IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: V Baiocchi *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **949** 012078

IOP Conf. Series: Materials Science and Engineering **949** (2020) 012078 doi:10.1088/1757-899X/949/1/012078

Geomatic measurement of "New Aniene" and "Claudia" roman aqueducts for flows estimation

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Abstract. The aqueducts are the most impressive and original building of the ancient Rome. The aqueducts moved water only by gravity, being constructed with a slight downward slope, within conduits of stone, brick or concrete. All along valleys or plains, the conduit was supported by buildings with arches, or its contents were placed to pressure in lead, ceramic or stone pipes. The aim of this work is to study and determine the slope and so to evaluate the actual flows, considering also that the area is interested by crustal movements. To evaluate it a geomatic survey of a part of the New Aniene and Claudia roman aqueducts was realised. The measured average slopes have values close to the value of 2 ‰ described in ancient texts that report the details of the realization of the Roman works. From the slopes through a hydraulic model the flow rate has been calculated. The general lowering of the study area was also highlighted through the comparison of reconstructed lines slope and those realized in 1917, approximately equal to 0.45 m.

Introduction

The aqueducts are the most impressive and original building of the ancient Rome. Until the year 312 B.C. the Romans were satisfied to use the water that drew from the Tiber, from wells and springs. Subsequently, with the increase of the city, it became more and more urgent the problem of water supply and, especially following the diffusion of the baths, the wells and springs were no longer sufficient. The Romans then began to build numerous aqueducts to bring water from distant sources in their cities, supplying thermal baths, fountains and private homes. The aqueducts moved water only by gravity, being constructed with a slight downward slope, within conduits of stone, brick or concrete. All along valleys or plains, the conduit was supported by buildings with arches, or its contents were placed to pressure in lead, ceramic or stone pipes. Most of the systems of aqueducts included sedimentation tanks, sluice gates and distribution tanks to adjust the supply according to the needs. In the present work a 1917 survey of a part of the roman aqueducts was repeated (where possible), and widened to study a model to better estimate their water flows.
Water, as said, flowed to the point of arrival only by the force of gravity, and then the aqueduct had to have a constant, though minimal, slope. For this reason, the water had to be drawn from springs located

in the hills, higher than the position of Roma, particularly around the east of the city, and every step of the long road had to be carefully planned, depending on the characteristics of the ground. These majestic and immortal buildings have been the focus of the work carried out in this project that is in the field of Metric documentation of cultural heritage [1]. The interest in these ancient structures has always been large within the scientific community, due to the multiple aspects related to them [2]. The aim of this work is to study and determine the original slope of the structure to evaluate the historic actual flows, also taking into account that the area was and is interested by crustal movements [3]. Following the calculations realized during the first part of this project and the reconstruction of the gradient profiles of ;the New Aniene and Claudia aqueducts, it was decided to estimate the flow rates inside the channels finally, these were compared with the flow rates achieved by this type of aqueducts as planned by ancient Romans. To realize these estimates, we used slopes, calculated through total station and GNSS receiver survey, the area of transit sections of flow rates, reconstructed in previous studies in the literature, and the equations of flow in conditions of uniform motion of free surface flow in pipelines.

To realize the reconstruction of the gradient profiles aqueducts we used the data measured during the survey phase of this project, in particular the heights of points on the bottom of the specus and their distances measured along the track of the aqueducts. Particular attention has been paid to the correlation between the altimetric reference system used in 1917 and that currently in use [4,5,6].

The aqueducts studied, follow a route from the boundaries of Roma (Roma Capannelle) and then down into the city center arriving close to Porta Maggiore. In particular, the last measured point belonging to the line of the New Aniene aqueduct is located near Porta Furba, while for the Claudian aqueduct near "Mura Latine" Street. It was then realized an initial estimate of the gradients for the two lines of aqueducts. To realize this estimate it was decided to divide the route into segments for which it would be guaranteed a positive gradient of the aqueducts. In fact, in some parts the subsidence of the structures, already analysed in the preceding step of the project [7], has caused a new trend of the profile that presently does not respect the hydraulic requirements for the outflow of water.

