Post Driveability Study for Caesar’s Rhine Bridge 55 B.C.

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ABSTRACT

As the story goes, in the early summer of 55 BC the Roman general Julius Caesar had a 400 m long bridge built over the Rhine within just 10 days and then demolished again after a few days. According to Caesar, the bridge was built to be able to carry out a punitive expedition against the Germans on the right bank of the Rhine. The bridge was undoubtedly a beam or yoke bridge. The distances between the yokes were at most 12 m, so that a total of 30 - 35 yokes were required. The piles consisted of tree trunks pointed at the bottom, most likely without the iron pile shoes that were otherwise common among the Romans. The piles were driven into the riverbed with specially designed pile drivers, which means that there must have been experience with taking pile driving conditions into account and understanding of those conditions at the job site. Nowadays a pile driveability study would have been part of the bridge design process. The authors took up the challenge to perform a post driveability study for this bridge based on the limited data available and the results are presented in this paper. The predictions were performed with the wave equation program AllWave-PDP.

1. INTRODUCTION

As the story goes, in the early summer of 55 BC the Roman general Julius Caesar had a 400 m long bridge built over the Rhine within just 10 days (Figure 1). Knowledge of this technical masterpiece has been preserved for posterity as Caesar himself included the feat in great detail in his war report "De bello Gallico" (Book 4, 11 – 18), which he wrote in his traveling carriage as his troops marched onwards. At that time, Caesar was proconsul in Gaul and he had travelled to the Rhine as part of a punitive expedition against the Germans on the right bank of the Rhine (territory that was not part of the Roman Empire). Despite or maybe even because of the archaic construction, the bridge was extremely resilient and allowed the Roman troops to cross the river immediately after completion, as Caesar stated in his report (Book 4, 18:1). To protect against enemy attacks or the destruction of the bridge, troops were stationed on each side of the bridge. After 18 days Caesar decided to end the punitive expedition and together with his troops he returned over the bridge, which was then demolished (Book 4, 19:4). It is interesting to note that no mention is made how long the demolition work took. The exact place where this first bridge over the Rhine was built has not been definitively determined (Ditchen, et all. 2012). The latest archaeological investigations contradicted earlier assumptions that put the location near Bonn. It is now assumed that it was built not far from the confluence of the Moselle and the Rhine near Neuwied, just north of

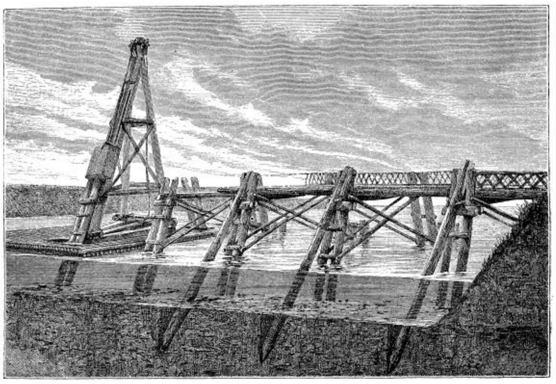

Fig 1. Artists impression of Caesar's Rhine Bridge. construction with floating pile driving rigs, 55 B.C.

Koblenz (Figure 2). Oak posts, which were dated to the first century AD, were found there in the Rhine. If this assumption is correct, this bridge should have had a total length of at least approx. 260 m, based on the width of the river there.

Fig. 2 Assumed route of the Roman troops and the location of the Rhine Bridge location near Koblenz.

2. AVAILABLE INFORMATION

Caesar describes the structural design of the bridge in great detail in his war report (Book 4, 17). As stated earlier, the war report claimed this Rhine bridge was completed 10 days after his soldiers had started to gather the timber (Book 4, 18:1). On the one hand, countless soldiers specialized in building trades were available to Caesar from the legions; on the other hand, it must not be forgotten that Caesar fought this Gallic War mainly to further his political career in Rome. Therefore, it cannot be ruled out that he embellished the descriptions included in his war report (Ditchen, et all.).

