_S correlation. Therefore, the analysis suggests that for the earthquake scenarios that contribute the most to the 2,500-year earthquake ground motions, there is a low potential for liquefaction at the site.

Summary & Conclusions

Recent geological, seismological and paleoseismological studies in the northeastern United States provide important clues regarding past occurrences of soil liquefaction in this region and, hence, highlight the future potential for liquefaction. Assessing liquefaction potential in the Providence, Rhode Island, area is complicated because of the uncertainty in the seismic ground motions as well as the uncertainty of the cyclic resistance of the silts that underlie the city. To provide insight on this issue, a deterministic evaluation of liquefaction potential at a study site in Providence using a cyclic stress-based approach was presented.

The CSR was estimated for two earthquake scenarios. These scenarios corresponded to the two predominant modal events identified in the deaggragation matrices obtained from the USGS for the 2,500-year spectral accelerations for oscillator periods closest to the fundamental period of the site. The two scenarios considered were a small event (M5.4) occurring locally, and a large event (M7.4) originating from the Charlevoix Seismic Zone, Canada. The CRR of the silt at the study site was evaluated using empirical correlations based on SPT blow count, CPT tip resistance and in-situ shear wave velocity. The shear wave velocity correlation used in the analysis was developed from an extensive laboratory study[9] using the silt recovered from the study site. A comparison of the CRRs resulting from the three correlations suggests that the SPT-based method gave the lowest predictions, while the CPT-based method provided the highest resolution with depth.

Comparing the CSR and CRR predictions indicate that there is a low potential for liquefaction at the study site. However, given that the results depend to a large extent on the site characteristics, this finding is only applicable to the study site. This narrow finding further reinforces the need to perform site-specific evaluations of liquefaction potential for a given project.

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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.

FRANCIS E. GRIGGS, JR.

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

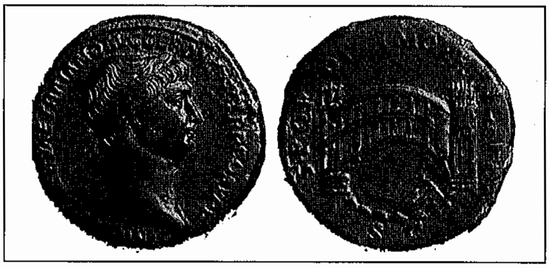

FIGURE 1. A coin issued in 105 showing Trajan and an idealized single-span bridge on the reverse.

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

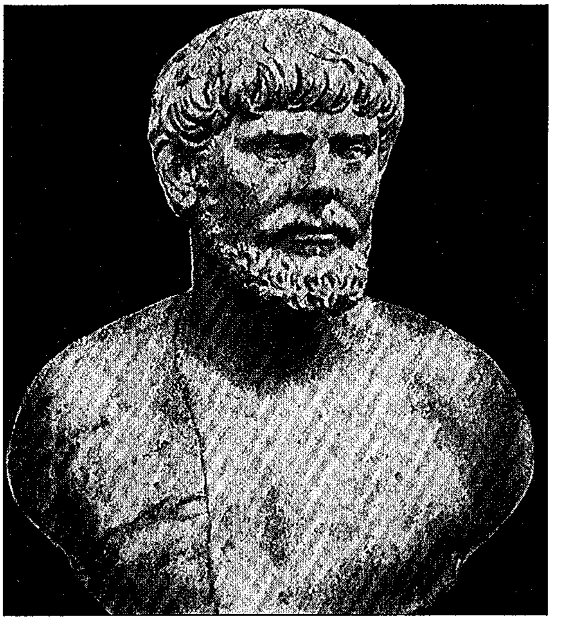

FIGURE 2. Apollodorus.

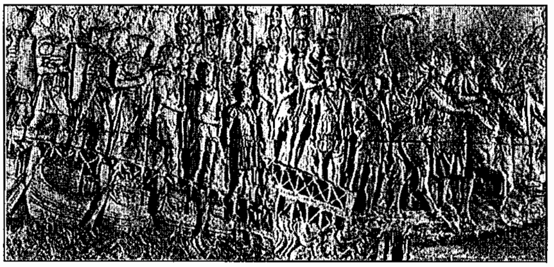

FIGURE 3. Trajan' s pontoon bridge, probably at or near future bridge site. (Note the double truss was over a wider part of the river.)

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

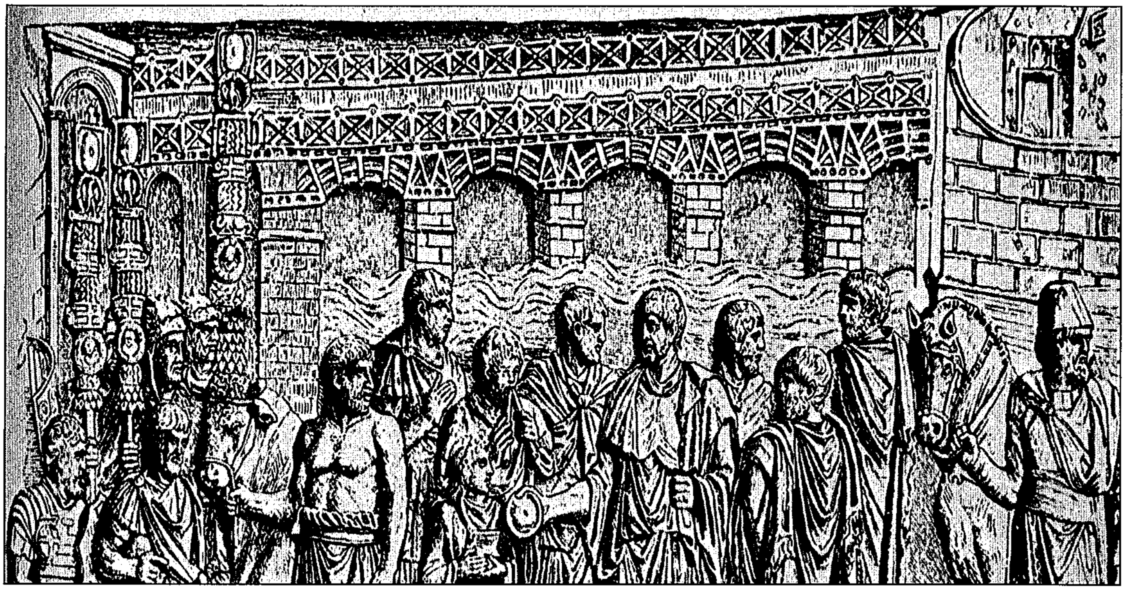

FIGURE 4. Trajan's Bridge, with Trajan in the center with his right hand extended.

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

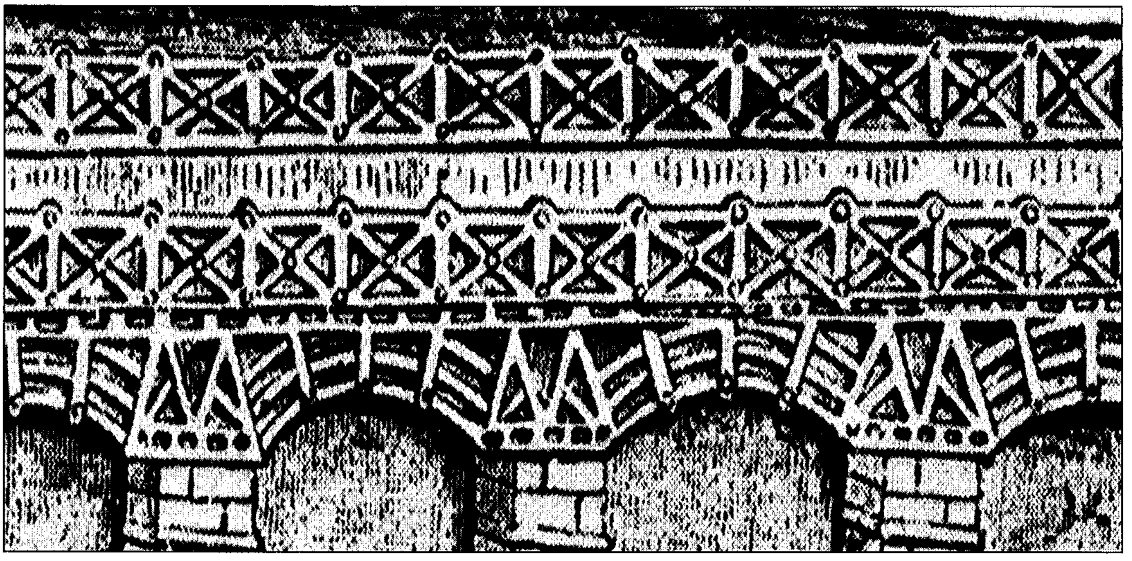

FIGURE 5. A close-up of Trajan's Bridge showing the central portion of the bridge.

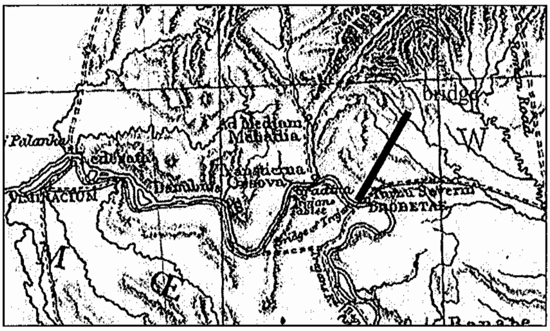

FIGURE 6. The location of Trajan's Bridge at a bend in Danube River near Drobeta. (From Ref. 3.)

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.

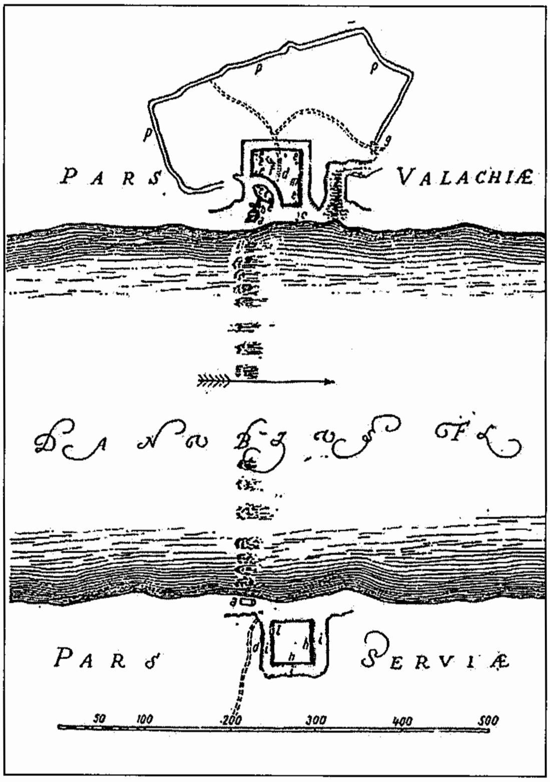

FIGURE 7. Marsigli's map of the site.

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]

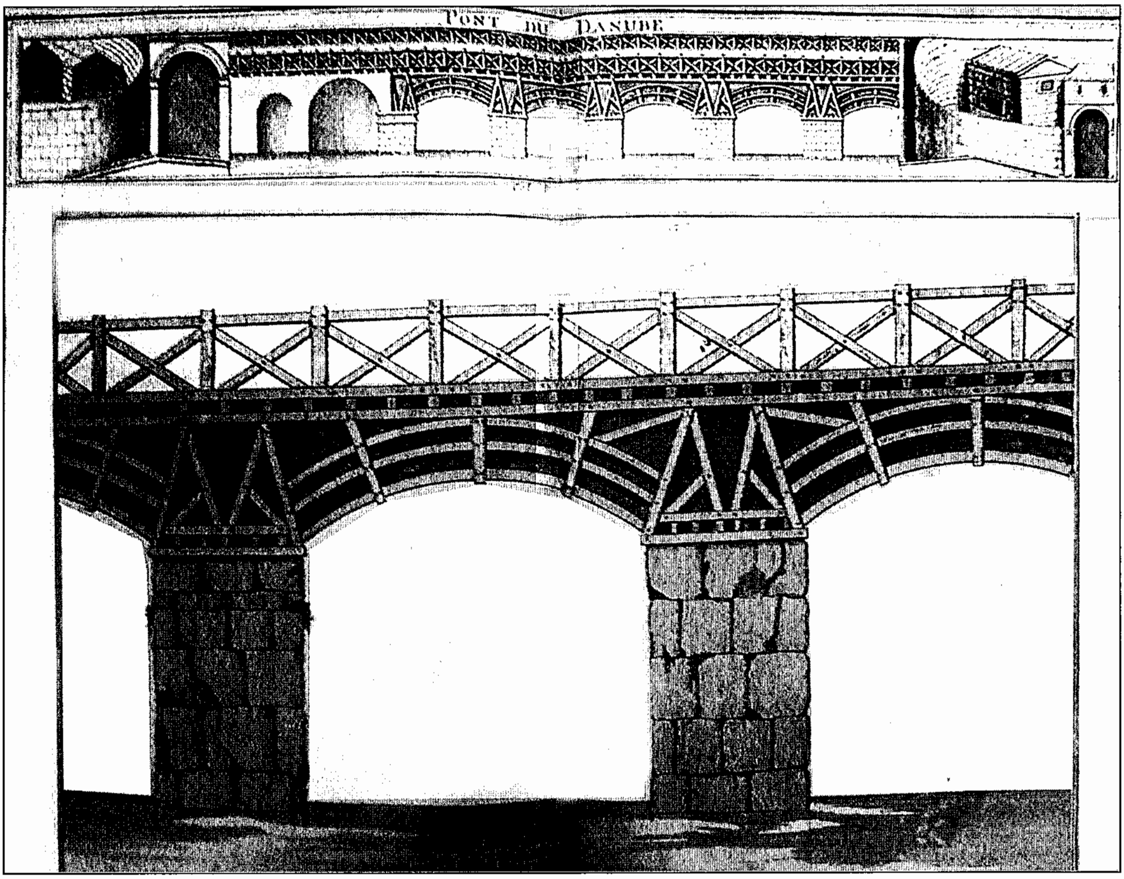

FIGURE 8. Montfaucon's bridge plan from 1722.

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

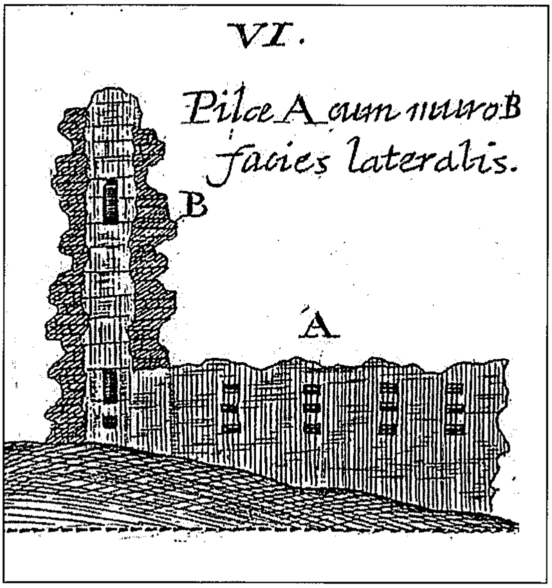

FIGURE 9. Cross-section of the Serbian abutment (by Marsigli).

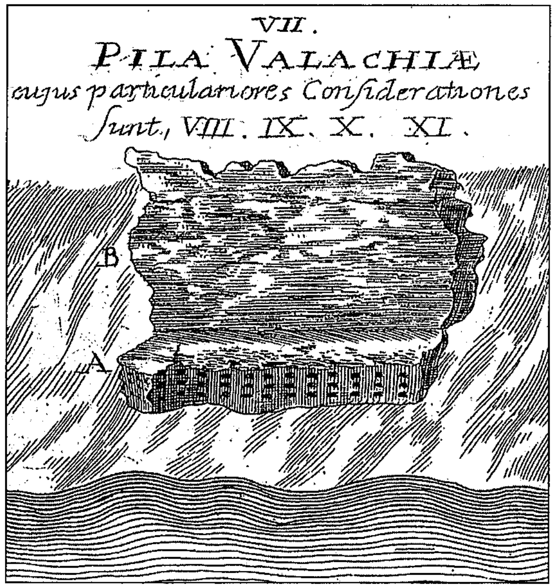

FIGURE 11. A view of the Romanian abutment (from Marsigli).

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.

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-

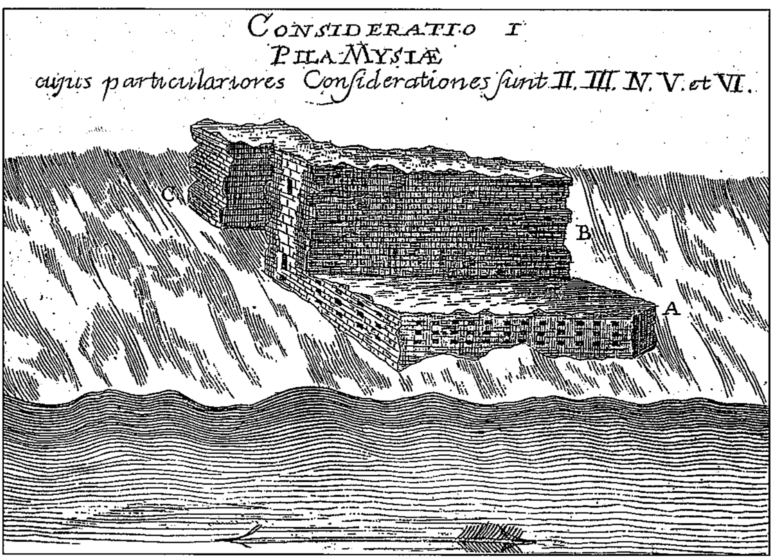

FIGURE 10. A view of the Serbian abutment (from Marsigli).

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

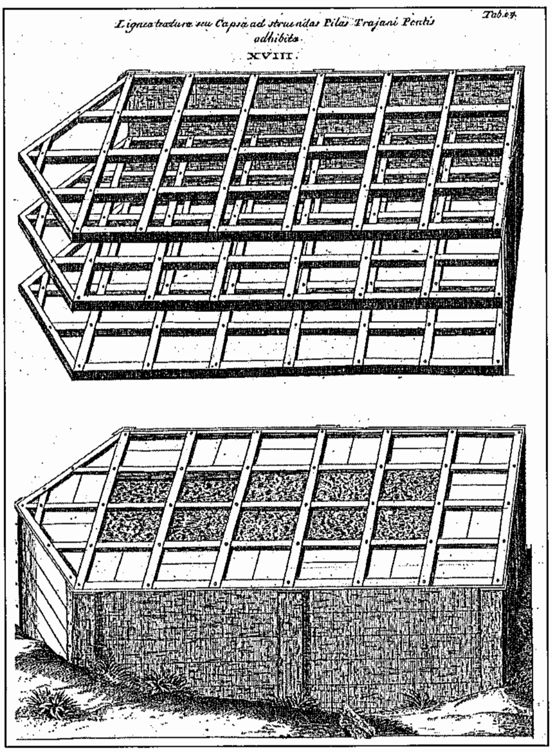

FIGURE 13. Marsigli's suggested pier caisson.

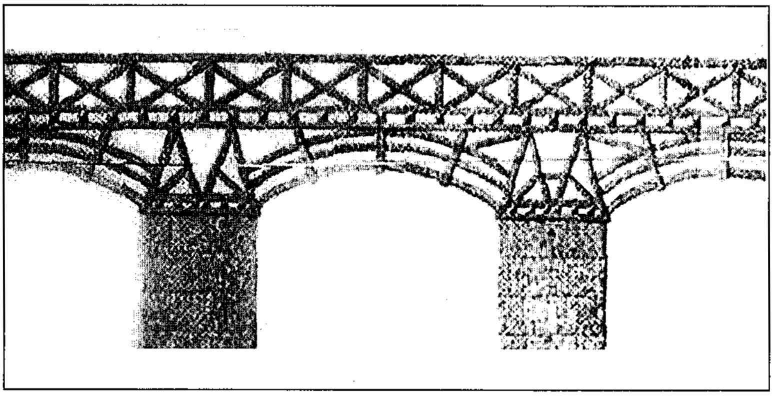

FIGURE 14. Trajan's Bridge as envisioned by Rondelet in 1810.