1. Study area

On the basis of the considerations set out in the introduction, it was decided to focus this project on the area between the Porta Maggiore and Roma Capannelle, with a total length of about 10 km, inside of which there are the remains of two massive aqueduct lines: The New Aniene aqueduct and the Claudia aqueduct.

These two aqueducts, built in the same period, followed their path one above the other taking the supplying of their waters from the distant Aniene valley. The reconstruction of the gradient profiles, through the measurement of the heights of several points placed on the bottom of the channels along the two aqueducts of interest, will allow to better study the aqueducts, but not only. In fact, it will hypothesized, through the knowledge of the flow rates of the historical runoff, the sections of the ancient channels, making possible a more accurate reconstruction of the ancient structures. It will be made, finally, a comparison with an ancient leveling, performed in 1917 by Reina et al. [8], which will allow confirming the actual vertical movements of the waterworks structures especially in the last 100 years. To compare these surveys a specific study was made to reconstruct the original height datum that is different from the presently used and that can be estimated measuring unchanged benchmarks as they are described in contemporary maps [9,10]. In fact, a map of the Istituto Geografico Militare (IGM) at a scale of 1:5000 of 1917 was available from previous research [11], on which were reported the benchmarks used for its realization. All the recognizable ones have been surveyed again and referred to modern height datum realized by the GPS/GNSS network provided by the Lazio regional administration. Thus, the differences between the heights measured by Reina et al. [8] in 1917 and the current ones were verified, both in terms of benchmarks and points measured on the aqueducts and currently recognizable.

Figure 1. Obelisk of St. John Lateran Square benchmark.

Figure 2. Santa Croce in Gerusalemme church benchmark.

About the landmarks that date back to the 1917 line leveling there were found two sure in total:

- Landmark located on the obelisk of St. John Lateran Square - start landmark of the 1917 levelling (figure. 1);
- Landmark located on the steps of the St. Croce in Gerusalemme church - 2nd landmark of the 1917 levelling (figure. 2).

As regards the height levelling points, there were found six instead: Points belonging to Marcio, Tepula and Julia aqueducts at Porta Maggiore (figure 3), point belonging to the Claudia aqueduct at Mura Latine Street and points belonging to Claudia and New Aniene aqueducts (figure 4), located in the Aqueduct Park (figure 5).

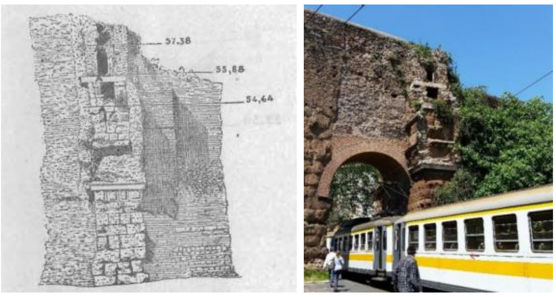

Figure 3. Marcio, Tepula and Julia aqueducts at Porta Maggiore.

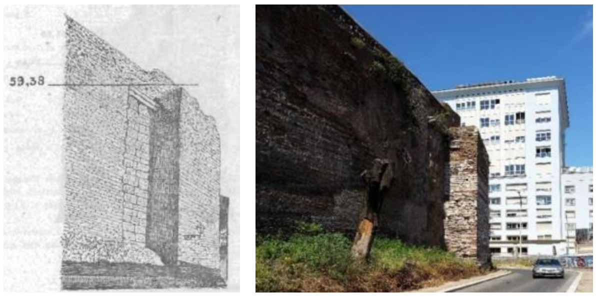

Figure 4. Claudius aqueduct at Mura Latine Street.