3. BRIDGE CONSTRUCTION

The bridge (Figure 3) was undoubtedly a beam or yoke bridge. Many have tried to reconstruct the bridge, including Napoleon III (Figure 4, 1866). The necessary materials (such as strong tree trunks, poles, brushwood, stones and soil) could easily be obtained in the surrounding (heavily wooded) area. About 50 large yokes were created, which at that time only consisted of freshly felled oak trees. As described in the war report, they were about 1.5 feet in diameter, i.e. about 444 [mm] (1 foot = 296 [mm][1]), slightly pointed at the bottom and adapted to the depth of the river. Logs were tied together at two feet intervals, put into position with canoes and rafts, and then driven into the bottom of the Rhine with a pile driver on a raft. In order to be able to withstand the current, the piles were inclined. To protect these piles against the current, wave breakers, consisting of groups of piles, were also installed. The deck was nine meters wide, covered with brushwood, and made of logs and wooden planks. The extraordinarily short construction time of just ten days (this also includes felling and processing the trees and probably procurement of all materials) suggests that work was carried out around the clock. The logistical and technical challenges of

Fig. 3. Artist impression of Rhine Bridge construction

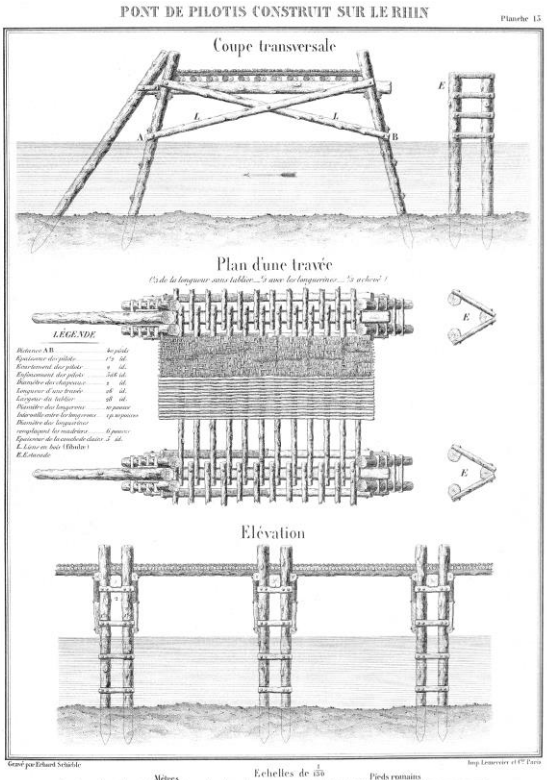

Fig. 4 Reconstruction of the Caesars Rhine Bridge by Napoléon III (1866).

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[1] The foot in roman times was slightly shorter than the foot in the inch-pound unit system.

this bridge building project are amazing. Although not specifically mentioned by Caesar, the credits should probably go to Mamurra, a member of the Equites, the Roman equivalent of the Cavalry, who served as Caesar's "Prefectus Fabrum" or Chief Engineer (as reported by Pliny the elder in his Natural Histories). He took part in the Gallic Wars and oversaw the construction of not only bridges, but also ships designed by him

4. PILE INFORMATION

The piles consisted of oak trunks pointed at the toe, most likely without the iron pile shoes (Figure 5) that were otherwise common among the Romans. The piles were 444 mm in diameter with an average length of 8 m, based on the assumed depth of the Rhine of 3 - 4 m at that time. The yoke piles were placed under a batter of 60° to 70°. The modulus of elasticity of the fresh oak piles is estimated as 10000 MPa and the density as 969 kg/m^3. The maximum compression strength is estimated as 15-20 MPa.