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

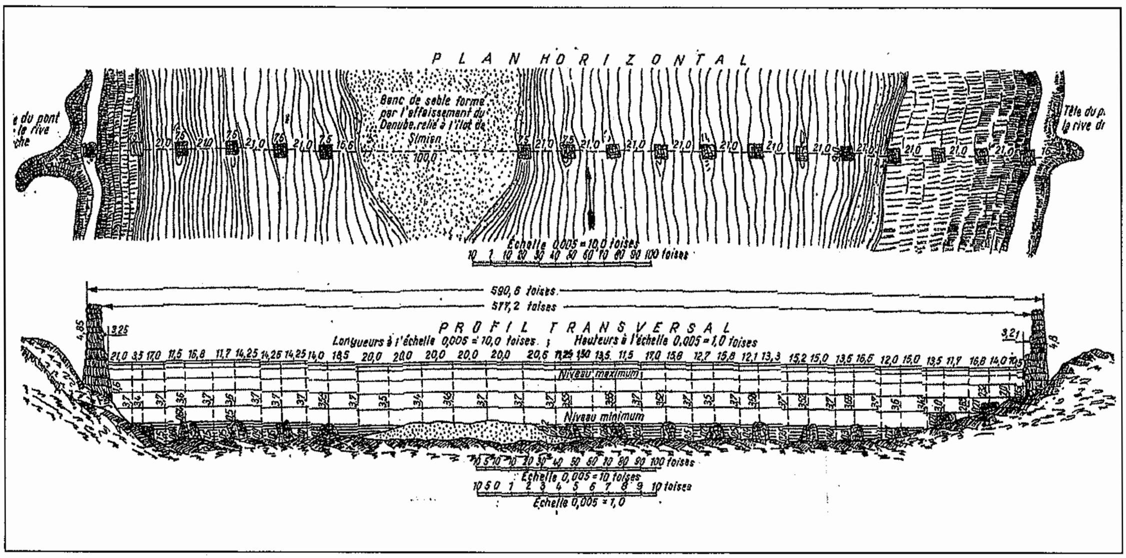

FIGURE 15. Popovici's plan and profile from 1858 (profile on 10 horizontal to 1 vertical).

(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).

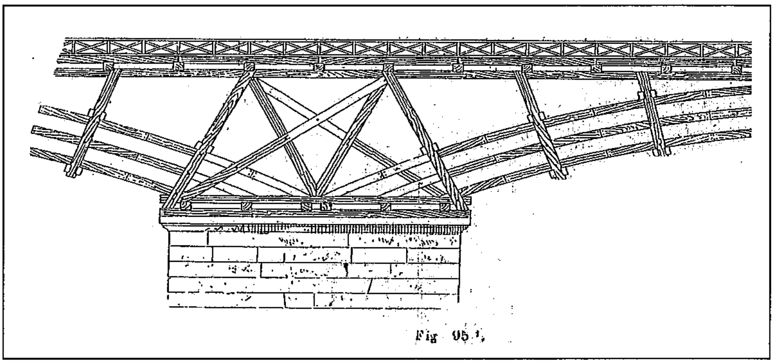

FIGURE 16. Choisy's framing.

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.

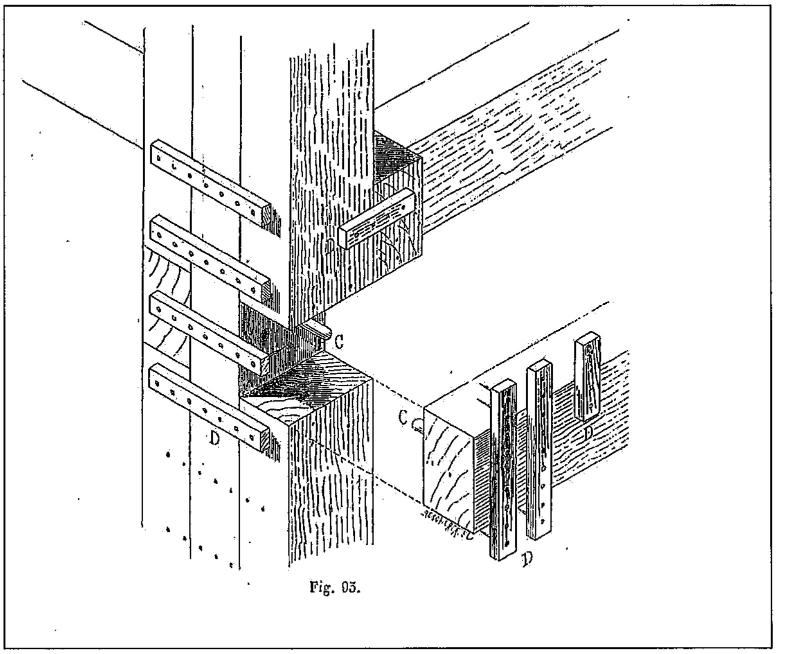

FIGURE 17. Choisy's framing.

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-

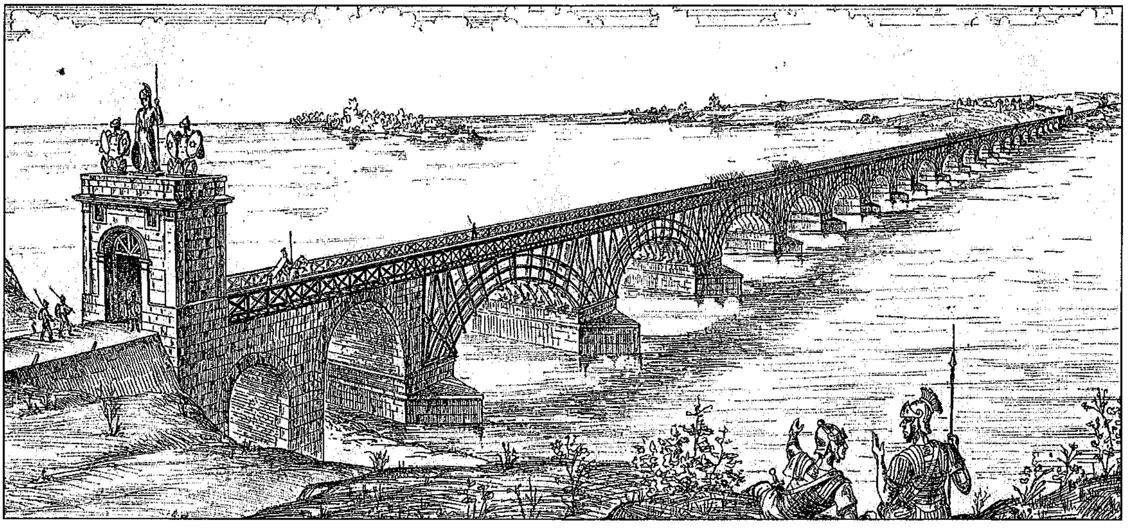

FIGURE 18. Duperrex's re-creation of Trajan's Bridge from 1907.

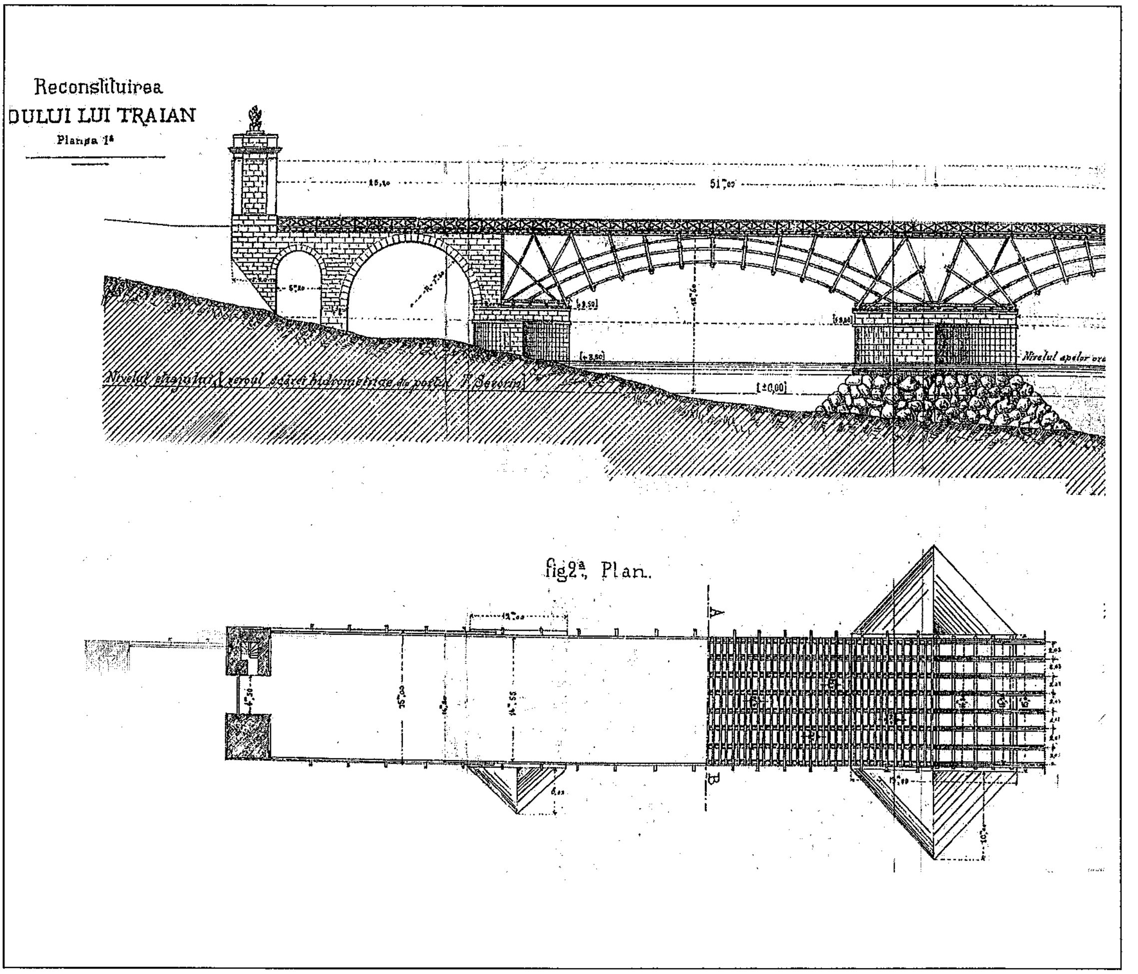

FIGURE 19. Duperrex's sketch of the end of bridge plan and profile.

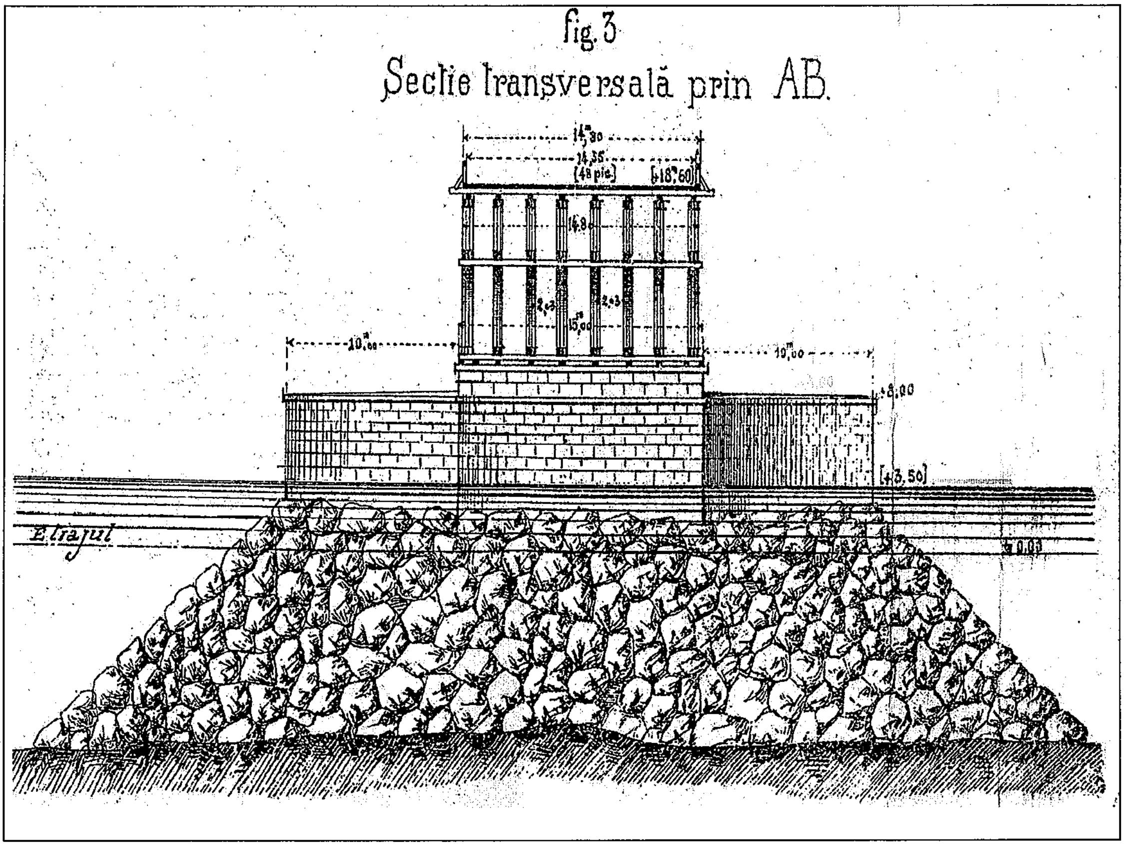

FIGURE 20. Duperrex's cross-section of the bridge.

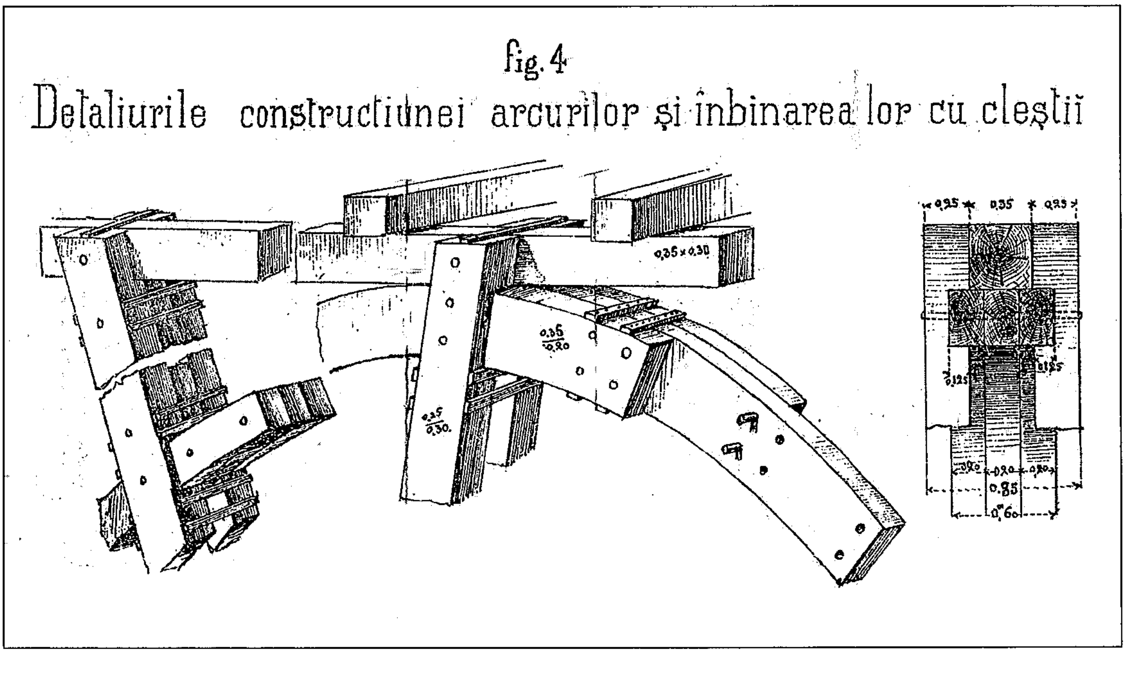

FIGURE 21. Duperrex's proposed framing for arches and radials.

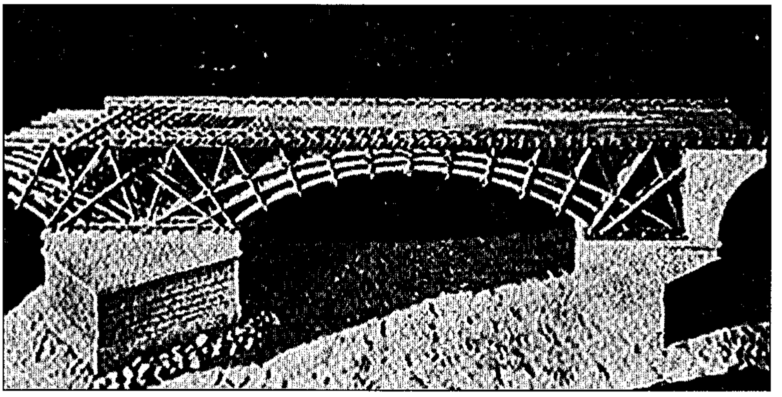

FIGURE 22. Gazzola's model of the bridge.

- 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

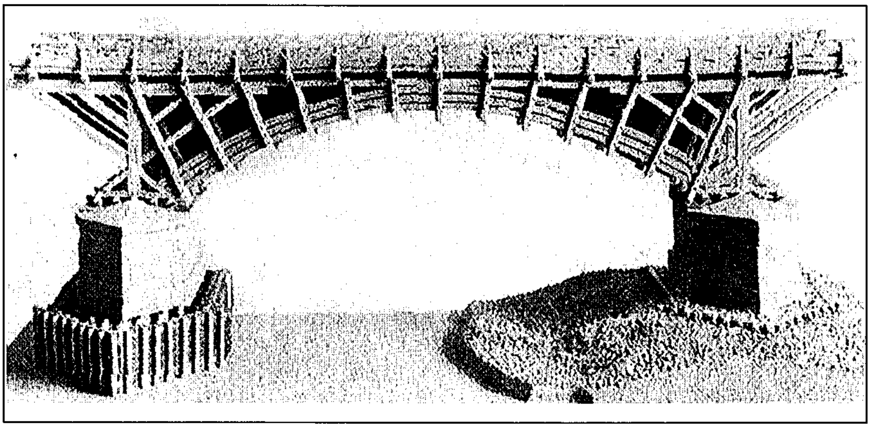

FIGURE 23. Model of a Roman bridge at Mainz that is similar to Trajan's Bridge.

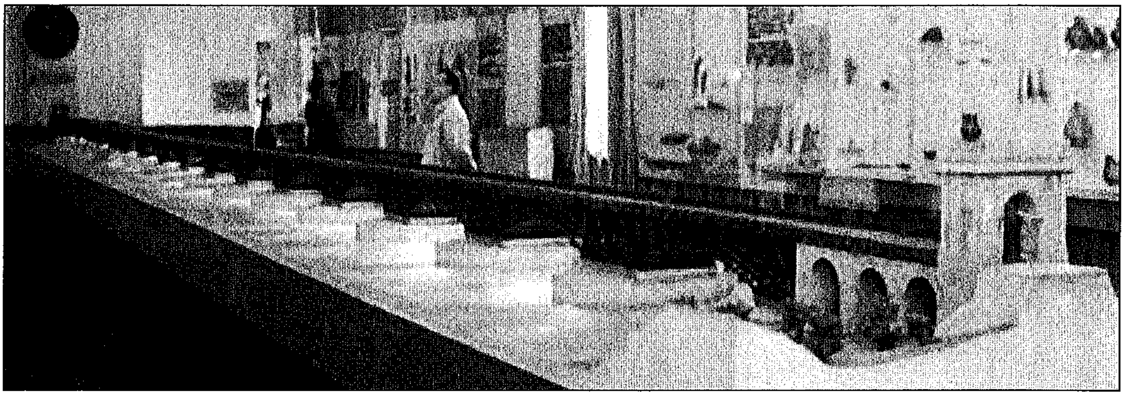

FIGURE 24. Model at the Iron Gates Museum, Drobeta, Romania.