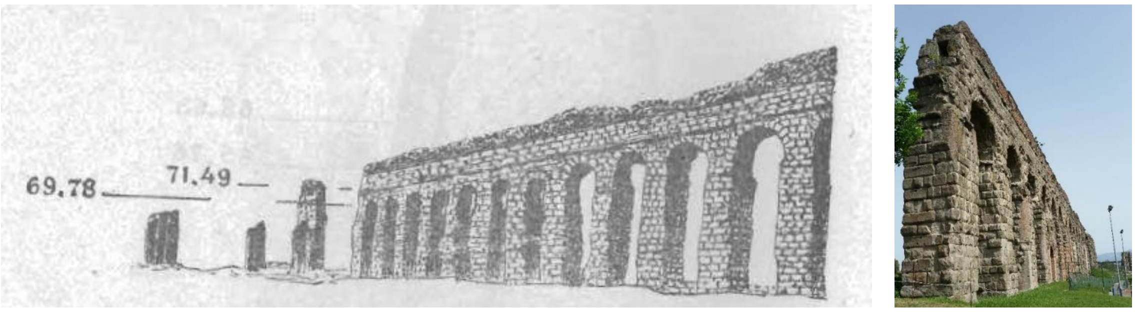

Figure 5. Claudia and New Aniene aqueducts in the Aqueduct Park.

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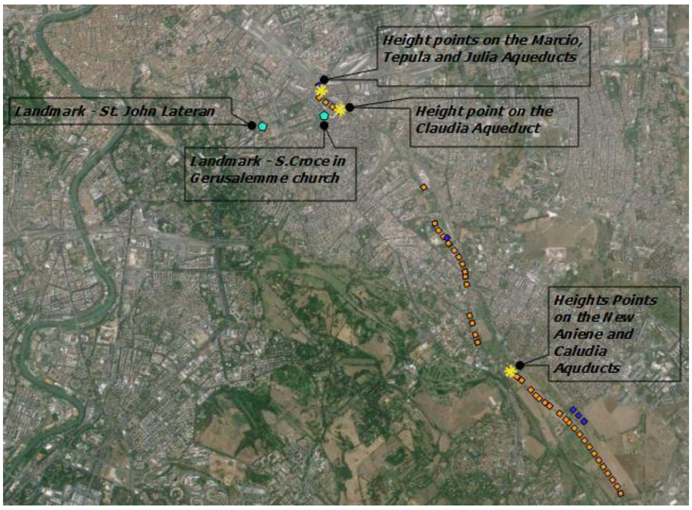

Figure 6. Survey Points common with the 1917 survey.

The items described and shown in figure 6 are the points that were surely identified and measured, all the other points that are certainly recognizable and visible from the ground have been measured. with. The total station's positions were measured by Topcon Legacy-E double frequency GNSS receiver; the GNSS data have been processed in post processing mode with reference to the network of permanent stations managed by the Lazio region [6]. Not being able to safely access the top of the aqueducts, the measurements were carried out from the ground with a total station Leica TRC703. On the same points using a Leica surveying tribrach, to be sure to station at exactly the same height, the antenna of the dual frequency GNSS receiver was subsequently placed. The ellipsoidal heights obtained from GNSS measurements were converted into orthometric heights using the ITALGEO2005 geoid model. In consideration of the declared accuracies for the total station and the GNSS receiver, the accuracy of the single height measurements is assumed to be centimetric. They have obviously been obtained by adding to the ellipsoidal height measured by the GNSS receiver the difference in height between the same station point and the aqueduct measured with the total station. The differences in altitude between points of the same segment of the aqueduct will therefore have accuracies of one or a few cm, while the absolute orthometric heights of the same points must be considered less accurate up to a few centimeters due to the approximation of the geoid model. However, it is important to consider that the orthometric elevations are here used only to compare the current measurements with those of one hundred years ago on which, however, we must consider the already illustrated effect of the uncertain knowledge of the altimetric datum of reference at the time of the measurements themselves. It is important to keep in mind these considerations on the accuracy of the quotas when observing the figures relating in particular to 9 and 10.