Fig. 5. Oak piles of the Großkrotzenburg Bridge with iron post shoes 136 AD, Saalburg Museum, Germany

5. SOIL INFORMATION

Borings performed in the Rhine where the bridge was assumed to have been located revealed a 4 m – 5 [m] deep layer of gravel. An example of recently excavated gravel from the riverbanks is presented in Figure 6. For modelling the soil resistance in top part of the gravel layers is estimated to be equivalent to a CPT tip resistance q_c in excess of 5 – 10 MPa and a friction ratio of 0.2 - 0.5 %.

Fig. 6. Nowadays gravel bed example near Koblenz

6. PILE DRIVING

According to Hinz (2017, Figure 7), assuming a width of 350 m – 400 m of the Rhine, 240-264 piles would have had to be driven. To fit the 10 days construction time, he concluded it would have required 3 pile driving rigs: two small ones and a big one. The piling rigs had to be manufactured on site by the military engineers and positioned on a raft that was anchored at the respective location. Heavy hewn stones served as drop weights (rams). The weights were lifted by human power using pulleys and then released. Probably more than 5 soldiers were active for the lifting of the ram. There is still a discussion going

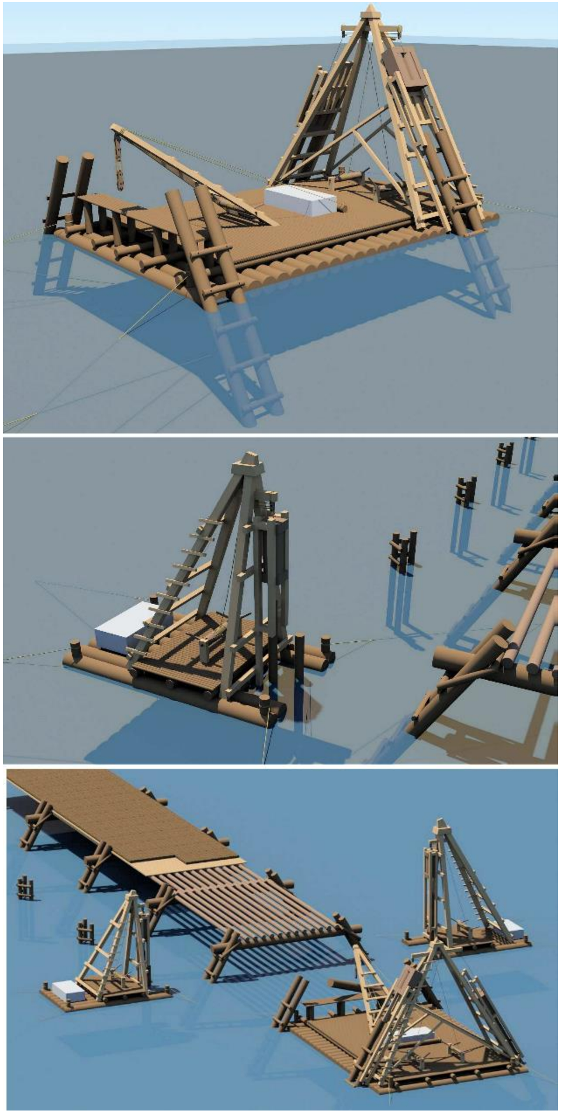

Fig. 7. Reconstruction of Caesar's Rhine Bridge and pile driving activities by Hinz (2017)

whether the piles were driven one at a time or as a yoke (i.e., a combination of 2 piles).

7. PREDICTIONS AND RESULTS

The predictions were performed with the Pile Driving Prediction program AllWave-PDP (Middendorp, 2022). Because the drop heights of the rams are not known, the maximum drop height is assumed to be restricted by the maximum compression strength in the oak piles of 15-20 MPa. The pointed toe of the pile is incorporated in the toe resistance modelling to start from 1 to 10 MPa over the length of the point (2 x diameter) and at 10 MPa for deeper penetrations. The predictions were performed at intervals of 0.05 m to a maximum pile toe penetration of 2 m for two different drop masses: 750 kg and 1500 kg. Further a lower bound and upper bound of the soil resistances were introduced to study the sensitivity to the change in soil resistance. The lower bound was 0.8 of the best estimate soil resistance and the upper bound 1.2 of the best estimate soil resistance. The impact energy for the 750 kg drop mass was 15.7 kNm and for the 1500 kg drop mass 31.4 kNm. The piles were modeled as 9 m long with a 0.444 m diameter and an