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

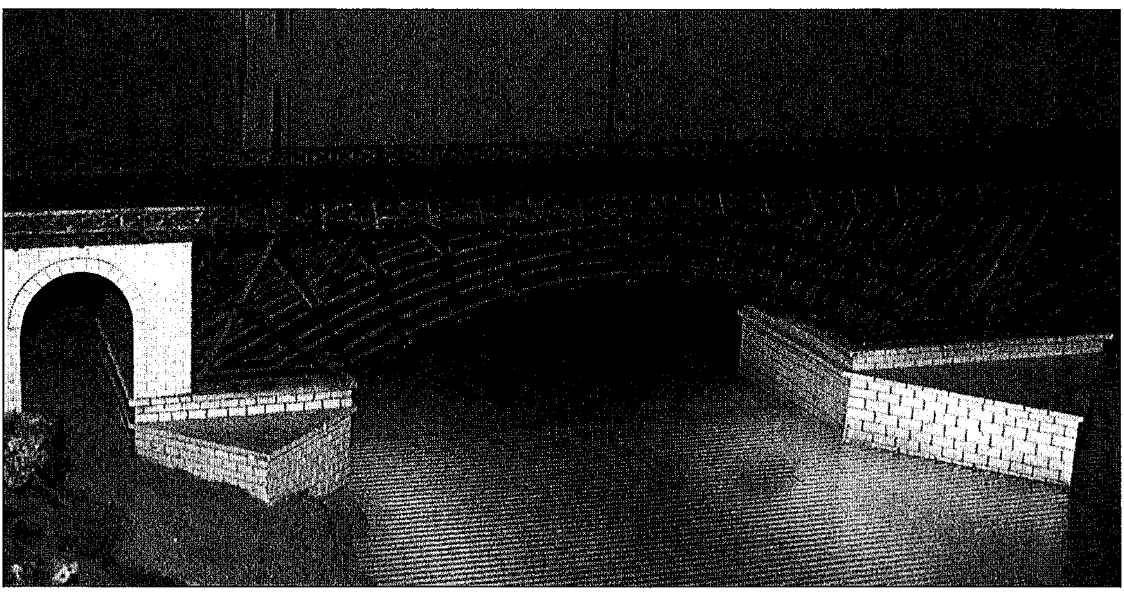

FIGURE 25. Close-up of a typical span from model at the Iron Gates Museum. It has eleven radial posts with several end struts.

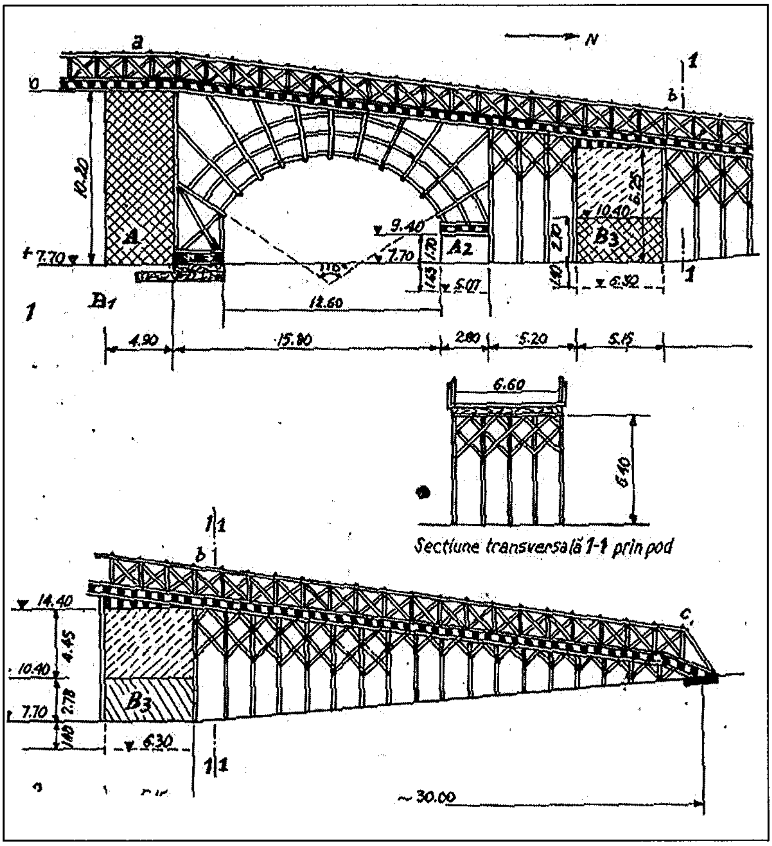

FIGURE 26. Hopkins's version of an approach to the bridge.

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

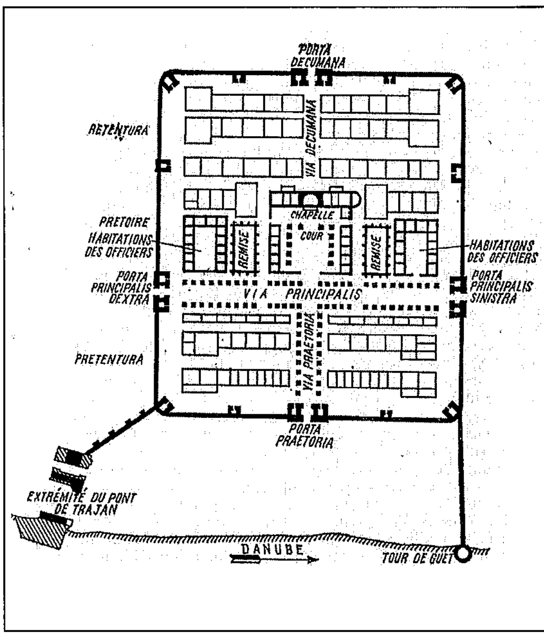

FIGURE 27. An approach to the bridge as envisioned by Tudor.

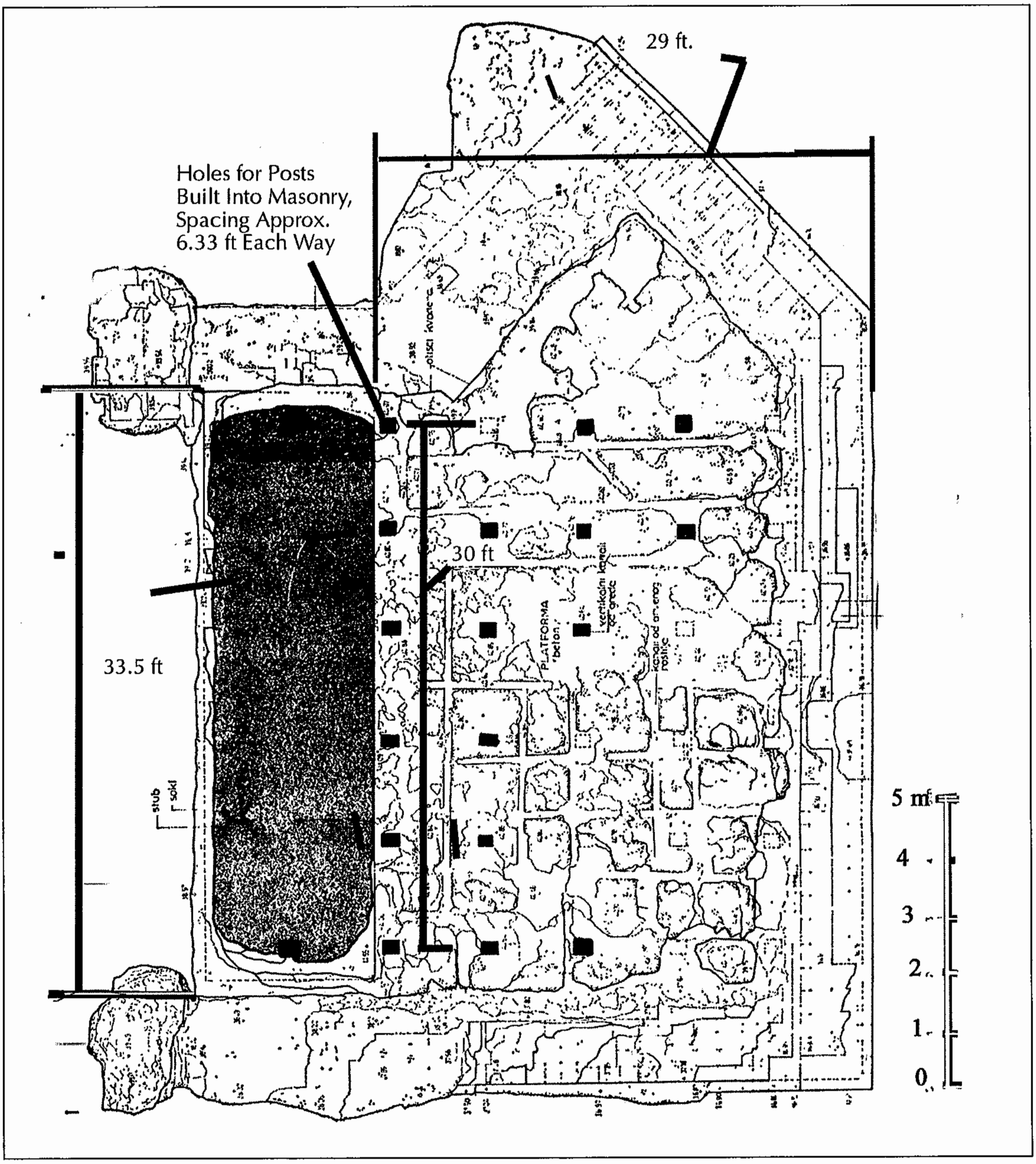

FIGURE 28. Garasanin and Vasic's plan modified with notes.

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

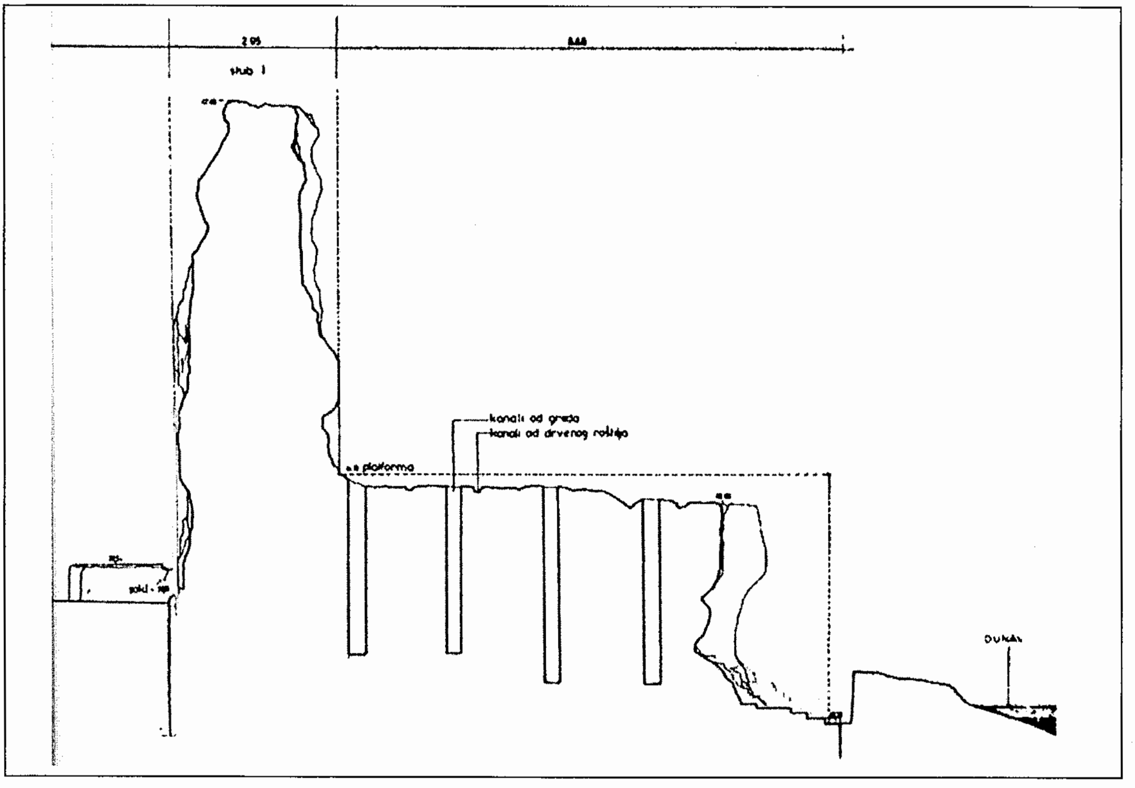

FIGURE 29. Elevation view of westerly abutment, by Garasanin and Vasic.

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

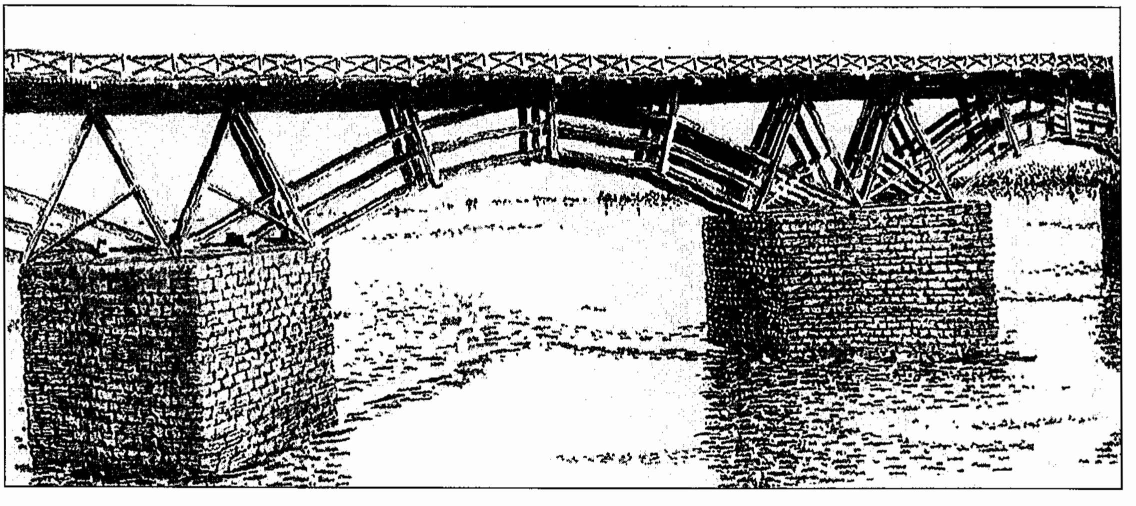

FIGURE 30. O'Connor's sketch of typical span.

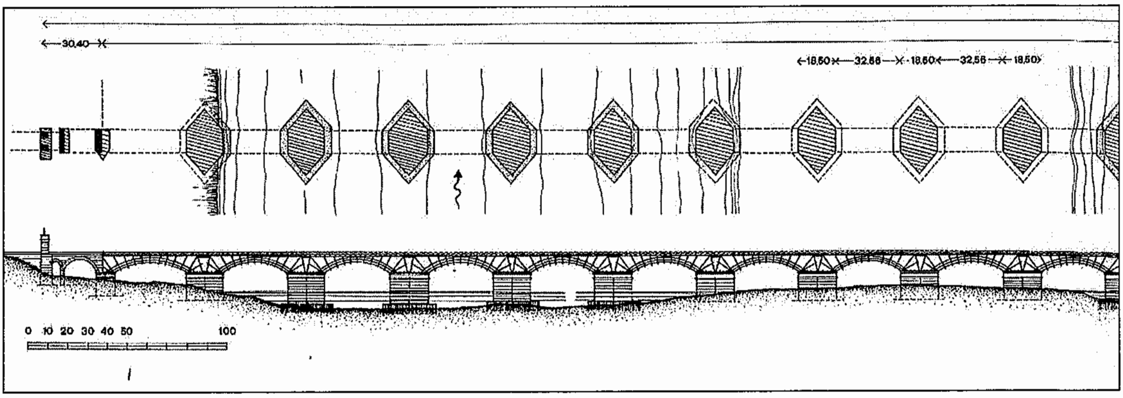

FIGURE 31. Galliazzo's vision of the bridge.

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

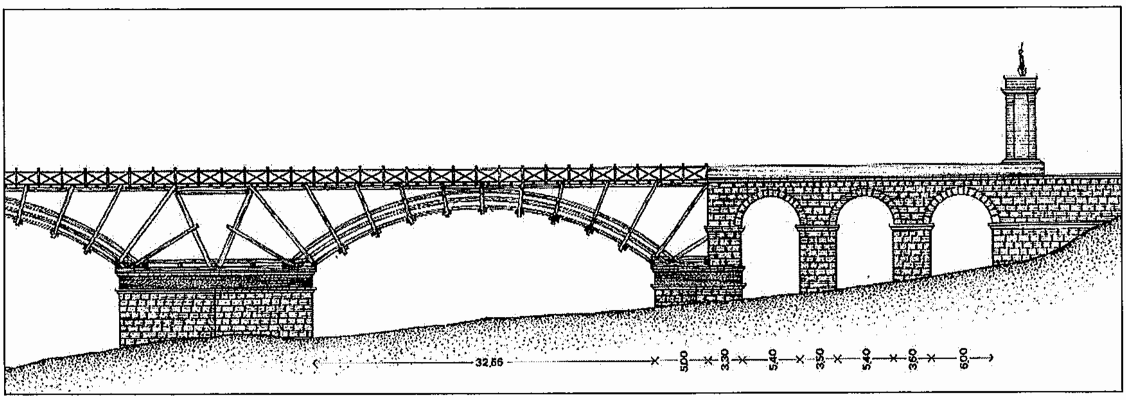

FIGURE 32. Galliazzo's version of the bridge showing the masonry approach on the Serbian side of river.

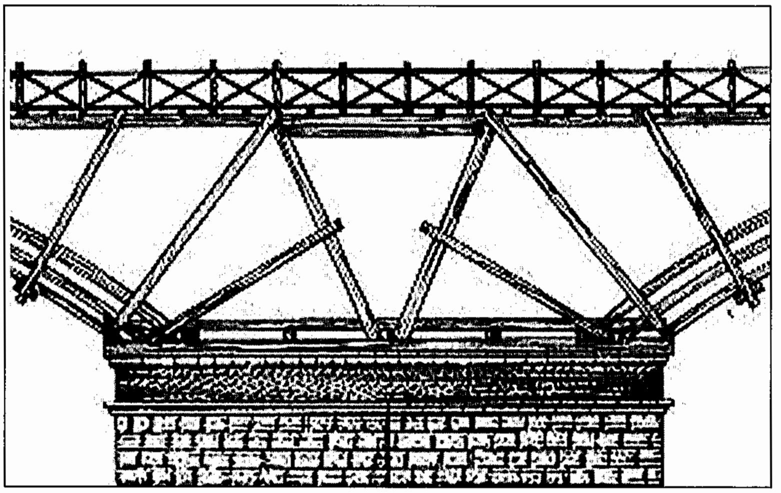

FIGURE 33. Close-up of framing on a pier (from Galliazzo).

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, 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]

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.

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

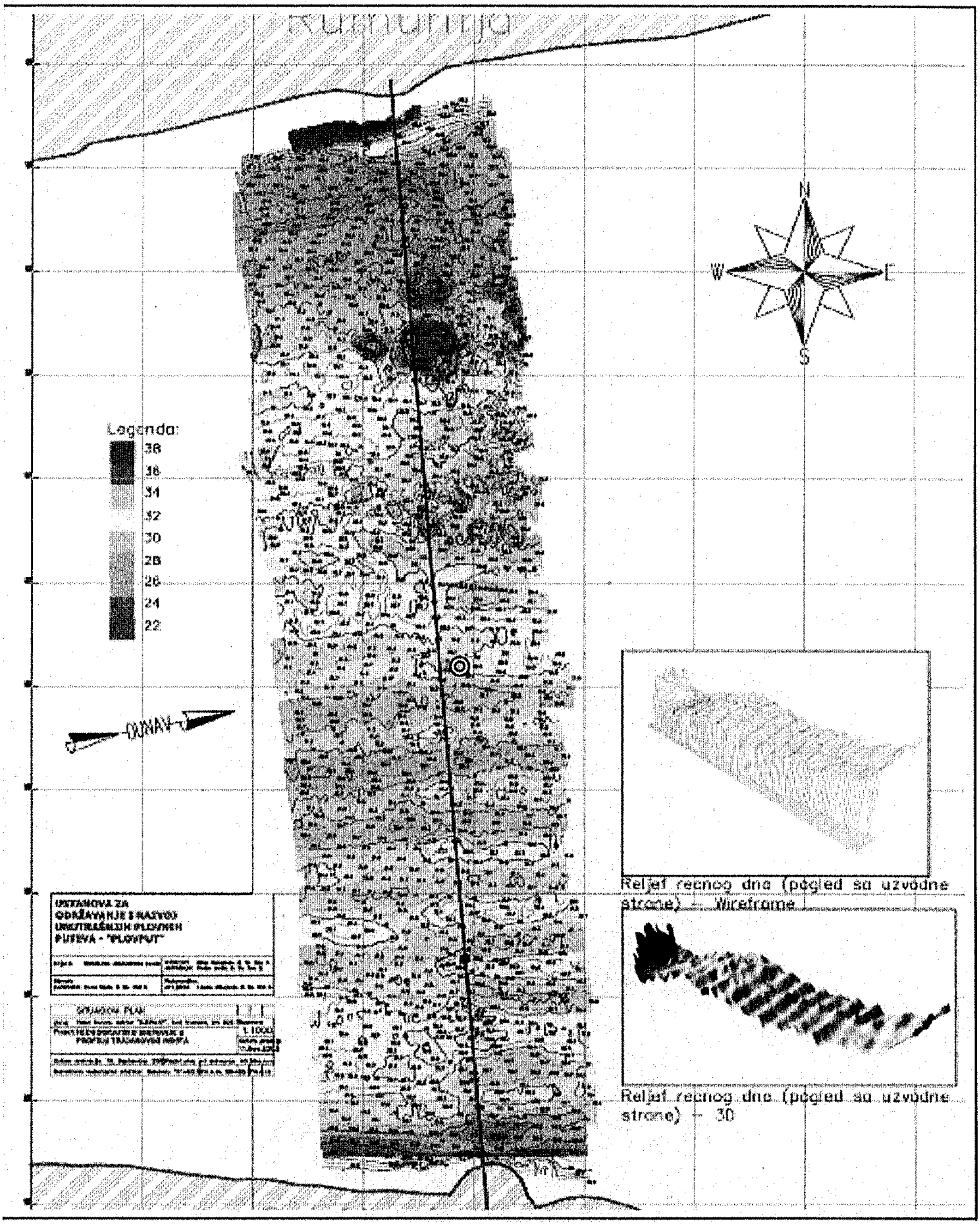

FIGURE 34. A contour map of the riverbed by Karovic and Nenadovic.