In the work realized by Reina et al. [8] are described geometric leveling campaigns performed on aqueducts New Aniene, Old Aniene, Marcia and Claudia. They have made in particular three different lines of leveling: from Rome to Capannelle, from Anagnina street to the estate of Pallavicina, from the estate of Pallavicina to Cineto Romano (figure 7). The segment of our interest, however, is only the first section of Rome-Capannelle, along which are presently visible the aqueducts New Aniene and Claudia.

2. Gradient profiles and flow of the ancient aqueducts

To reconstruct the lines of slope some points on the bottom of the channels of the ancient aqueducts have been acquired. The two aqueducts, as presented in figure 8, follow their path one above the other, maintaining a distance between the channels, almost constant at about 3 m.

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Figure 7. Aqueducts map.

2.1 Reconstruction of gradients

To realize the estimate of gradients, it was decided to divide the route into lengths for which would be guaranteed a positive slope of the aqueducts. In fact, in some parts, due to the subsidence of the structures, the trend of the profile does not respect the hydraulic requirements for the outflow of waters. These points are identified in red in the figure 8.

In figure 9 and 10 are reported the calculated slopes used as hydraulic gradient in the reconstruction of the outflow flow rates.

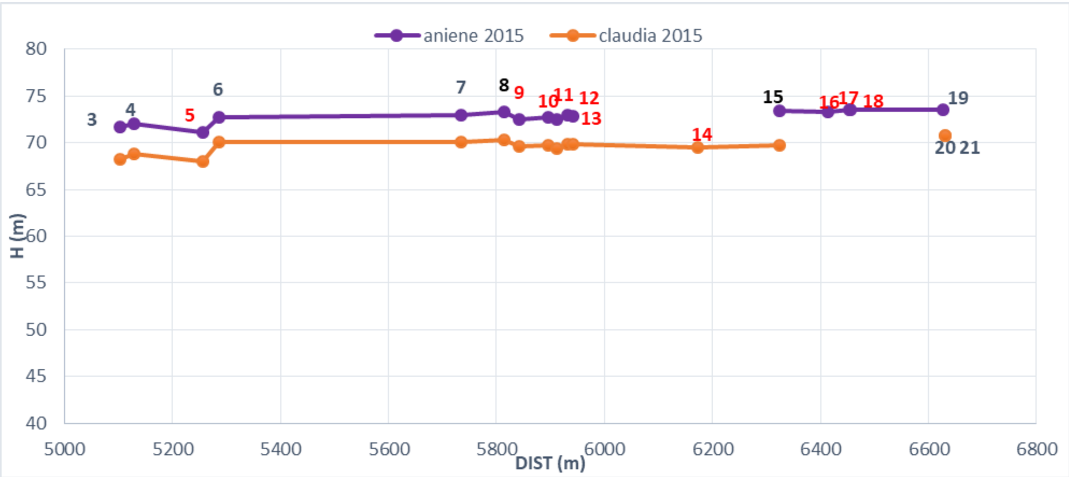

Figure 8. Height profiles of the Claudia and New Aniene Aqueducts– detail in the Aqueduct Park.