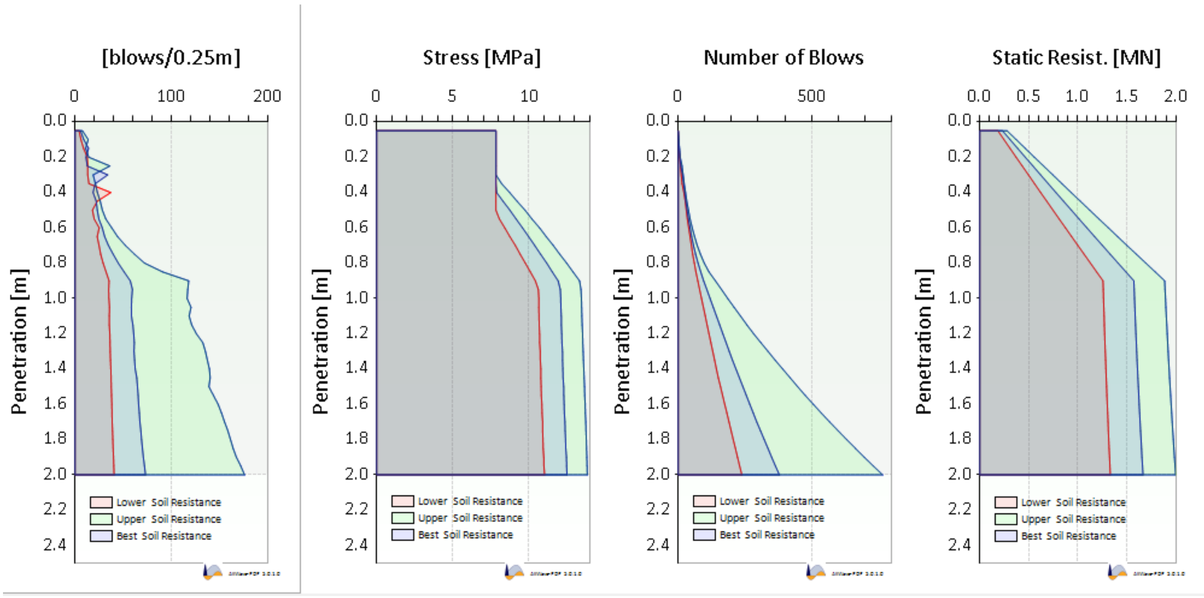

Fig. 8. Prediction results for 750 kg ram

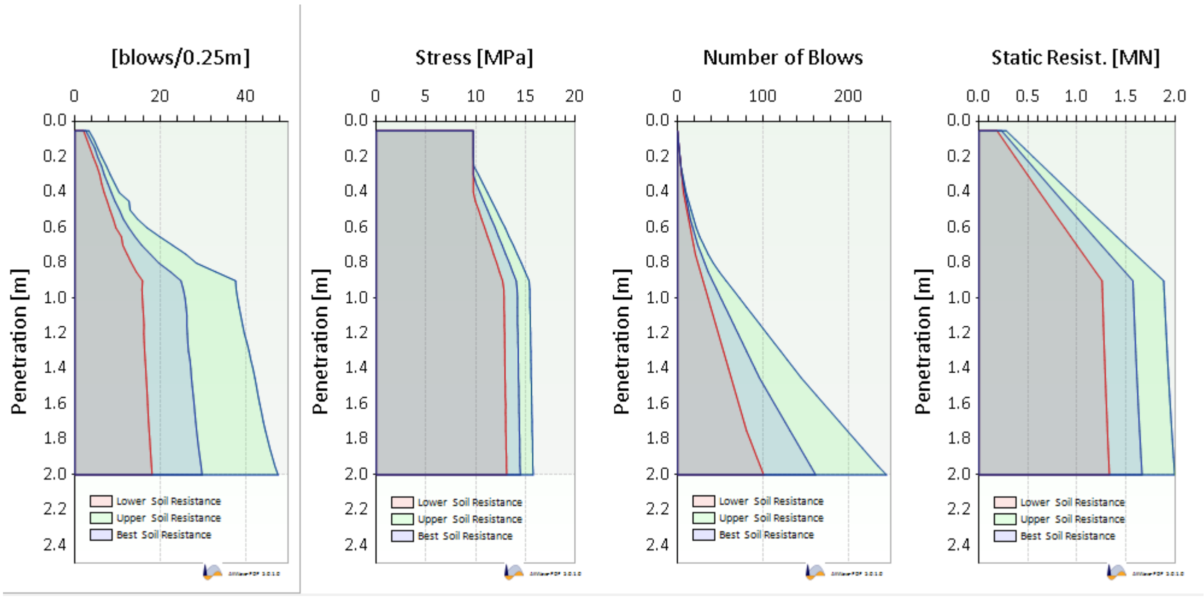

Fig. 9. Prediction results for 1500 kg ram

inclination of 70°. The results of the predictions with the 750 kg ram and 1500 kg ram are presented in the Figures 8 and 9. They represent as a function of the pile toe penetration in the river bed the blow count, the maximum compression stress, the total number of blows and the static resistance (bearing capacity) of the pile, respectively.

According to Hinz (2017), to meet the 10 days installation requirement, only one hour was available to drive a pile. Assuming that lifting and dropping of the ram took about one minute then the pile had to be driven to final penetration in 60 blows or less. Based on the best estimate results, a total of 60 ram blows would correspond with a penetration depth of 0.8 [m] for the 750 [kg] ram and a penetration depth of 1.1 [m] for the 1500 [kg] ram. In all cases the ultimate bearing capacity of the piles exceeded 1.1 [MN], strong enough to carry the vertical loads.

8. LATERAL FORCES

An estimate of the horizontal current forces acting on one pile can be made with the drag force equation

$$F_D = 0.5\rho C_d v^2 A$$

where F_d = the horizontal drag force on the pile [N], ρ = density of water [kg/m3], C_d = drag coefficient [-], v = the velocity of the river flow [m/s] and A = the vertical cross-sectional area [m^2] of the pile.