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]

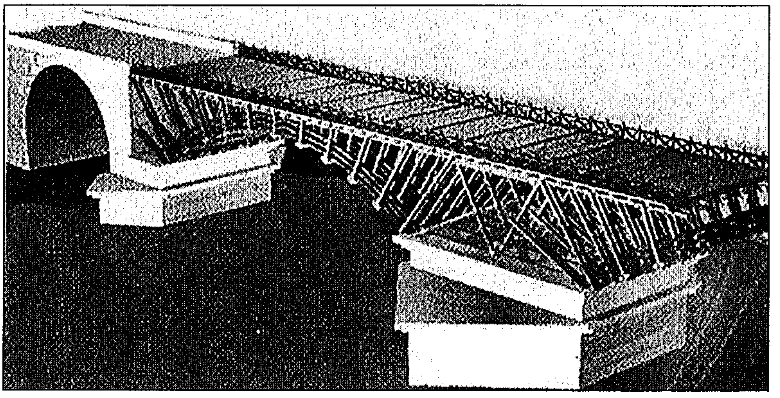

FIGURE 35. CAD model of the bridge by Ceraldi and Ermolli.

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.

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

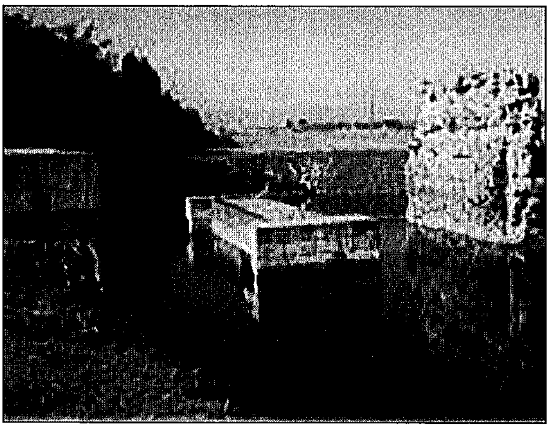

FIGURE 36. Abutment on the Romanian side of river showing remains of the end of the main bridge (on right) and foundation for the flanking masonry arches.

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

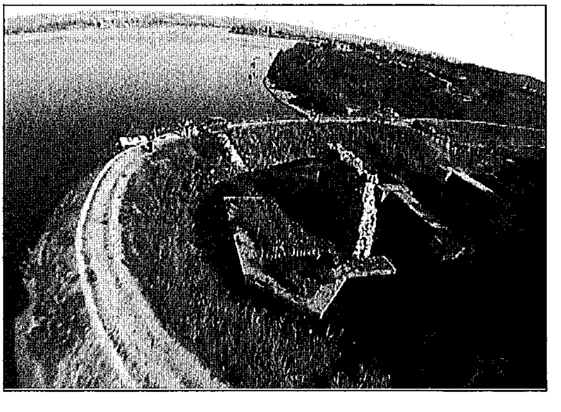

FIGURE 37. Romanian abutment encased in fill.

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

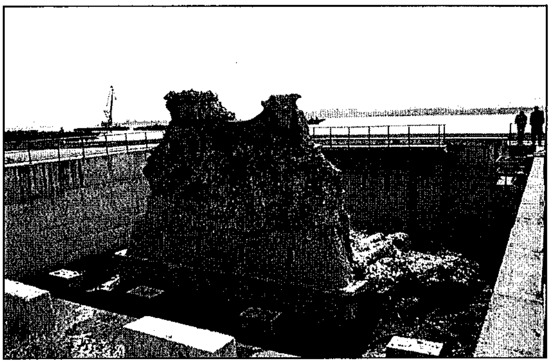

FIGURE 38. Abutment on the Serbian side of river.

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.

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-

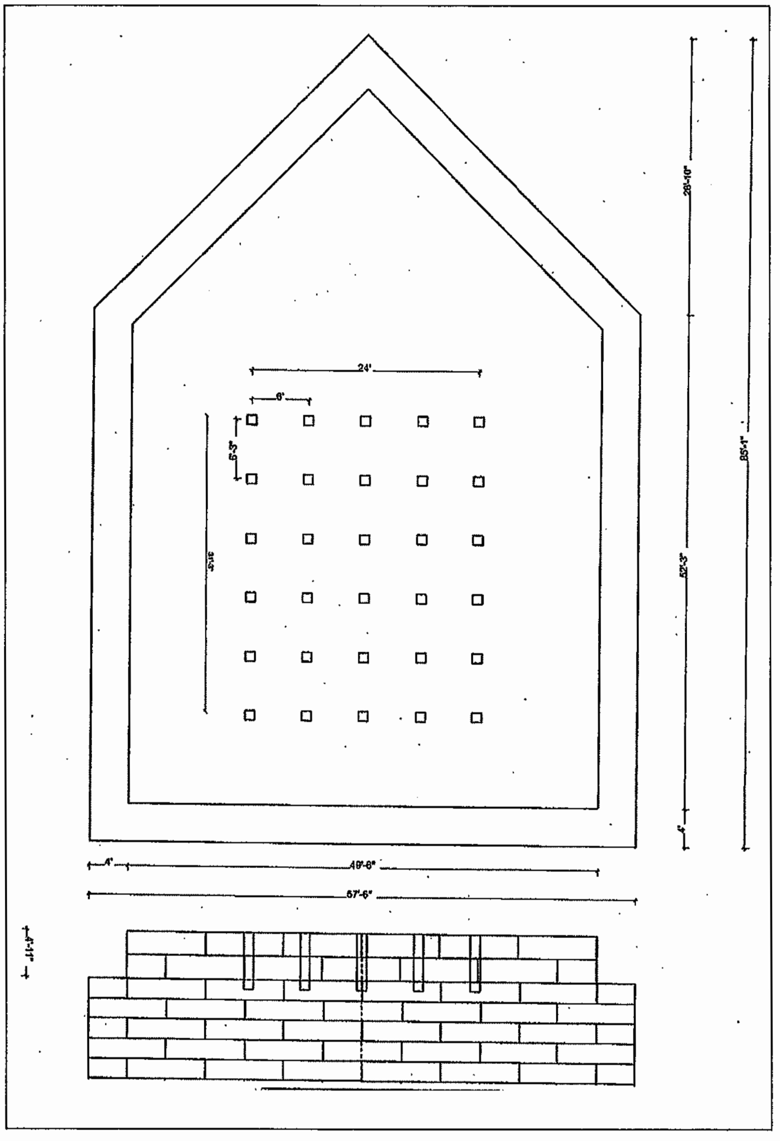

FIGURE 39. Suggested typical pier.

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.

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

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]

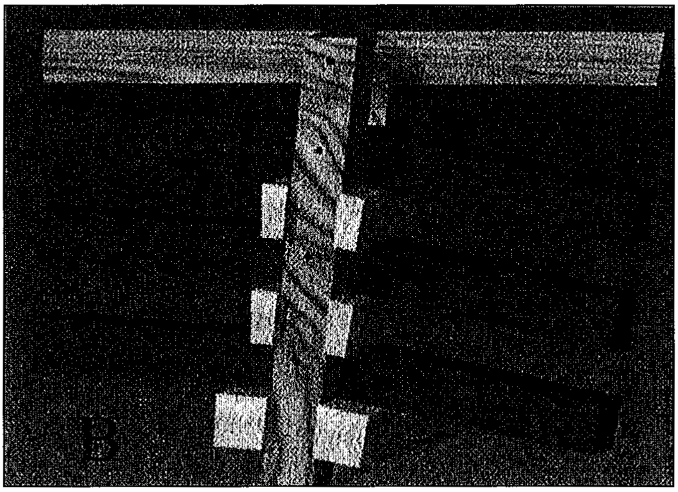

FIGURE 40. Ceraldi and Ermolli's structural model.

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.

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

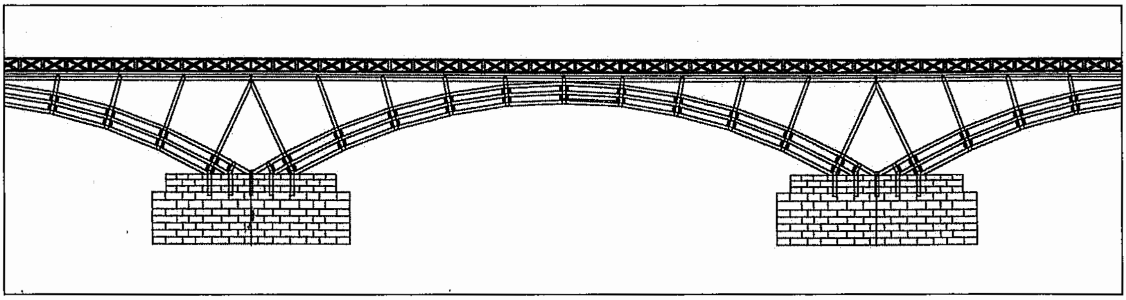

FIGURE 41. Typical possible span framing.

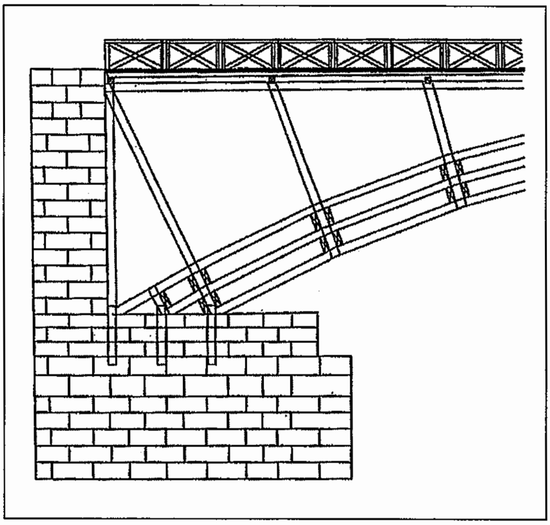

FIGURE 42. A detail at the ends of arch members on the abutment surface.

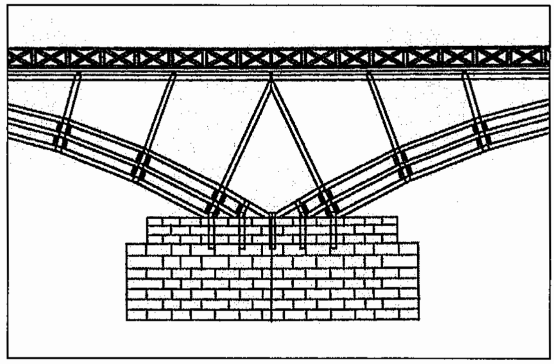

FIGURE 43. Possible pier framing detail.

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.

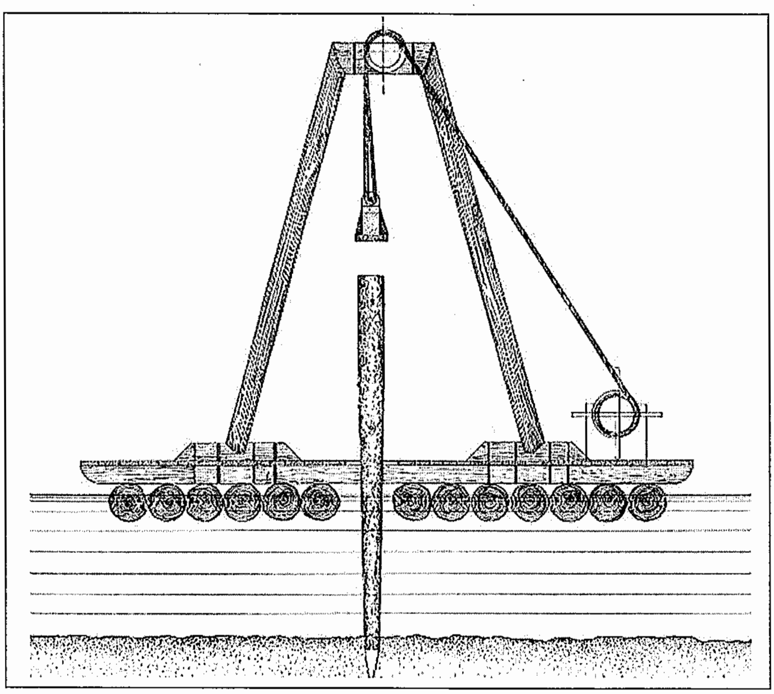

FIGURE 44. Galliazzo's proposed Roman pile driver.

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.

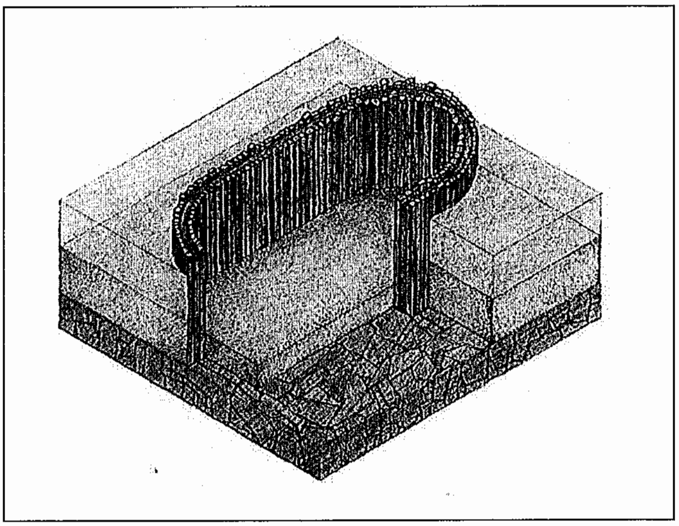

FIGURE 45. A Roman cofferdam.

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

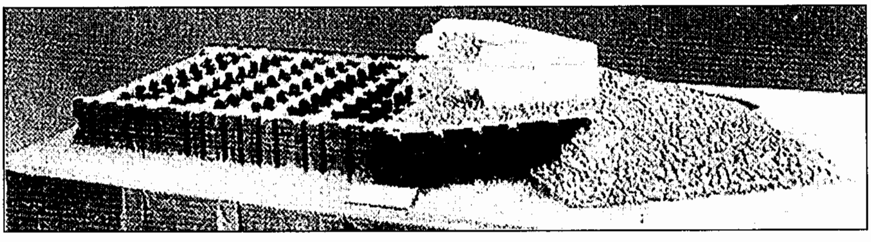

FIGURE 46. Model of a Roman foundation uncovered at Mainz.

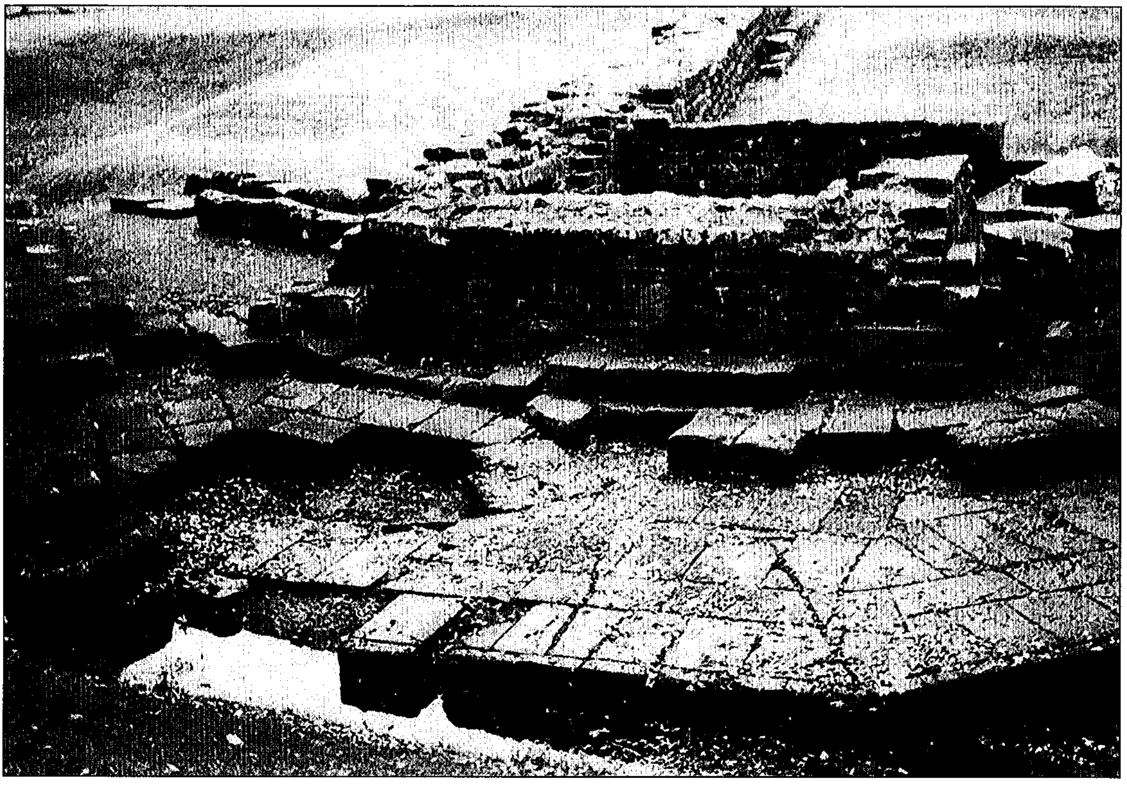

FIGURE 47. Bridge foundation from Hadrian's Wall at Chesters, England, from O'Connor (Ref. 18).

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 piledriving 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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The Newburyport Bridge: The First Long-Span Wooden Bridge in the United States

Using the truss in a way foreseen by Palladio, Timothy Palmer ushered in an age of long-span bridge building in the nation.

FRANCIS E. GRIGGS, JR.

The era of the long-span wooden truss bridge began with the construction of the Newburyport Bridge, also known as the Essex-Merrimack Bridge, across the Merrimack River between Salisbury and Newbury, Massachusetts, by Timothy Palmer in 1792. Using the lessons learned on this, his first bridge, Palmer went on to build three other bridges across the Merrimack and more over the Piscataqua River in Maine, the Potomac River near Georgetown, the Permanent Bridge over the Schuylkill River in Philadelphia and the Easton Bridge over the Delaware River. His construction methods and use of naturally curved timber set the stage for explosive growth in long-span bridge building in the United States.