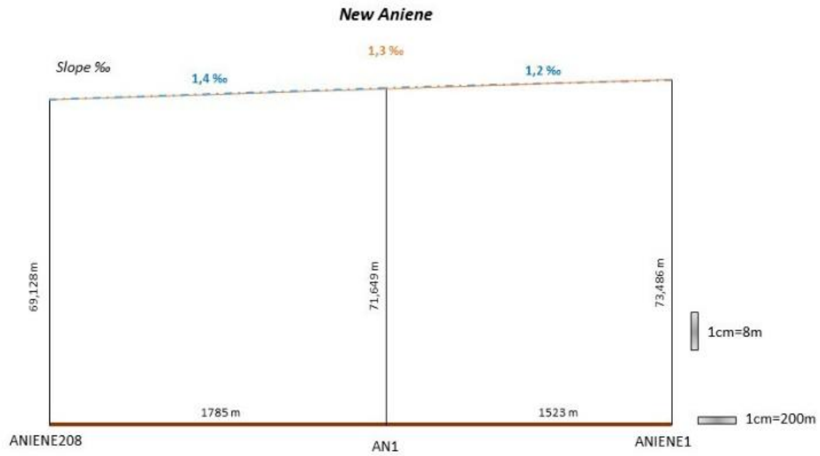

Figure 9. Slope profile – New Aniene Aqueduct.

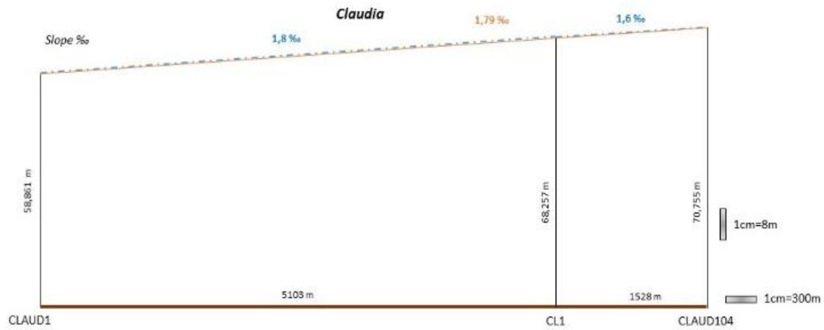

Figure 10. Slope profile – Claudia Aqueduct.

From historical documents and technical studies is assumed that the ancient romans materialize their works while keeping an almost constant slope of 2 ‰. This slope could vary slightly with regard to the routes that aqueducts were to follow, to the obstacles to be overcome and to the flow velocity desired. The calculated average slope for the New Aniene aqueduct in the analyzed section is 1.31‰ and for the Claudia aqueduct is 1.79‰. Those values are in agreement with those previously cited in historical documents.

2.2 Flow rate calculation method

The water flow into the aqueduct has been assumed to be as an open flow with a free surface [12]. Following this assumption, to calculate flow rate was used the equations of flow in uniform motion conditions in pipelines with a free surface. Considering the Chezy relationship to calculate velocity and the Manning ones for the friction factor, the flow rate can be calculated by the following formula (1),

$$Q = A\frac{1}{n}{R_h}^{\frac{2}{3}}\sqrt{S} \tag{1}$$

where R_h is the hydraulic radius, A is the flow area, S is the gradient of the channel or its slope and n is the Manning coefficient, fixed in this study to 0.019 s/m$^{1/3}$.

2.3 Reconstruction of the outflow sections and flow rate calculation

To realize the reconstruction of cross sections in which transited the flow rates of the ancient Roman aqueducts, with particular attention to the lines of the New Aniene aqueduct and Claudia aqueduct, were used some studies into literature. The study by Keenan-Jones et al. [13] (figure12) and the study by

Muench S. [14] have been used to reconstruct both section of the two aqueduct (figure 13). In table 1 are summarized the flow area and the wetted perimeter.

	New Aniene		Claudia
	Keenan-Jones et al. (2015)	Muench S. (2013)	
Flow area (m^2)	1.44	1.97	2.25
Wetted perimeter (m)	4.63	5.48	6.16

Table 1 – Estimate of flow area and wetted perimeter from literature

Using the gradients calculated in paragraph 2.1 and the equation reported in the previous paragraph, was made the estimate of the transited flow rates for the different sections established. In table 2 are reported the comparison between the calculated and the known flow rate.

For the New Aniene there is an underestimation in both geometrical configurations used. Then, the sections used are underestimated for the transit of desired flow rates. Therefore, the reconstruction of the trapezoidal channels of the aqueducts does not return the values of flow rate acceptable, unless a change of dimensions and shape. The rectangular shape can be suitable for the passage of the desired flow rates by increasing not too much the size of the channels.

