Supplementary material

Values and costs in history: A case study on estimating the cost of Hadrianic aqueduct's construction

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1. Description of the construction of Hadrianean aqueduct 134—140 AD

Underground research revealed new evidence regarding the tunneling technique applied (Figures S1-S4).

(a) (b) (c)

Figure S1. In situ research inside the Hadrianic aqueduct (a) Prof. Nikos Mamassis prepares to enter in the aqueduct by a well; (b, c) Members of the "Urban Speleology Research Team" entering to the aqueduct by wells.

(a) (b) (c)

Figure S2. In situ research inside the Hadrianic aqueduct (a) Second author, Panos Defteraios and Prof. Nikos Mamasis inside the tunnel of the aqueduct; (b) Prof. Nikos Mamasis inside the tunnel of the aqueduct (c) Member of the "Urban Speleology Research Team" in the tunnel of the aqueduct.

(a)

(b)

Figure S3. In situ research inside the Hadrianic aqueduct (a) Research team; (b) Forth author, Prof. Nikos Mamassis prepares to enter in the aqueduct by a well.

(a)

(b)

(c)

Figure S4. In situ research inside the Hadrianic aqueduct. (a, b, c) The tunnel of the aqueduct

The correction of deviations from the planned geometry of the tunnel is of special interest. Tunneling used to start at the bottom of a shaft and was directed to the bottom of the next one upstream, as indicated by S-shaped curved paths necessary to meet the next shaft. When the lateral deviation was small and the tunnel section passed higher or lower than the shaft bottom, then the tunnel was enlarged vertically to pass at the scheduled elevation; in this case, there was an elevation difference on both sides of the wells.

The larger section of the tunnel occurred downstream when the tunnel crossed the shaft too high and vice versa. In cases of both lateral and vertical deviations, the tunnel followed an inclined S-shaped path toward the targeted bottom of the adjacent shaft upstream.

Obviously, before tunneling, an accurate topographical survey was conducted, which determined the locations of the shafts and their depth; any deviation from this plan was corrected and absorbed in the section between two adjacent shafts. It was achieved in this way to reach the targeted point on Lycabettus Hill in Athens at the proper inclination and pass successfully the tunnel below streams and particularly the Kifissos River, dipping continuously downstream.

The tunnel followed a U-turn at the area across the Kifissos River, to gain the necessary route for smooth dip. The section of the ancient tunnel below the river used to pass a few (about three to five) meters below the riverbed in antiquity and survived until 1930, when it was eroded during a torrential rainfall; it was then replaced with an iron pipe encased in concrete. Upstream tunneling implies that the starting point was at the surface, for the natural flow of the water during the tunneling stage.

2. Phases of the construction of Hadrianean aqueduct

Feasibility study

(a) evaluation of water potential of Parnis and Penteli areas (experimental wells, local springs discharge estimation); (b) preliminary surveying works (length, dimensions and slope of tunnel, number and height of wells); (c) evaluation of several scenarios of the course of the aqueduct considering geological and hydraulic conditions and final design.

A wide team of Roman engineers and local technicians was needed. During this stage information must be gathered about water resources of the area (springs, existing wells). Also, experimental wells must be opened in order to estimate the ground water characteristics and the geology at tunnel level. Preliminary surveying works must be done to design the hydraulic characteristics (slopes, possible courses) of the system. Finally, several scenarios of aqueducts course and auxiliary works must be evaluated for the final design.

In this phase the header team has to consider the fronts of the construction. As some parts of the aqueduct are under the water horizon and there are inflows of water through the direction of the aqueduct, the construction process had to begin from down to up in order, the lower part of the aqueduct to be functional during the construction. If this did not happen, the laborers should work underwater where the ground water horizon would be higher than the aqueduct.

We consider that a team of 5 officials, 30 high skilled workers (engineers) and 60 workers would be occupied for 12 months.

Surveying works

(a) definition of the course of the aqueduct and the position of the wells to the ground; (b) assistance during excavation works (height of the wells, slope and direction of tunnels) [1-3]

A wide team of engineers must trace the positions of the wells on the ground and determine their depth. Also, during next stage (excavations) surveyors must assist the workers checking continuously the course (direction and altitude) of the tunnel in several fronts. We have to imagine that the surveying works have to be very accurate as the construction must have a slope about 2‰ starting from the beginning for more than 10km, in order to pass under the river Kephisos and find the springs from Parnetha.

We consider also a team for supervision as follows: leaders equal to (number of workers/100); high skilled workers (engineers) equal to (number of fronts); people working to logistics equal to (number of workers/20).