Timothy Palmer

Timothy Palmer was born in Rowley, Massachusetts, on August 22, 1751, the first of eight children of John and Mary (Cressey) Palmer (see Figure 1). The Palmer and Cressey families had their roots in the Rowley area since the early days of the Massachusetts Bay Colony. His family moved to nearby Boxford in 1767, when he was sixteen years old. He marched as a Minuteman towards the Battle of Concord but turned back when the British retreated to Boston. He also fought in what was called the Battle of Bunker Hill before returning to Newburyport to apprentice under Moody Spofford as a millwright and architect, designing churches and meeting houses. He married Anna Wyatt on December 16, 1776, in Newburyport. She died in 1786 at the age of thirty-two before Palmer began his bridge-building career. He later married Hannah Downer on March 9, 1795. He had no

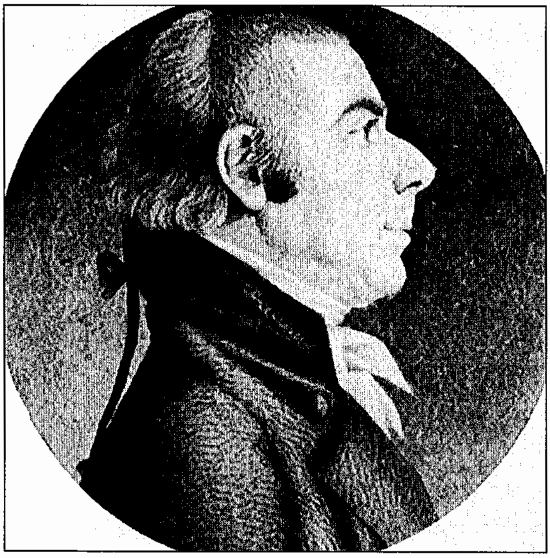

FIGURE 1. Timothy Palmer.

children by either of these marriages and died in 1821.

Little is known of Palmer and the life he led before, during and after his career as bridge builder. It is best to bear in mind the words of Christopher Wren, the famous English architect who designed and built St. Paul's Cathedral and much of London after the Great Fire. He said that, "If you want to see my monuments, look around." Palmer's works were truly his monuments. While no bridges have survived, their impact on bridge building and transportation in a young country was significant in earning him the title "The Nestor of American Bridge Builders." Many of his bridges were not well documented, but several were, including the Newburyport Bridge.

Bridge Location

Palmer's involvement with bridges was minimal when he began his bridge-building career at the age of forty-one. He would have been familiar with the bridge in Newbury over the Parker River, a tributary of the Merrimack River and the Thorlay Bridge over the Parker River, which was initially built in 1654 as a toll bridge. The only other bridges he might have known were the Charles River bridges and the other bridges located between Newburyport and Boston — all of which were short-span beam bridges.

In 1790, the federal census indicated that the town of Newbury had 3,972 inhabitants and 538 homes, while Newburyport, much smaller in area, had grown to a population of 4,837 inhabitants and 616 homes. The town of Salisbury, directly across the Merrimack River from Newburyport, had a population of 1,780. Newburyport was a major port city, ranking thirteenth in population in the country at that time, and was the home port to a large number of ships, brigantines, schooners and sloops. It was a very prosperous community due to its involvement in shipbuilding. In addition, it was situated on the main road from Boston north to New Hampshire. In 1790, several ferries crossed the river at Newbury and Newburyport.

The ferries across the Merrimack River were dangerous at times; however, they met the needs of the traveling public at a cost most could afford. In 1791, a group of local leaders proposed that a bridge be built across the river at a point just upstream from the town (see Figure 2). A bridge near the proposed site had actually been built across the river at what was called Carr's Ferry as early as 1650. George Carr was authorized to build this floating bridge 5 feet wide from an island he owned that was located in the channel of the Merrimack over the north branch of the river. When completed, this bridge was one of the earliest in the New World. Over time, Carr's Ferry was discontinued as the traffic shifted westerly, closer to Newburyport.

Initiating the Project

In the eighteenth, nineteenth and even into, but to a lesser degree, the early twentieth centuries, bridges were mainly built by private corporations that were issued charters by state legislatures to build and operate them. The stockholders were generally given a monopoly on river crossings for a certain distance upstream and downstream and were authorized to charge tolls that were approved by the legislatures. A charter typically was granted for a specified period of time and generally had a clause where the state could purchase the bridge at a fair price in the future. It was in this environment that a petition was prepared for approval by the legislature. The first step in this process was the distribution of a subscription on May 30, 1791, stating:

> Whereas a bridge over the Merrimack River from the land of Hon. Jonathan Greenleaf in Newbury to Deer Island, and from said Island to Salisbury, would be of very extensive utility by affording a safe conveyance to Carriages, Teams, and Travellers at all Seasons of the year at all times of the Tide. We, the subscribers, do agree that as soon as a convenient Number of Persons have subscribed to this, or a similar writing, we will present a petition to the Hon'ble General Court of Massachusetts praying for an act incorporating into a body politic of the subscribers to said Writing with liberty to build such bridge and a right to demand a toll equal to that received at Malden Bridge and on like terms; and if such an Act shall be obtained, then we severally agree with each of the others that we will hold in the said bridge the several shares set against our respective names, the whole of two hundred shares being divided, and that we will pay such sums of money at such times and in such manners as, by the said proposed Corporation shall be directed and required.[1]

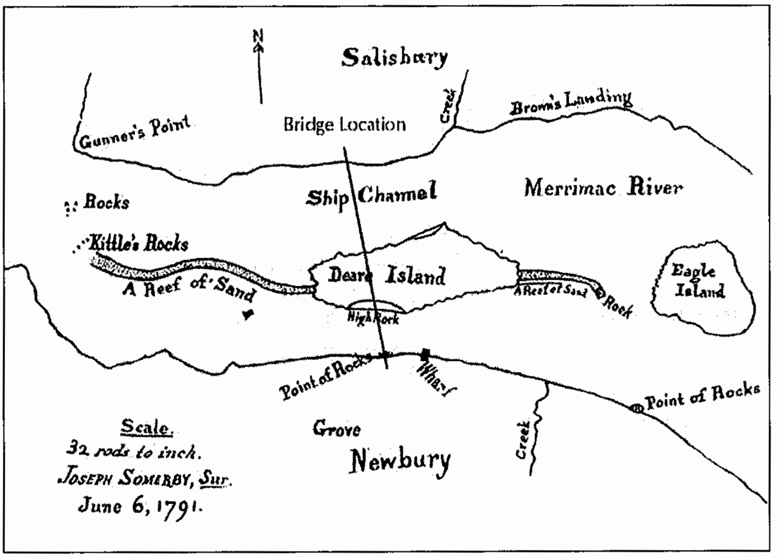

FIGURE 2. A map showing the location of the bridge.

The subscription was signed by forty individuals pledging between one and twenty shares. To meet the preliminary expenses of obtaining the approval of the legislature, surveying the site and preparing conceptual plans, each subscriber was required to pay an assessment of six shillings per share.

The formal petition to the legislature dated June 1, 1791, stated:

> To the honorable the Senate and to the honorable House of Representatives of the Commonwealth of Massachusetts in General Court assembled
>
> The petition of the subscribers, Citizens of the said Commonwealth shews
>
> That a bridge across Merrimack River from a place called the pines in Newbury in the county of Essex to Deer Island, so called, and from the said Island to Salisbury in said County would in the opinion of your petitioners very greatly subserve the public interest and convenience by affording a safe, prompt and agreeable conveyance to carriages, teams and travellers at all seasons of the year, and at all times of tide, whereas great dangers are incurred and great delays often suffered by the present mode of passing in Boats.
>
> Your petitioners further represent that they with others have associated for the purpose of erecting a bridge at the aforementioned place provided the countenance of the honorable Legislature can be so far obtained as to authorize the measure.
>
> Your petitioners therefore humbly pray your honors to take this subject into your wise consideration & that an act may pass incorporating our petitioners with such others as are or hereafter may be associated with them into a body politic, with permission to erect the said bridge with power to demand such reasonable toll as to your honor shall appear an adequate indemnification to them for the risk and expense

> attending this undertaking, and with such further corporate power as to your honors shall seem necessary or proper for carrying the said under taking into effect. And your petitioners as in duty bound shall ever pray.[2]

Nine gentlemen, including the leading citizens of the town, signed this petition. As a part of the process, the legislature on June 13 required them to make public their petition in "three weeks successively in the month of September next in Adam's independent *Chronicle* printed in Boston and in Mycall's *Essex Gazette* printed in Newburyport, to the intent that any person may appear on the second Wednesday of the next session of the General Court and shew cause if any he may have why the prayer of the said petition should not be granted."[3]

Since the construction of such a structure would have been a great advantage to people using the ferries, the subscribers thought there would be universal support from the citizens, with the exception of those who made a living from the ferry business. Such was not the case since Newbury on three occasions at their town meeting voted to instruct its representatives to the legislature to vote against the act of incorporation. They sent a "long remonstrance to the General Court objecting to the proposed obstruction of the navigation of the river."[4] The town of Salisbury also voted against the bridge, as did the town of Haverhill upstream from the bridge. Haverhill had as its reason "that the piers would lessen the tide up the river" and that "the committee of this town say that there was not more than nine feet of water over the shoals in common tides, and they feared it would be greatly lessened if the proposed bridge should be built."[5]

The same opposition to any bridge over a navigable river was made for the next eighty years as shipping interests were against any pier being built that would inhibit free navigation of the river. It must be understood that this opposition occurred before the introduction of steamships, starting in 1807 with Fulton's steamship on the Hudson River. The first steamship on the Merrimack River did not appear until 1828. Shipping interests were properly concerned since bridge building at this time required many wood or stone piers in the waterway because it was not possible to span distances of much over 30 to 40 feet with beam-type structures. A bridge of this type across the Merrimack River would have put a stop to shipping as far as Andover at Bodwell's Falls. The people against the bridge, however, did not know what type of bridge that Palmer and the subscribers had in mind — one with spans upward to 160 feet, thus keeping the navigable waterway fairly clear.

The subscribers submitted their plans to the legislature at the time of the petition. These plans included a description of the spans and width of the bridge. The act of incorporation was approved by the legislature on February 24, 1792, and was signed by Governor John Hancock. The five-page, handwritten document set up the corporation, stating:

> And be it further enacted by the authority aforesaid that the said proprietors be and they are hereby permitted and allowed to erect a bridge over the Merrimack River, from the place called the pines in Newbury aforesaid to Deer Island so called and from the said island to Salisbury aforesaid.[6]

The toll was set up in part as follows:

> For each foot passenger two thirds of a penny.
>
> For each horse and rider two pence.
>
> For each horse and chaise chair and Sulkey seven pence.[6]

The right to charge tolls was good for fifty years, but at the expiration of thirty years the legislature could regulate and determine the toll rate. From an engineering view, the legislation probably contained at least a preliminary design by Palmer since the act stated:

> And be it further enacted by the authority aforesaid that the said bridge shall be at least thirty feet wide; that between Newbury & Deer Island there be an arch one hundred and sixty feet wide — that between Deer Island and Salisbury there be an arch one hundred & forty feet wide, a

convenient draw or passage way for the passing & repassing of vessels at all times fifty feet wide with well constructed substantial and convenient piers on each side of the bridge & adjoining said draw sufficient for vessels to lie at securely; and also another arch fifty feet in width; and that the crown of the arch between Newbury & Deer Island be at the least forty feet high, and that each of the abutments thereof be twenty eight feet six inches high in the clear above common high water mark; and that all the abutments and piers be built of wood below high water; and laid in the crib work manner, so called; and that the bridge be covered on the top with plank or timbers and the sides be boarded up two feet high & be railed for the security of passengers four feet high at the least, and the same shall be kept in good safe and passable repair, and that said draw shall be lifted for all ships and vessels without toll or pay by night and day: And all ships and vessels intending to pass the said draw shall be free of charge at the wharf or pier until a suitable time shall be offered for passing the same; And said proprietors shall constantly keep some suitable person or persons at said draw for lifting up the same for the purpose aforesaid, and also an anchor placed in the bed of the river at a proper distance on each side of the bridge with a buoy and such other accommodations as shall be necessary for the safe passing and repassing of vessels, through the said draw, & shall keep said bridge furnished with at least five good lamps on each side of the same which shall be well supplied with oil and kept burning through the night.[6]

The spans listed in the legislation were similar to those of the bridge as built. When the legislation referred to the bridge as being "covered on the top," it was referring to the decking. Railings were common, but normally they were not boarded up 2 feet high. The legislature was very careful to protect the rights of ships and vessels moving up and down the Merrimack River and required that no toll be charged for any such vessel passing through the draw. Even with opposition from the Haverhill, Salisbury and Newbury town boards the act was passed.

Records at the Newburyport Historical Society contain letters from Joshua Davis and Thomas Sumner in response to an announcement that the directors of the bridge placed in a local newspaper regarding the submission of plans for the bridge. Keep in mind that the directors already had preliminary plans they submitted to the legislature from someone who could have been Palmer or Moody Spofford. Davis wrote that "having four days hence observed your Publication concerning a Bridge over Merrimack River & having had some experience in superintending work of that kind in times past I loath to present to you a very rough sketch of a model that kind altho my expectations are very small of being the one expected."[7] His three-page letter talks about member sizes, connections and foundations, but without the rough sketch he mentioned it is difficult to understand most of it. Sumner's letter was much in the form of an apology for even offering a proposal since he wrote that "perhaps you will think it presumption in a young man to presume to write to a gentlemen he never saw, But Sir encouraged by the fairness of your character & the intent you take in erecting a bridge over Merrimack River & knowing that all are invited & many will try. Consequently if refused I shall not be alone, then I with the more readyness offer my product to your patronage. As the hope of gain inspires everyman with the spirit of ambition, I selected my scattered ideas upon the subject & put them together upon paper. But knowing that a plan is not so soon understood by every person, I determined to make a compleat model. Which I now send you."[8] Sumner went on to talk about connections and choice of wood for his various parts and concluded in his charming manner that "sir, if my plans do not answer the purpose & you will be kind enough to convey them back in the same channel, you will lay under a great obligation."[8]

By early April, the directors evidently had many proposals, consisting of drawings, models and extensive descriptions of bridge styles. It is still not known if Spofford and Palmer's bridge plan had been submitted by that time.

The directors, having no one on the board competent to make engineering judgments, sent out a letter on April 10, 1792, to eleven men, who apparently were bridge builders or individuals with some standing in the area asking:

> The Directors of the Essex-Merrimack Bridge request the favour of you to take an early opportunity to take a deliberate view of the several Models proposed for the Arch, and give us the result of your Examination, to which of the said Models you give the preference, and if neither of them appear to you on the whole proper to be executed, we request you further to take into your consideration whether new plans cannot be formed from those already exhibited, and if you shall be of that opinion, we further request that you would with all convenient speed furnish us with such a one.[9]

Apparently, eleven men voted on the proposals since, according to the Newburyport Historical Society, the final vote was as follows:

Numbers that give the preference to:
6 — for Number 20 with some amendments
3 — for Number 3 with some amendments
1 — for Number 8 with some amendments
1 — for a well constructed deck bridge beams to [word illegible] one inch to a foot or more is necessary.[10]

Unfortunately, no record survives that indicates exactly what proposal Numbers 20, 3, and 8 referred to. It is probable, however, that Number 20 was Palmer's proposal, and it is also likely that his plan was the basis of the original proposal to the legislature. The level of interest in building the bridge was, however, clear. If proposals were numbered sequentially, there were at least twenty, and possibly more, submitted. It is also unfortunate that the models and drawings are lost. If they could be reviewed, they would show the state of bridge building in the latter part of the eighteenth century in the United States.

With a new, or enhanced, plan in hand, the directors evidently decided that the original legislation was not acceptable and proposed changes to be submitted to the legislature. In May 1792, Samuel Cutler received a sketch for the 160-foot span showing heights of abutments above high water and showing the rise in an arch and thickness of an arch. This arrangement gave the structure a height above water of 36 feet (in contrast to the 40 feet called for in the legislation). The directors requested a change in the law to permit a lowering of the arch and an alteration in the braces of the bridge. The bill was submitted to the legislature on June 9, 1792, and representatives from the towns of Haverhill and Amesbury, among others, saw a chance to kill the project on the second reading of the bill the following Wednesday (June 13). State Senator John Mycall wrote a letter to the directors on June 9, noting that "more opposition, I believe, had seldom been made, and there is every reason to suppose that it will recommence with increased fury at the second reading — during the interval, it stands re-committed, — and the members from Haverhill and Amesbury have this day taken their departure for home in order to stir up their constituents, that some means may be devised to frustrate the design of the proprietors — they have also engaged Mr. Blodget in their services who is now in town, and to tarry until the final issue of the bill."[11] Samuel Blodget was a well-known builder in the area, having placed improvements on the Merrimack River farther upstream at Manchester, New Hampshire. He may have submitted a proposal for the bridge that was one of those turned down in favor of Palmer's. Enoch Titcomb, a member of the House, wrote to Captain Coombs, saying that the House had "in order for Mr. Carr & Mr. Wingate time to go home & consult their constituents, — they are both very much opposed to any braces or any alteration which they think will in least obstruct the passage of boats & it was said in court that Mr. Blodget was in town, & could remove all the difficulties without having any braces — if either of the concerns in the bridge desire to be heard, further before the second meeting of the Bill, they will have [opportunity] — I mentioned to Mr.

March last evening that it might be of advantage to have Mr. Palmer here, to explain in one of the lobbys to the members the proportions of the model, distance, &c — it was much admired by many members, & some encomiums made on it. I am much inclined to think the Court will lower the arch & also the braces — be assured the Representatives of Newburyport will do all in their power honorably to serve the proposition of the bridge, & the Public Interest."[12]

The act was passed on June 22, 1792, and it modified the restrictions and limitations of the first act with regard to the height above high water mark, braces, etc. The change evidently came about after Palmer was selected as chief bridge engineer, as noted by a comment from Titcomb.

The revised act stated:

> Whereas the Directors of *Essex Merrimack Bridge* have petitioned this Court, setting forth, that in the execution of the said undertaking, sundry inconveniences have arisen to them from the particular restriction of the said Act respecting the form of the said bridge, and praying the interposition of this Court for the removal of the same:
>
> Sect.1 *Be it therefore enacted by the Senate and House of Representatives, in General court assembled, and by the authority of the same,* That in the building and completing of the said bridge, any alterations from the limitation and restrictions of the said Act, so far as the same respect that part of the said bridge which lies between Deer Island and Salisbury, be and hereby are authorized as allowed; anything in the said act to the contrary notwithstanding.
>
> Sect. 2 *Provided nevertheless,* That there shall be one arch, at least one hundred and ten feet wide, and a convenient draw for the passage of vessels, at least forty feet wide; and they provided also that there shall not be in the whole less vacancy for the passage of the water, that in and by the said Act is required.
>
> Sect. 3 *And be it further enacted by the authority aforesaid,* That the crown of the arch to be erected between Newbury and Deer Island may not be less than thirty-six feet high, and that each of the abutments thereof may not be less than twenty-four feet and a half high, above common high water mark; and that braces or shores may be placed from the abutments of the said arch, at four feet and a half from common high water mark, to pass up to the said arch, at not more than forty-eight feet distance, from the top of the said abutments; any thing in the said Act to the contrary notwithstanding.[13]

The directors got what they and Palmer requested, namely a lowering of the arch on the Newburyport side from 40 to 36 feet and a reduction of abutment height from 28.5 to 24.5 feet. They also got permission to place braces under the arch off the abutments. This alteration was extremely important, since Palmer's truss would have received significant support from these braces or struts. The span of 160 feet would not have been buildable without the braces due to the limitations on timber sizes available at the time. In addition, if Palmer used the full distance out to the lowest brace of 48.5 feet, the clear span through which vessels could pass would be only 64 feet. From a shipping standpoint, these specifications made the Newbury to Deer Island opening very restrictive and almost forced ships to pass through the Deer Island to Salisbury draw span. On the Salisbury side of the bridge, they reduced the draw span from 50 to 40 feet, and added the unenforceable clause that there "shall not be in the whole less vacancy for the passage of the water." In other words, they did not want the bridge to block the waterway to any significant degree so they could say that they had addressed the concerns of upstream cities like Haverhill. This consequence may be why Palmer increased the span length of the Salisbury arch to 113 feet from the required 110 feet.