The river flow velocity v of the river Rhine varies nowadays between 6 and 12 km/hr. At that time the river was less deep and wider, and it can also be assumed that Caesar would not build the bridge at high water levels with high current velocities. A current velocity of about 8 km/hr, which equals 2.2 m/s, has been assumed

Assuming ρ = 1000 kg/m^3, C_d = 1.17, v = 2.2 m/s, and A = water depth x diameter = 5 x 0.444 = 2.2 m^2

$$F_D = 0.5\ x\ 1000\ x\ 1.17 x\ 4.84\ x\ 2.2 = 6229\ [N]$$

It should be noted that actual drag forces on the piles would have been lower given the installed wave breakers.

The reacting lateral gravel force F_g can be calculated with

$$F_g = \sigma_g A_l$$

The lateral resistance pressure of the gravel σ_g is estimated as 2.5 MPa, A_l is the lateral cross section and depends on the pile toe penetration p.

Assuming that at least the pile toe point was fully driven into the gravel, the lateral cross section would then be A_{toe} = 0.5 x D x 2D = 0.197 m^2, resulting in a lateral resistance F_g of 0.197 x 2.5E6 or 492500 N. This lateral resistance value already exceeds the current drag forces calculated above.

9. CONCLUSIONS

The post driveability predictions show that for Caesar's Rhine Bridge, driving the pile toe to a penetration level generating capacities high enough to carry the top loads and withstand the current drag forces must have been possible based on the assumptions made.

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