Excavations works

(a) wells; (b) tunnels

The excavations works is main effort of the construction and demands a large number of workers for a long time period. These two parameters are depended on (a) the number of different fronts that excavated simultaneously and (b) the working time during a year. The digging of the wells must have been made first. This is convenient not only for management purposes but also to have an indication of the stage of water depth that determined the process of tunneling. This consideration is also supported from the unfinished structure that constructed during 4th century B.C for Lake Copais drainage. The project included the construction of a tunnel using 16 wells. All the wells were built but the tunnel never started [4].

Next step was the tunnel excavation. Tunneling used to start at the bottom of a well and was directed to the bottom of the next one upstream. The correction of course deviations from the planned geometry of the tunnel is of special interest, as indicated by S-shaped curved paths necessary to meet the next shaft. When the lateral deviation was small and the tunnel section passed higher or lower than the shaft bottom, then the tunnel was enlarged vertically to pass at the scheduled elevation; in this case, there was an elevation difference on both sides of the wells. The number of simultaneous fronts is of special interest and is strongly depended with the time scheduled but also the management of ground waters during excavation. The simultaneous construction of a number is probable.

Finishing works

(a) coating of the wells and the tunnel; (b) final construction (plasters etc); (c) auxiliary works (cisterns, lateral inflows etc)

The finishing works include the coating of the wells and the tunnel and the auxiliary works. The coating of the wells must have been done simultaneously with excavation stage. The final configuration of the tunnel (coating, plasters erc) could be started earlier than the finish of total excavations in parts of the aqueduct that have been excavated.

3. The efficiency of workers in different phases

Workers

As slaves were not economic efficient, workers should be free people who would be paid for their work. There should be a hierarchical division of labor and therefore a stratification of salaries. Their working days would be 250 per year with 6 hours per day.

For well excavations

The area of the Hadrianic wells is in average 1 m^2 and permits the work of 2 workers (one to dig and one to remove the excavation material). Taking into account the calculations of Konofagos (5.76m^3) we consider a shift of 2 workers ("continuous workers").

The difference of wells from the tunnels was that as wells in Laurion were rectangular with typical area of 2 m^2 Konofagos considered that the area permitted the simultaneous work of 3 "continuous workers". So, the progress was calculated to 3*5.76 m^3/2=8.64 m/month. Also calculates the progress to be 5.76 m/month in case that 2 "continuous workers" were used and mentions the hypothesis of Ardaillon [8] with 2 "continuous workers" that estimated a progress of 5 m/month.

For the tunnel excavation

To estimate the time and the effort of the project a significance source is the work of Konofagos [5]. The book describes the procedures for digging wells and tunnels and exploit silver and lead in ancient Laurion mines [6] an area that prevail marbles.

Konofagos considering the used tools and the ability of the worker in the front of the tunnel, estimated that he can excavate about 0.008 m^3/h. As the worker must be shifted every few hours, several workers are necessary for a 24h operation [7]. Konofagos hypothesizes a 12 hour for a worker which can work in the front for 5 hours. However, Laurium mines used slaves in contrary to the construction of Hadrianean, therefore smaller labor time should be considered.

Using the term "continuous worker" Konofagos describes a procedure where the front is dug 24h per day 30 days per month. A quantity of 0.008 m^3/h*24h*30d= 5.76 m^3 is excavated per month. Considering that the average Hadrianean tunnel area is 1.08/ m^2 (that corresponds to an excavation volume of 0.6 m^3 per meter of the tunnel) the maximum progress is estimated to be about 5.76m^3/1.08 m^2=5.3m/month. Konofagos also mentions the estimations of Ardaillon [8] of 7.2 m^3/month that correspond to a progress of 6.6 m/month.

A typical Hadreanean part of tunnel has dimensions 0.5x1m (0.9x1.2m without coating) and length 40 m between 2 wells. Taking into account the calculations of Konofagos (5.76m^3) we consider a shift of 3 workers. They will be rotated in (a) worker in the front (b) supporter of the worker in the front and (c) a worker which will move the excavation material out of the tunnel.

For coating

According personal communication with traditional stone builders in these circumstances a shift of 2 person for 8 hours can coat an area of 4 m^2.

For Stones

The estimated stone used for coating is about 40,000 tones. One skilled with two assistant workers are needed, in order to product and transfer $0.4m^3$ or 1,250kg of stones in 5 hours [9]. A continuous worker will product $60m^3$ or 187.5 tons per month.

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