It is not known how Palmer secured the contract to build his first bridge over the Merrimack River, but apparently his association with Moody Spofford was helpful. *The Massachusetts Magazine,* in May 1793, reported that "this bridge was built, under the prospect of advantages much less encouraging, than

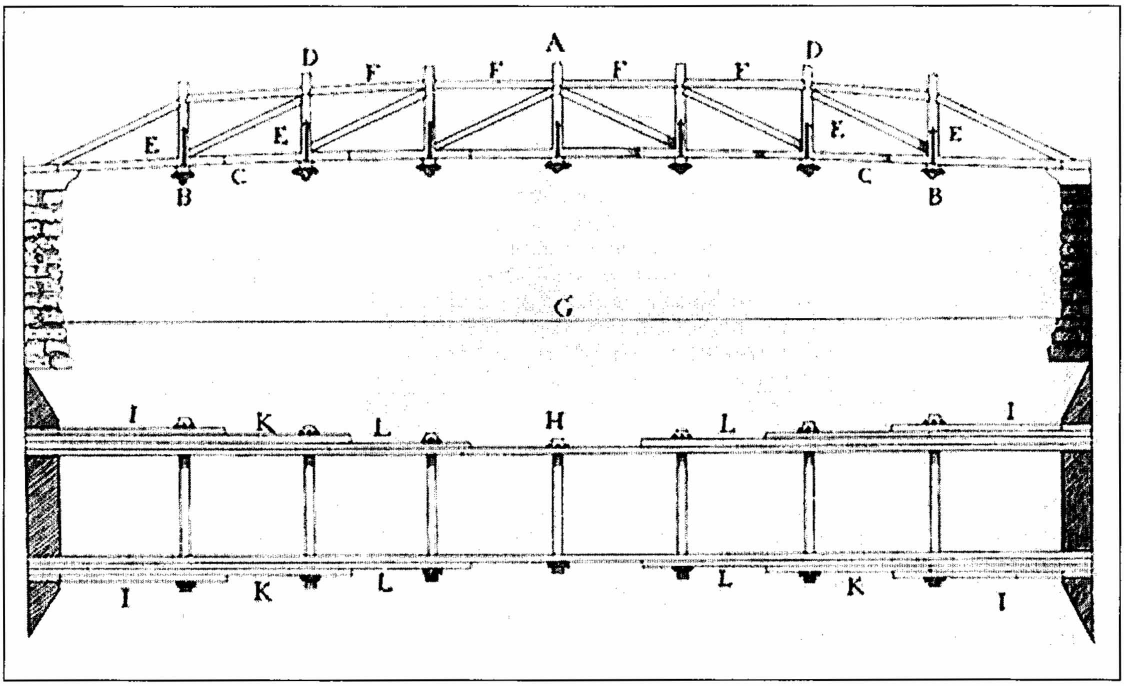

FIGURE 3. Palladio's truss bridge.

any which have been granted by the legislature to undertakings of a similar kind."[14] The site was a good fit since the meandering river narrowed there on a sharp bend. In addition, the existence of Deer Island (comprising over one-third of the width of the river bank to bank) cut down on the bridge spans needed to cross it. The bridge location on the Merrimack River at this spot was only a few miles from the Atlantic Ocean and on the main road north from Boston to points north to New Hampshire and what was to become Maine. It was also only less than 3 miles from Palmer's home.

The Breakthrough

Where did Palmer get his inspiration to do what no one else in the United States had done before? What made him think he could design and build a bridge over 1,030 feet long, with one span of 160 feet over water that averaged 34 feet deep?

A genius has been defined as someone who sees what everyone else sees but thinks what no one else has thought. This definition applies to Timothy Palmer. It has been written that he was the first American to utilize the truss in a way that was proposed by Palladio, in the sixteenth century in Italy (see Figures 3 through 5). It can be seen in Figure 3 that Palladio had his top chord and bottom parallel with a single compression strut in each panel. In another design, shown in Figure 4, he used twin parallel arches. It can also be seen that Palladio had two braces in each panel and the line of action of his braces did not go through the intersection of his chords and verticals (radials).

This truss pattern is similar to James Eads' St. Louis Bridge that was constructed in steel much later in the nineteenth century. Palmer did not have either of his chords acting in compression on his abutments, relying instead on trussing action to take out any horizontal loading on his piers or abutments.

Palladio's third truss was a trapezoidal truss with very flat diagonals (see Figure 5). This truss was a pure truss and it bears resemblance to Palmer's truss (see Figure 6). No plans or engineering drawings of the bridge are available, except for the representations of the bridge shown in Figures 6 and 7. Based on Figures 3 and 6, the following conclusions can drawn:

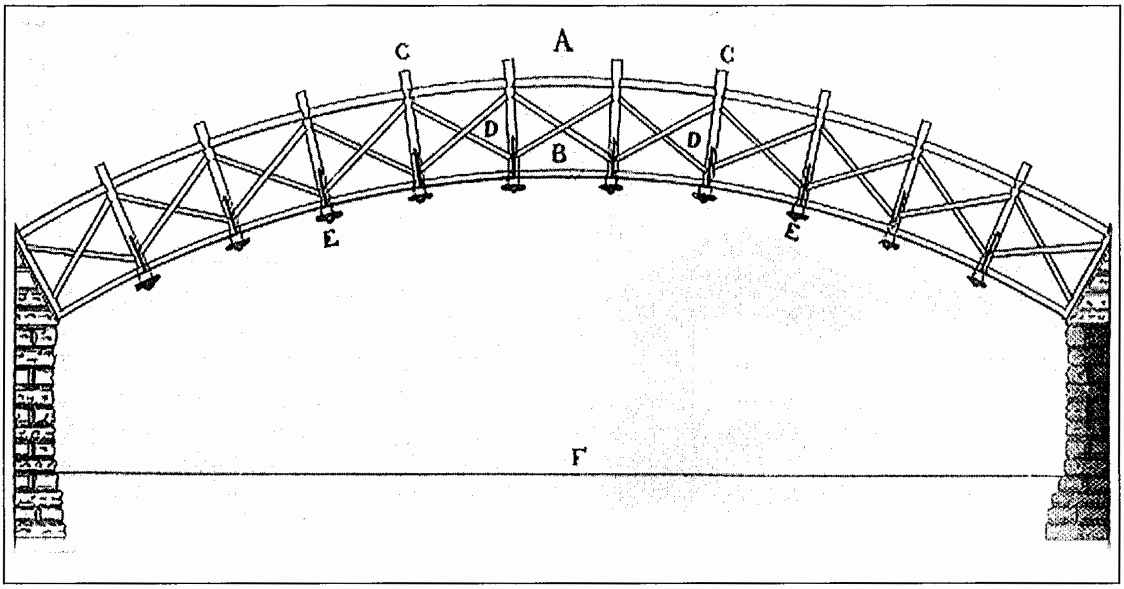

FIGURE 4. Palladio's arch bridge.

- Palladio's panel lengths were about twice the truss height, compared to Palmer's 1:1 ratio.
- Palladio's verticals ran through both the top and bottom chords. Palmer's verticals were tied to his top chord by straps and/or a mortise and tenon joint. It appears that Palladio connected his verticals to his lower chord with iron straps. Palmer notched members and connected them with bolts or treenails.
- Palladio had the size of his bottom chords widen as he approached the ends of his truss. It almost looks like he was cantilevering the bottom chords out from the abutments and using the overhead truss-

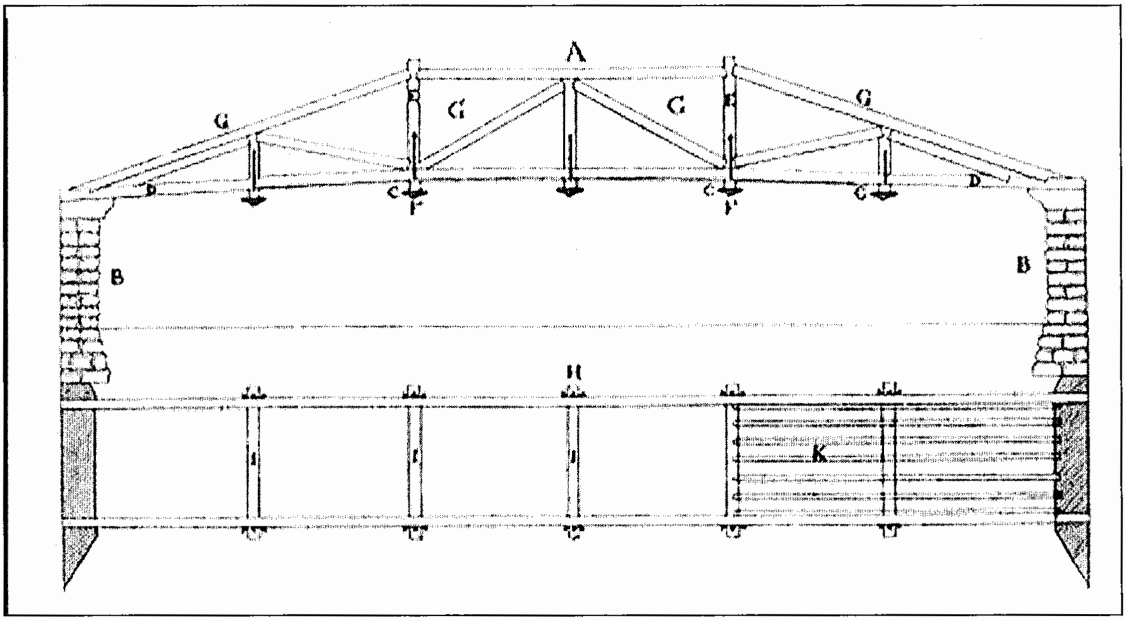

FIGURE 5. Palladio's truss.

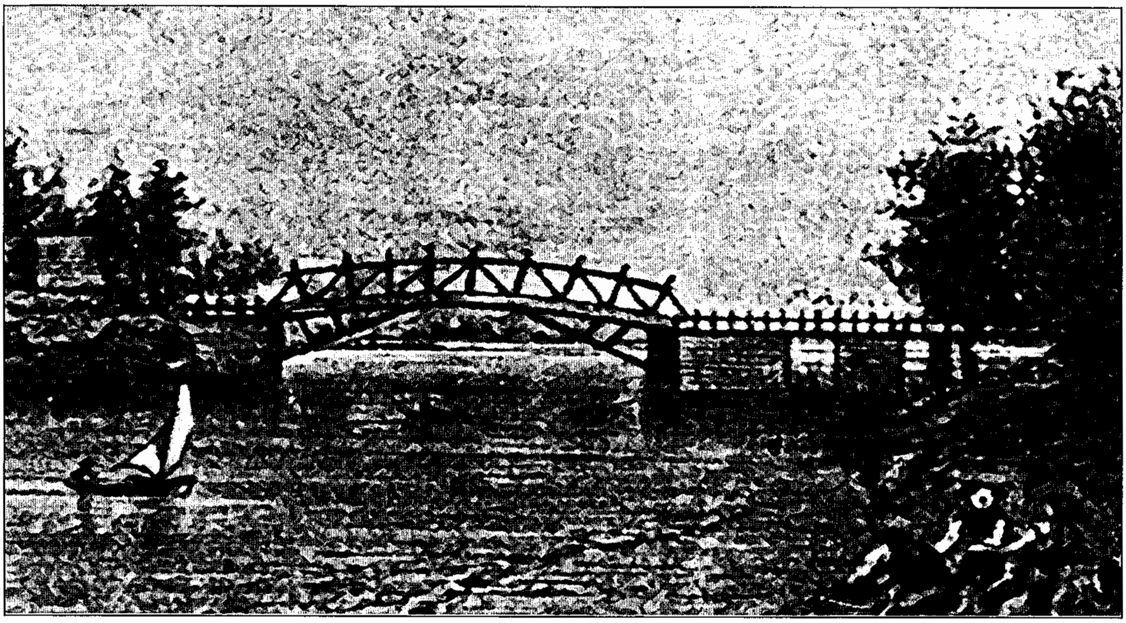

FIGURE 6. Palmer's truss with a 160-foot span.

ing to stiffen the cantilever. There is no illustration, however, of how he anchored his lower chord (cantilever arm) to the abutment. If he visualized his structure as a cantilever, he would have been correct in showing the member as he did. Palmer enlarged his bottom chords a small amount as he moved to the ends of his truss. Later knowledge showed that the bottom chord could actually get smaller as the ends of the truss were approached.

- Palladio had a small camber in his bridge, while Palmer had a large one. This large camber is what caused many to call Palmer's bridge an arch.
- Palladio had no apparent way to resist the lateral thrust coming from his diagonals to the upper and lower chords. Palmer attached a horizontal member to the top of his lower chord and the bottom of his upper chord to resist this lateral force.
- Palladio apparently broke his top chord at each vertical. Palmer's top chord was, through splicing, continuous throughout its length.
- It appears that Palladio hung his floor beams from his verticals with the same strap that connected his lower chord with his vertical. Palmer usually set his floor beams on top of his lower chord at the panel points.

It is very probable that Palmer knew of Palladio's designs since he was an architect and Palladio's work was common knowledge in architects' offices around the world. It is also very probable, given these significant differences, that Palmer did not base his design on Palladio's bridges but may have been inspired by Palladio's writings to expand on his ideas and design a bridge of his own.

Early illustrations of the longest span of his Newburyport Bridge show it with ten panels of approximately 16 feet, with a panel height equal to the panel length yielding compression diagonals on approximately a 45-degree angle, later shown by Squire Whipple a half century in the future to be the most efficient orientation for a diagonal.

Palmer used what has been called by some a trussed, or braced, arch as his supporting system. In reality, it was more like a truss that was later called a Long, or Howe, Truss since it had a single compression diagonal in each panel with verticals (radials) in tension. Howe made use of iron verticals and usually had a vertical end post. The idea of having a compression diagonal was common in both Long's

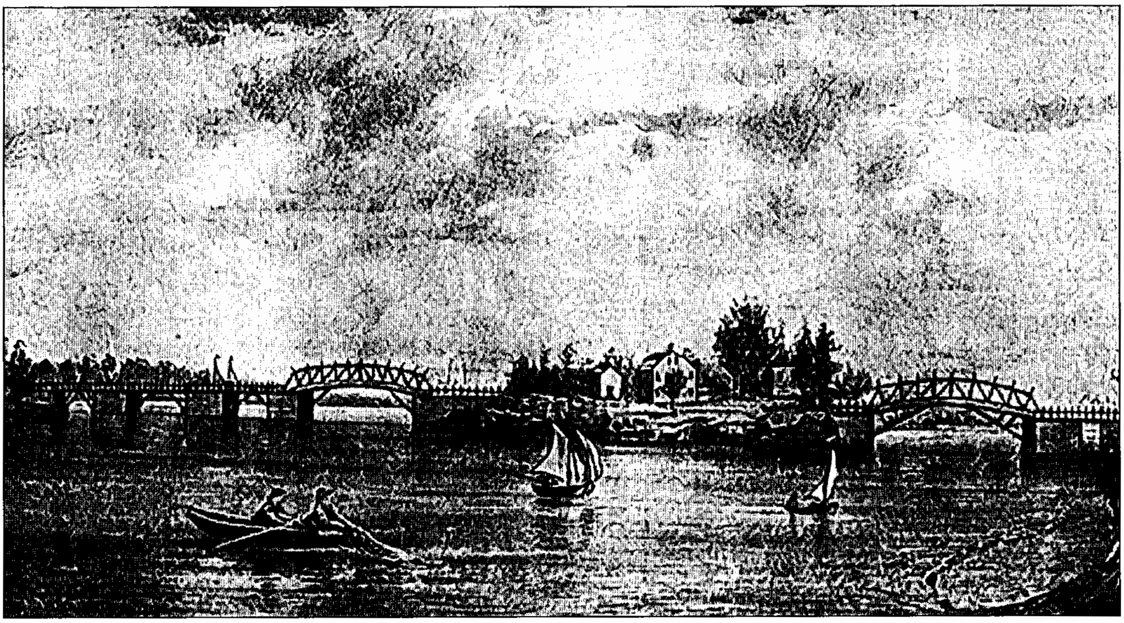

FIGURE 7. A rendition of the Newburyport Bridge (from Ref. 14).

and Howe's trusses as well as Palladio's. It was also the first "trapezoidal" truss since the end top chord member was inclined upwards from the abutment or pier. How the truss/arch worked depended greatly on how the members were connected at the upper and lower chords as well as the stiffness of the lower chord. If the lower chords were very stiff, then the structure would act more like a braced arch if it were built into the abutments that prevent longitudinal movement at the ends of the member. Evidence on his later bridges indicated that he used large wedges at the ends of his lower chords braced off the abutments or wood work on his piers to counteract any shrinkage of wood, or possibly to preload (prestress) his truss. If the lower chords were less stiff and not anchored to the abutment, then the whole structure would act more like a cambered truss with radial tension posts and compression diagonals. In the arch the lower member would be in compression and bending, and in the truss it would be in tension so that if there were any splicing required, it would have to be significantly different. Due to a lack of detailed sizes of members and types of connections, it is not clear how the structure acted, but it appears that it behaved more like a truss, possibly with both ends pinned and preloaded, and less like Palladio's trussed arch.

Bridge Design

Assuming that Palmer saw his structure acting like a truss, how would he have sized the members, and, equally as important, how would he have connected the members? It is likely that having built relatively long-span roof structures in his church buildings, at least two of which still exist in and around Newburyport, he would have used trusses and developed methods of connecting his large wooden members. Christopher Wren, the seventeenth-century architect, used trusses in several of his buildings and published his drawings and truss patterns. With that background, it is known that Palmer used models to illustrate bridges that he planned on building and later evidence indicated that he test loaded his models in demonstrations for the bridge companies that were buying his bridge designs. While it is difficult to project the load-carrying capacity of a long-span truss from tests made on models, it is possible to get an idea of how a trussed assemblage of wooden members would act under load. With a trial and error process, it would be possible to gain a better understanding of truss action, mem-

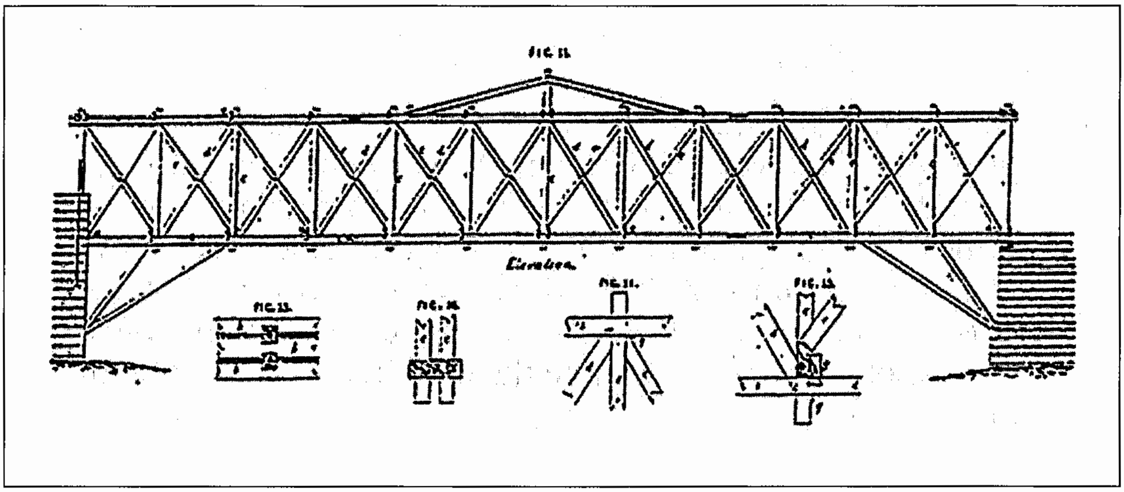

FIGURE 8. Long's 1830 Jackson Bridge with struts.

ber connections and relative sizes. Iron was very expensive in the United States at that time so Palmer made very little use of it except for bolts, washers and plates. This method of test-loading models continued through the iron bridge building era until 1847 when Squire Whipple developed the analysis technique that permitted the designer to actually size his members by calculation. Without a full understanding of truss action, it is understandable why Palmer built in such a large camber since he was apparently hoping for some arch action as well. Without a record of how Palmer understood his structure to act, it can be only assumed, based on later developments, how the bridge was designed.

The foundations for the superstructures were probably supported by wood pilings or by stone-filled wooden cribs (which were Palmer's standard foundation methods), sometimes with piling and sometimes without. In the language of the day, they were called "huge log piers which extended far below the water line to a firm foundation of either stone, hardpan or gravel."[15] On most of his bridges, Palmer did not design or build the foundations and only did so when the piers and abutments were in place. With the foundations in place, he would construct wooden falsework on which to build his deck structures and his arches/trusses.

For the curved lower and upper chords, he used what Theodore Cooper in his fine work on railroad bridges called "crooked pieces of timber, so that the fibre might run in the direction of the curves."[16] Palmer actually specified timber with a given amount of curvature so that it almost amounted to little more than crooked timber. In the engraving of the bridge, it can be seen that he used trussed struts off the piers extending out several panel points to help support his arches as permitted by the modified Act of the Legislature (see Figures 6 and 7). These braces would, of course, have changed the manner in which vertical and horizontal loadings would have been transferred to the abutments.