	Flow Rate (m^3/d)		
	Keenan-Jones et al. (2015)	Muench S. (2013)	From literature
New Aniene	85,868	165,525	196,627
Claudia	-	219,706	191,190

Table 2 – Comparison of calculated flow rate and literature value

In the case of Claudia aqueduct, the calculated flow rates are overestimated and by modeling the degree of the aqueduct filling channels the results are close to the historic ones, confirming a degree of filling of about 90%.

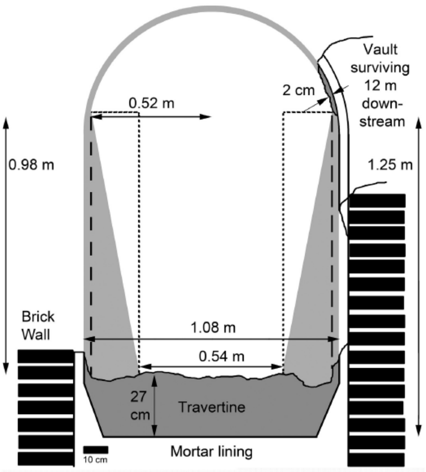

Figure 11. The internal section of the New Aniene Aqueduct [13].

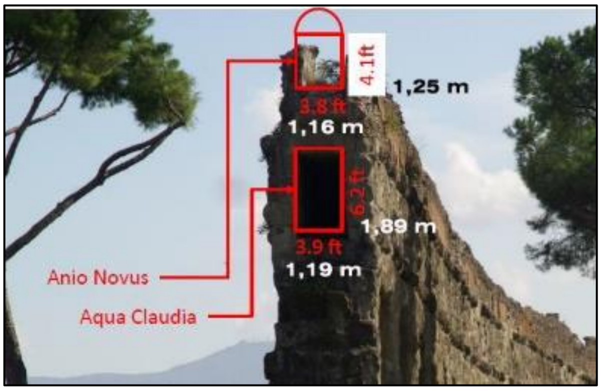

Figure 12. Sections of New Aniene and Claudia Aqueducts [14].

3. Conclusions

In this work has been surveyed, reconstructed and estimated the slope profiles of the New Aniene and Claudia ancient Roman aqueducts, within the south-east area of the Rome city. Unless the errors due to the instrumentation used and environmental aspects during the acquisitions (± 2 cm), it was possible to reconstruct in some detail the path followed by the two lines of aqueduct. The starting points used for the reconstruction of the two profiles were respectively: for the New Aniene aqueduct Mandrione Street, where there are impressive remains of the aqueduct and for the Claudia aqueduct Mura Latine street, in which the aqueduct is visible in a portion leaning against the ancient walls. The arrival point for both lines is ultimately located inside the Park of the Aqueducts. The average calculated slopes have values close the average value of 2 ‰ described in ancient texts that report the details of the realization of the Roman works. In particular, were obtained average values equal to: 1.79 ‰ for the Claudia aqueduct; 1.31 ‰ for the New Aniene aqueduct. These slopes have allowed defining the water flow and consequently to check the size of the channels in which such water flowed. To reconstruct the cross-section of both aqueducts, the study by Keenan-Jones et al. [13] and the study by Muench S. [14] have been used. The calculation of flow rate using measured and existing data highlights two different conclusions for the two aqueducts. The New Aniene aqueduct shows a flow rate lower than the historical one indicating the possibility that it was working in pressure condition. Instead, the Claudia aqueduct presents calculated flow rate higher than the expected one. In this case the filling of the channel respects the historical value (90%).

A general lowering of the study area was highlighted also through the comparison of reconstructed lines slope together with those realized in 1917 [15]. Taking into consideration the shift between the altimetric reference systems used in the two different periods of survey, the subsidence is approximately equal to 0.45 m.

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