Lengths working from the northerly shore (the Salisbury shore) were: 124 feet abutment, 50 feet water, 45-foot pier, 50 feet water, a 40-foot draw structure, 50-foot feet, his arch of 113 feet and a 60-foot abutment to the northerly shore of the island. The bridge then ran from Deer Island 93 feet, with an arch of 160 feet, and then 185 feet to the Newburyport shore. The struts off the piers may have been based on Enoch Hale's Bellow's Falls Bridge or the European bridges of the Grubenmanns. S. H. Long, in a patent for his 1830 Jackson Bridge, also adopted the use of struts (see Figure 8).

Shortly after the opening of the bridge, *The Massachusetts Magazine* in 1793 noted:

> The two large arches, one of which is superior to anything on the continent, were both invented by Mr. Timothy Palmer, an

ingenious house wright of Newburyport, and appear to unite elegance, strength and firmness beyond the sanguine expectation.[15]

An article by Fletcher and Snow entitled, "A History of the Development of Wooden Bridges," published in the *ASCE Transactions* included a statement that Palmer "may well be called the Nestor of American Bridge builders" for this bridge and the others he built over the next fifteen years.[17] In the book, *Ould Newbury*, Currier stated:

> The principles upon which it was constructed were novel and hitherto untested; but the beauty and strength of the structure, when completed, demonstrated their practical value and utility.[1]

The bridge opened in December 1793, but apparently the official opening came on July 4, 1794, when Timothy Dexter gave an address that was published in several of the local newspapers.

Travelers' Impressions

Timothy Dwight, President of Yale University, traveled through much of New England in 1794 and 1795, and later in 1812. An associate published a record of his travels in 1821 after Dwight's death. Dwight described two other Palmer bridges in greater detail, but he did write this about the Newburyport Bridge:

> Between Salisbury and Newbury the Merrimack is crossed on Essex Bridge... It consists of two divisions, separated by an island at a small distance from the southern shore. The division between the island and this shore consists principally of an arch, whose chord is one hundred and sixty feet, and whose vertex is forty feet about the high water mark. In appearance and construction, it resembles Piscataqua Bridge; the whole length of Essex Bridge is one thousand and thirty feet, and its breadth thirty-four. I have already mentioned that Mr. Timothy Palmer, of Newburyport, was the inventor of arched bridges in this country. As Mr. Palmer was educated to house building only and had never seen a structure of this nature, he certainly deserves not a little credit for the invention... The workmanship of the Essex Bridge is a handsome exhibition of neatness and strength.[18]

John Drayton, another traveler through New England in the 1790s, also wrote about the Newburyport Bridge. He listed all the individuals who subscribed to the publication and included three sketches. It was the only bridge he took time to describe:

> Two or three miles beyond Newburyport is a beautiful wooden bridge of one arch, thrown across the Merrimac River: whose length is one hundred and sixty feet; and whose height is forty feet above the level of high water. For beauty and strength, it has certainly no equal in America: and I doubt whether as a wooden bridge there be any to compare with it elsewhere. The strength of the bridge is much encreased above the common mode in use, by pieces of timber placed upon it, and shouldered into each other. They run upon the bridge in three lines; parallel with the length of the bridge, and with each other; so as to make two distinct passageways for carriages. These braces, are some feet in height, and are connected on the top by cross pieces, affording sufficient room for carriages to pass underneath without inconvenience. It is said, that the upper work has as great a tendency to support the weight of the bridge; as the sleepers upon which it is built.[19]

Drayton included a sketch (see Figure 9) of the bridge that he prepared later from memory, stating:

> I had not time to stay here longer than five minutes; so must be excused in a sketch which I have taken of it: and that was not done upon the spot, but only by recollection. If in so doing, I should persuade others to enquire more particularly respecting it; and to adopt what may be good in its mechanism; my object will be gratified.[19]

It is clear that Drayton did not have a very good recollection of the bridge and that he

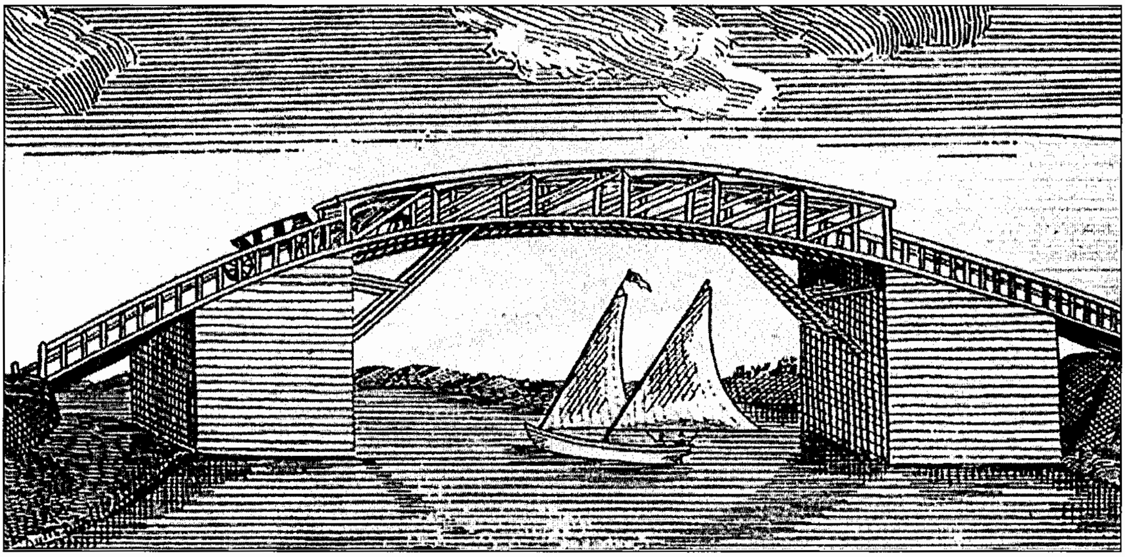

FIGURE 9. Drayton's sketch of the Newburyport Bridge.

exaggerated the arch, but he did know that it had large abutments in the river and that the bridge was a truss with the top chords tied together across the bridge. Drayton did have all Palmer's diagonals running the same way from the lower left of the panel to the upper right rather than having them running from the lower right to the upper left on the right half of the truss. He did show the under deck struts correctly.

In the years 1795, 1796 and 1797, the Duke de la Rochefoucault Liancourt, a French nobleman, traveled the country and wrote his treatise, *Travels Through the United States of North America the Country of the Iroquois and Upper Canada.* He visited the bridge and wrote:

> Before you arrive at Newbury Port, you have to cross the river Merrimack, by means of a bridge, which, prior to the building of that thrown over the Piscataqua, was considered as the most elegant in New England. It is at least shorter by one-third than the latter, and the arch, which measures only one hundred and thirty feet in width, is supported by a crooked piece of timber, measuring twenty feet, which gives the bridge, at first sight, a heavy appearance.[20]

Liancourt, like Drayton, did not have perfect recollection of the bridge and probably meant to say that the chords were made of crooked timber 20 feet in length that were spliced together and tied into the diagonals securely.

Robert Gilmor, from Baltimore, visited the bridge in 1797. While he did not give a written description of the bridge, he did make a sketch and included it in his *Memorandums Made in a Tour to the Eastern States in the Year 1797* (see Figure 10).[21] It is very similar to *The Massachusetts Magazine* sketch.

Thomas Pope wrote, in 1811, in his treatise on bridges (the first bridge book printed in the United States):

> Over the Merrimack River, in the County of Essex, near Newburyport, is a Bridge that was planned by Mr. Timothy Palmer, in the year one thousand seven hundred and ninety-two, constructed with two arcs; the one is one hundred and sicty and the other is one hundred and thirteen feet chord, and is erected forty feet above the level of high-water.[22]

Joseph Sanson, a well-known banker from Philadelphia, made a New England trip in 1795. In a letter dated August 27, he briefly described the Newburyport Bridge to his parents as follows:

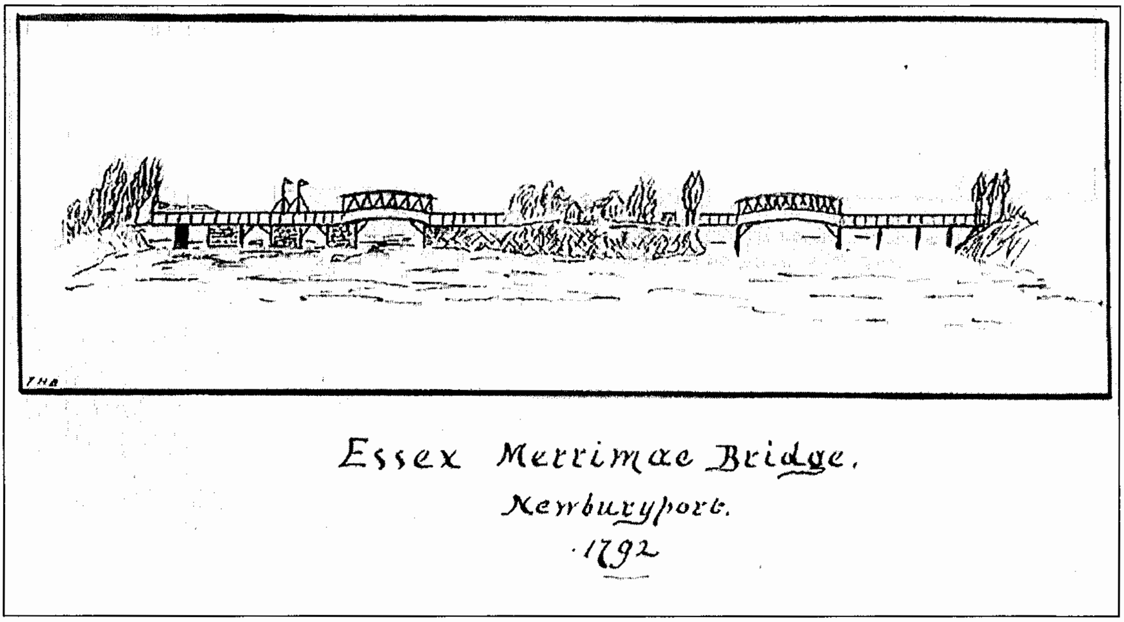

FIGURE 10. Gilmor's sketch of the Newburyport Bridge.

> That over the Merrimack near Newbury in Massachusetts is a beautiful arch of one hundred and eighty feet span, and forty foot chord, which being painted white glitters, like a feary vision, through a tall grove of white pines as you approach it from one side.[23]

The Massachusetts Magazine carried this description in announcing the opening of the bridge:

> The bridge over the Merrimack River between the towns of Salisbury and Newbury is now opened for the use of the publick. The arch is deemed the largest on the continent. The whole work contains more than six thousand tons of timber. Mr. Timothy Palmer, an ingenious housewright of Newburyport, has received a medal for the best construction of an arch.[14]

Bridge Facts

The bridge was built for $36,397 and its first dividend was paid on February 25, 1794, to forty-three stockholders, many of whom were different from the group that petitioned the legislature for permission to incorporate and build the bridge. Dividends were paid quarterly up to May 1807 so the bridge, which averaged over $4,000 per year in tolls, was a good investment. The incorporating act was amended on February 15, 1793, shortly after the bridge opened, with the statement:

> Whereas the Proprietors of Essex Merrimack Bridge have represented to this court, that the said bridge has been much more expensive than upon calculation was expected; and it being reasonable to grant to the said Proprietors some further benefit that in said Act is contained: Be it therefore enacted by the Senate and House of Representatives in General Court assembled, and by the authority of the same, that the toll in and by the said Act granted and established shall continue to be received by the said Proprietors for the term of fifty years from the day of the first opening of said bridge.[24]

The original act indicated that the legislature could change the toll after thirty years. *The Act Authorizing a Bridge Between Haverhill and Newbury* (Rock's Village Bridge), dated June 14, 1794, contained a clause that stated:

> Whereas the erection of said bridge may diminish the emoluments of The Proprietors

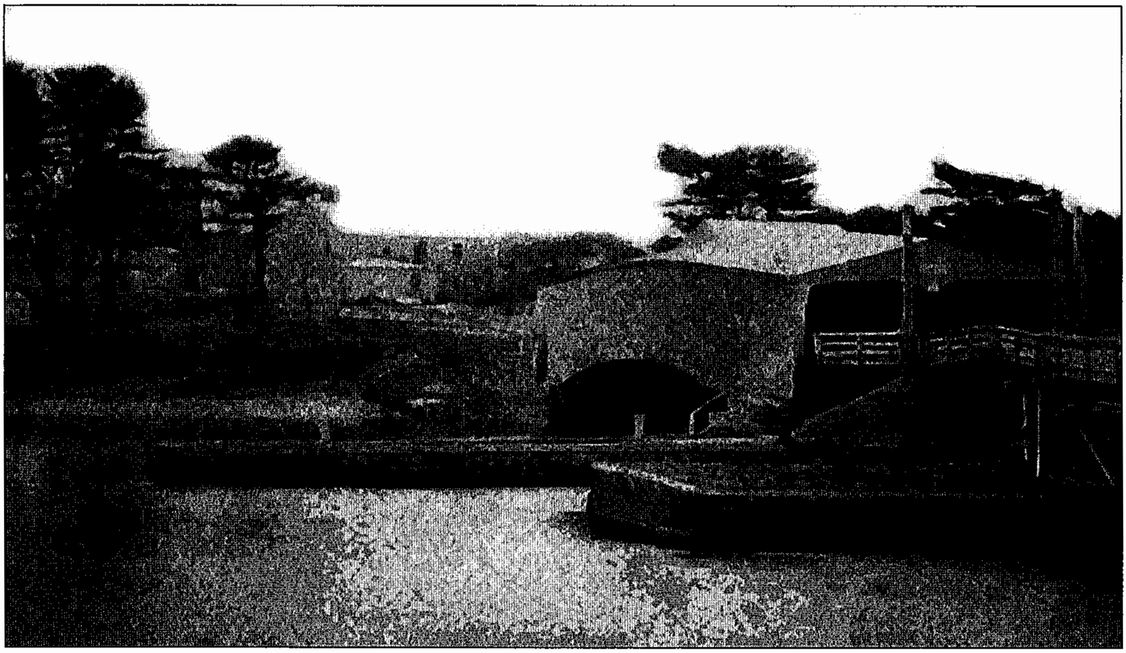

FIGURE 11. The Salisbury Truss, post-1808, with lift span, looking south.

> of the Essex Merrimack Bridge built at Deer-island, which was a work of hazard and public utility; be it enacted That the Proprietors of Essex Merrimack Bridge shall continue to be a corporation and body Politic for and during the term of seventy years.[25]

In other words, the legislature, in granting the charter for the Rock's Village Bridge, extended the corporate life of the Newburyport Bridge for another twenty years.

Usually, uncovered wooden bridges only have a life expectancy of 12 to 15 years. It is highly probable that the bridge had begun to exhibit signs of decay in the first decade of the nineteenth century. The bridge was rebuilt in 1807 (roughly thirteen years after it was opened). This rebuilt bridge was similar to the Permanent Bridge that Palmer built in Philadelphia in 1804. This rebuilt bridge had three tiers of longitudinal timbers. In a letter to Richard Peters, President of the Schuylkill River Bridge Company, for whom Palmer would build a bridge later on, dated July 11, 1808, Palmer wrote:

> Last summer, I rebuilt one of the Arches; the span of which is one hundred and thirteen Feet and is on the same principle with your Bridge. With much persuasion, I obtained liberty to cover it. There were many doubts in the minds of the Stockholders as to its stability against strong winds.[26]

This covered span survived until 1882. In the same letter, Palmer informed Peters that:

> [On] the 17th of June last there came on, one of the most tremendous gales of wind, ever known in this country. The wind blew down from the North West, for about thirty minutes — The most sturdy oaks and elms were torn up by the roots; some twisted off. One meeting house was blown down in the neighbourhood of this town; and a new dwelling house was slipped thirty inches off its base broke off the chimney and went no further — The reason of my being thus particular in this reason is — Essex-Merrimack bridge stands nearly in the centre of the direction of this tempest; and stood like mount Atlas amid the warring elements.[26]

Richard Allen in his book, *Covered Bridges of the Northeast*, presented an exaggerated sketch

FIGURE 12. A view of the Salisbury Truss, post-1812, from *Gleason's Magazine*.

from *Gleason's Magazine* of this truss and wrote "that from a distance it resembled a half squeezed accordion."[27] This covered truss can be seen in the historical photograph presented in Figure 11. Figure 12 shows the entire view of the bridge, post-1812, including the covered span that Allen was describing; however, Figure 11 puts the span in a different light.

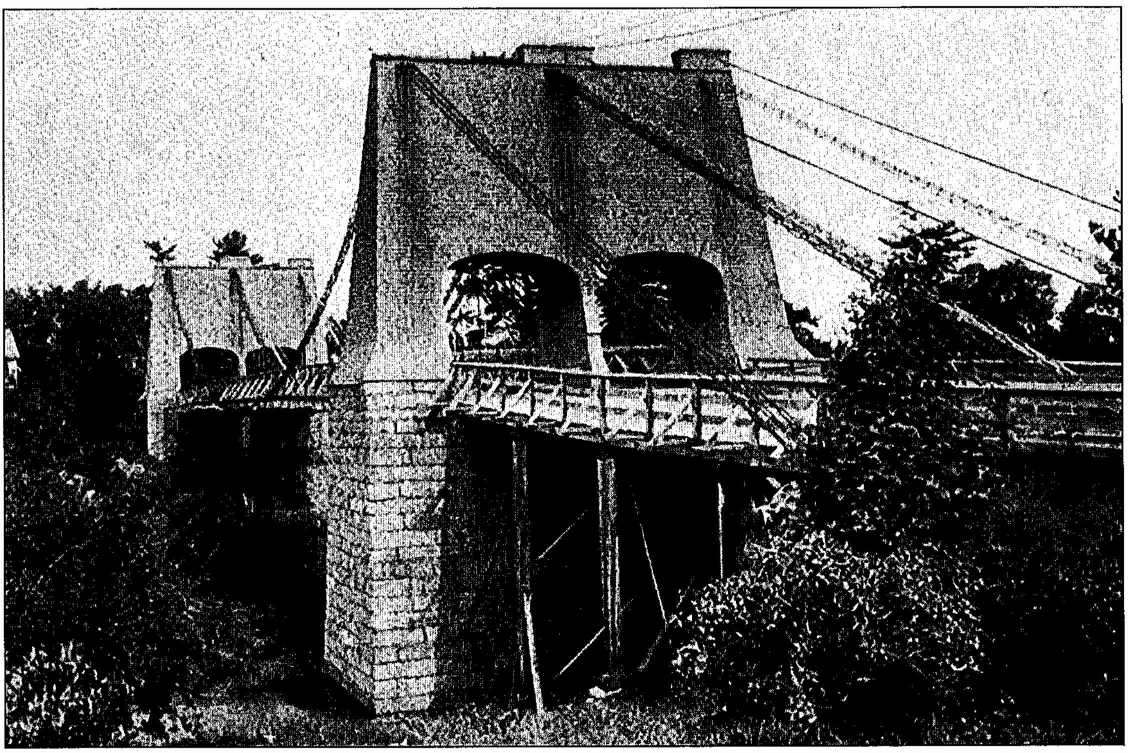

FIGURE 13. Templeman's bridge.

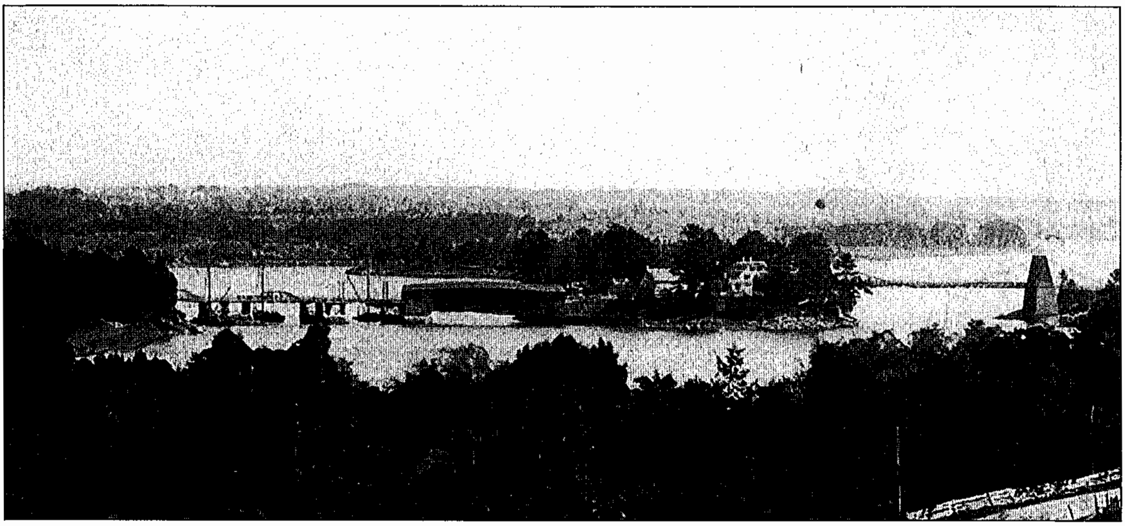

FIGURE 14. A view of the Newburyport Bridge, post-1812, with Templeman's chain suspension bridge.

FIGURE 15. A view of the concrete towers for the wire cable Newburyport Bridge built in 1909.

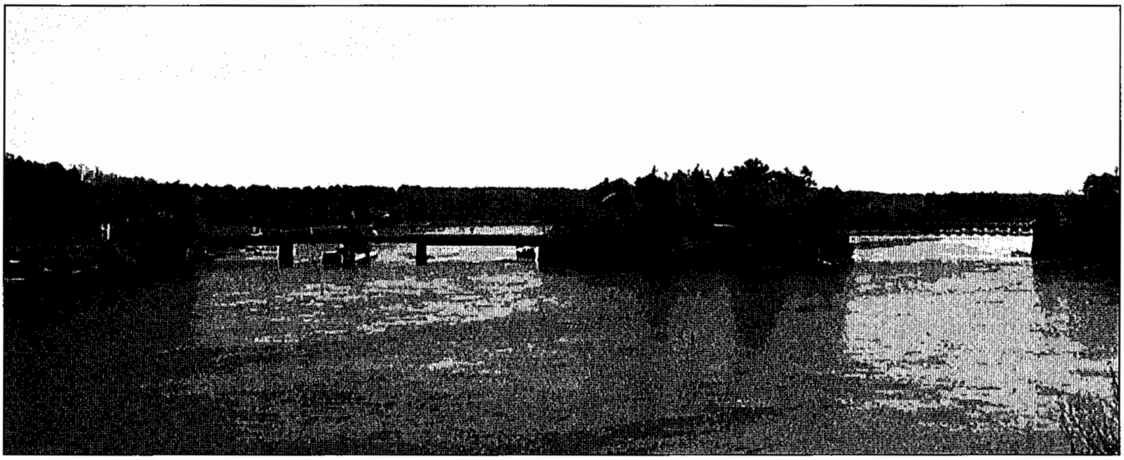

FIGURE 16. The bridge site in 2003.

In 1810, John Templeman, using James Finley's suspension bridge patent, built a chain suspension bridge to replace Palmer's 160-foot arch (see Figures 13 and 14). Palmer's span had been, in the words of boatmen, a "menace to navigation." By going with a 244-foot suspension span, as contrasted to a 160-foot truss with abutments extending greatly into the river, it was possible to open up the southerly passage around Deer Island. The northerly abutment had been 93 feet long and the southerly abutment 185 feet.

The bridge was a long-term financial success since the total toll receipts over its lifetime were $302,276. In 1868, it was purchased from the stockholders by the Commonwealth of Massachusetts for $30,000. In 1909, the bridge was replaced with a wire cable suspension bridge. This new bridge's concrete towers were meant to replicate Palmer's wooden towers (see Figure 15).

Conclusion

Palmer built the first successful long-span wooden truss in America near Newburyport, Massachusetts, in 1792. Drayton, with his sketch and description, did — along with descriptions of Dwight, Gilmor, Liancourt and Pope — "persuade others to inquire more particularly respecting it, and to adopt what may be good in its mechanism."[19] Palmer's reputation was made and the construction of long-span wooden truss bridges can be traced back to his work over the Merrimack.

Figure 16 presents a view of the bridge site in 2003, taken from the Interstate 95 bridge, showing the house still on the island. The lift span on the Salisbury side is now a swing bridge. At the time the photograph was taken, the Chain Bridge (from circa 1909) was in the process of being rehabilitated. Figure 15 shows the bridge after this rehabilitation. The rehabilitation cost $4,583 570.

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Aqua Teen Hunger Force Attacks I-93!

Are structures, such as bridges, that are designed to be sleek and "clean" destined to always remain so?

BRIAN BRENNER

In the "we have more things to worry about than this" department, a strange story unfolded in Boston on January 31, 2007. A cable television network unleashed a guerilla advertising campaign on the citizens of the metropolitan area. The network was advertising one of its late-night television cartoons, *Aqua Teen Hunger Force.* This show is about talking French fries and a meatball. The advertisements consisted of small electronic signs that lit up at night. These little signs were posted all over the city, and several were placed on bridge columns. The lights formed the shape of one of the television show's characters. The concept behind the unconventional advertising campaign was that it would be able to bypass traditional, older outlets and methods (with their older customers). The ads were directed at hard-to-reach young men, who apparently do not read much but like to buy things and drive their cars.

At night, the small signs looked like something made out of "Lite-Brite" toy panels — not very threatening. During the day, it was a different story. The signs had wires poking out the back, with exposed circuitry and batteries. They looked like bombs. For several weeks the signs were not noticed (and that is another issue worth contemplating). Then, a transit worker saw one attached to a steel column supporting the double-deck structure of I-93 just north of the Zakim Bridge. Not knowing what it was or why it was there, the worker called in an alarm, and forces quickly mobilized to detach and destroy the threatening device. More signs were found, setting off a chain reaction of hysteria paralyzing half the city. Interstate 93 was closed, along with the Mass. Avenue Bridge and Storrow Drive. A hospital was temporarily evacuated. Sapper squads were called in to disarm more signs as they were located. The signs were blasted and disabled by water cannons. Eventually the media got wind that the devices were harmless. After many hours of massive traffic jams and dislocation that some thought rivaled the *War of the Worlds* radio broadcast in 1938, things eventually quieted down and the incident moved into the recrimination phase.

Aftermath

Bridges are prime targets for guerilla advertisers because of their high visibility and low

FIGURE 1. Protest banner hanging from a bridge.

clutter. A sign can really stand out on a bridge because these structures are not designed to be billboards. Bridges also provide a built-in audience of thousands who drive across and under them. Sometimes this audience is held captive in traffic jams, and then what better place than that to provide a diversion? However, bridge structures are usually not designed for advertisements because engineers envision sleek superstructures with graceful lines and smooth surfaces. Lite-Brite advertisement panels are usually not included in construction bid documents. But the jarring discord of the ads is part of the appeal for underground advertisers, who get an effective, low-cost product that really sticks out and makes an impact. Although, in the case of the cartoon campaign in Boston, the ads also had another, unanticipated impact.

Public Structures & Public Forums

Recently, bridges have started to be used for a lot more applications than just crossing roads and rivers. Banners are now hung from bridge decks and pedestrian fencing. Many of these banners are large sheets welcoming soldiers home from tours of duty abroad. Some banners have been used as a means of protest (see Figure 1).

A website created by a group in North Carolina protesting the Iraqi war provides helpful, practical instructions on how to hang a banner from a bridge.[1] For example, one instruction from the site states that protesters should "attach about nine grapefruit-sized water balloons to the bottom edge of banner" to help avoid having the banner ravel and roll.[1] The instructions did not include asking for permission to hang the banners ahead of time, but they did suggest that participants should take photographs to document the event. This way, the protest and message could live on through the Internet and blogs.

In 2005, a bridge in England unwittingly served as the canvas for a nasty divorce battle.[2] The participants hung dueling banners.

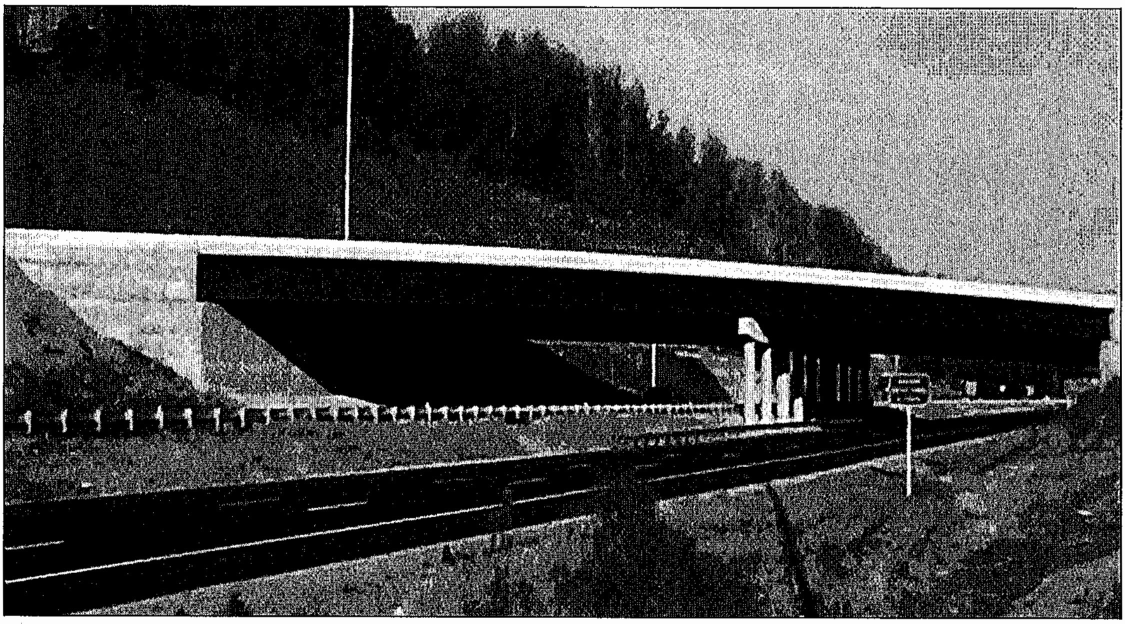

FIGURE 2. A bridge with pier cap and columns too thin in proportion to girders.

His said: "WENDY, I WANT A DIVORCE. JBS." Hers said: "NO WAY. YOU ARE THE CHEAT! WENDY." Documentation is not available on whether or not JBS or Wendy prevailed, but apparently the bridge made it through fine.

Banner Maintenance

A lot of energy goes into hanging up the banners. Not much goes into taking them down. Driving around on the freeway these days many examples of decaying banners, frayed sheets with fading, running lettering can be seen. However virtuous the original message, torn and frayed banners become no better than graffiti, defacing the bridge and its surroundings. Sometimes the message is unintentionally sad, like when a soldier is being welcomed home, but the sheet is ripped and you cannot read all the letters. At that point it is not much of a welcome.

The Issue of Aesthetics

In its essence, the bric-a-brac hung on bridges is jarring because it violates the fundamental principle of "form follows function." It can be argued that beauty is in the eye of the beholder, but most manuals on bridge aesthetics offer a different argument — that good aesthetics can be achieved by the proper dimensioning of a bridge structure and the treatment of its details. This engineer-friendly approach stipulates that aesthetics can be quantified to an extent. Engineers do not have to be artists to design aesthetically pleasing bridges. Guidelines can be followed to at least end up in the right ballpark. For example, piers should be in proportion to beams, not too wide and not too thin. Figure 2 shows a beam bridge where the pier columns and caps are too thin in proportion to the girders. Bridges should appear and be proportioned with dimensions that properly reflect the structural function. To an extent, this design approach is even clear to non-engineers, although they probably do not have the vocabulary and training to understand why a particular structure is ugly.

With the basic form and shape of bridge properly determined, other treatments can be thought of as "add-ons." Context-sensitive design stipulates that structures should be designed in harmony with the surroundings and not oblivious to them. The Federal Highway Administration defines a context-sensitive solution (CSS) in this way:

> "CSS is a collaborative, interdisciplinary approach that involves all stakeholders to develop a transportation facility that fits its

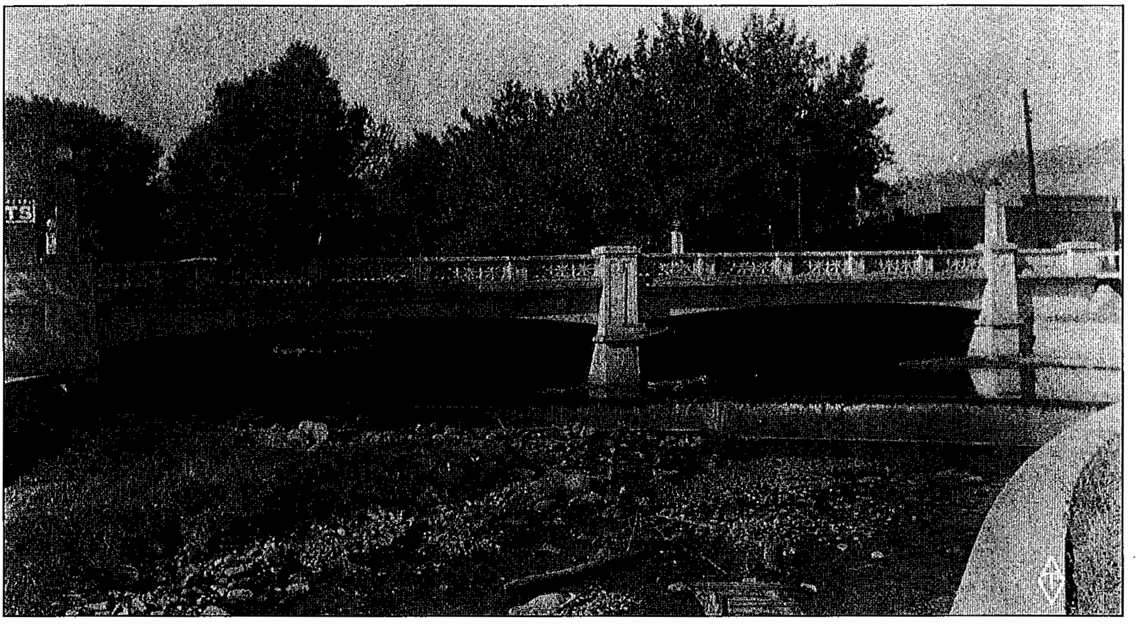

FIGURE 3. The original Broadway Creek Bridge.

> physical setting and preserves scenic, aesthetic, historic and environmental resources, while maintaining safety and mobility. CSS is an approach that considers the total context within which a transportation improvement project will exist."[3]

This design goal is admirable (and somewhat obvious). A subset of the approach states that the appropriate context can be achieved for bridges by improving surface, texture and color. Sometimes a context-sensitive design argument supports a false architectural façade in front of the actual structure. For example, a beam bridge may have masonry arch panels stapled in front to make it look like an arch bridge. For the Broadway Creek Bridge reconstruction in Boulder, Colorado, the original, historic masonry structure (see Figure 3) was replaced by a concrete beam bridge (see Figure 4). The new bridge had arch-shaped fascia panels.

This approach to bridge aesthetics can work if the underlying structure is properly dimensioned to begin with. The Broadway Bridge project manager commented:

> "A lot of bridges, such as this one with its false arch façade, are very utilitarian in their design... Often in a bridge rehabilitation, the architect will cover the bridge up to look like something it isn't... One of the things that we stressed in the design was that we wanted it to be elegant and pure in form."[4]

So, if the underlying structure is not properly dimensioned, the results may be less than optimal. To paraphrase Dick Cheney, who paraphrased someone else, "You can put lipstick on a pig, but it's still a pig."

Implications

There has been a long-standing debate over whether we should have a squeaky clean, ordered infrastructure versus a more free-wheeling, laissez-faire approach. Some argue that graffiti is art, and others argue that it defaces the environment. Boston's Aqua Teen bridge assault is not likely to resolve things one way or the other, or lead to a constructive contribution to this discussion. The company that conceived the advertising campaign was widely denounced for its seeming lack of basic common sense — in the year 2007, is it really a good idea to advertise with devices that look like bombs? The parent company ended up paying millions of dollars to Boston agencies to pay for overtime and emergency services provided during the height of the hysteria, and the head of the cartoon company resigned. However, that payout was only a fraction of the total cost of the event since there were also the thousands of hours of lost time of people stuck in the traffic jams, and the ensuing lost business. Yet, the offending company could have easily paid ten times as much and not gotten the quality of exposure and buzz that advertisers crave. Even with the black eye, the multi-million dollar payout and a top executive falling on his sword, the campaign was probably determined to be (behind closed, hermetically sealed doors) a whopping success.

So there is a built-in motivation and drive for future guerilla marketing approaches of this type, maybe not as brazen as the Lite-Brites and, it is hoped, not as disruptive. In these future campaigns, bridges may be not just bridges but giant spanning billboards, ripe for the next huckster to sell their wares.

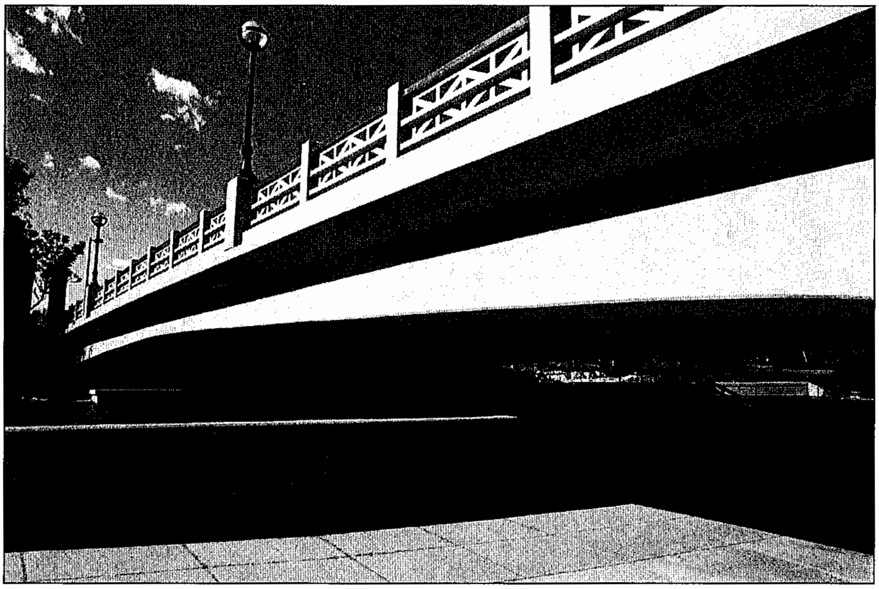

FIGURE 4. The new Broadway Creek Bridge.

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Dilatometer & Cone Penetration Tests on Peat Soil in Carver, Massachusetts [Supplement]

ASSEM ELSAYED

In the article entitled, "Dilatometer and Cone Penetration Tests on Peat Soil in Carver, Massachusetts" that was published in the Fall/Winter 2006 issue (Vol. 21, No. 2) of *Civil Engineering Practice*, there was insufficient acknowledgement for material presented therein. Therefore, the author wishes to acknowledge the following sources and contributions to that article:

- The subsurface investigation in the project was designed, conducted and sponsored by the Massachusetts Highway Department by Nabil Hourani, Peter Connors and Edward Mahoney.
- The cone penetration testing was conducted by WPC Engineering, Environmental & Construction Services of South Carolina under the supervision of Dr. Edward Hajduk.
- The dilatometer data presented in Figures 5, 6 and 7 were collected by Dr. Heather Miller (of the University of Massachusetts-Dartmouth), Dr. Jean Benoit (University of New Hampshire) and Kevin Stetson (Sanborn Head Associates) as part of a research project funded by the Massachusetts Highway Department.
- The interpretation of the cone penetration test and dilatometer data was conducted under the guidance of Professor Pradeep Kurup as part of the author's studies at the University of Massachusetts-Lowell.
- The author's study at the University of Massachusetts-Lowell entitled, "The Characteristics and Engineering Properties of Peat in Bogs," was related to the Route 44 construction and was sponsored by the Massachusetts Highway Department via Geosciences Testing and Research of North Chelmsford, Mass. That work was conducted under the guidance of Professor Samuel G. Paikowsky (of the University of Massachusetts-Lowell), who contributed the write-up of the project description and some of the figures that appeared in the article.

Professional Services

Professional Services

A view of buildings of One International Place in Boston.
Photo by Patrick Barber.