

HYDRAULIC ENGINEERING IN ROMAN TIMES: FROM HYDRAULIC STRUCTURES TO WATER CONVEYANCE

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Abstract: *The Roman engineers developed an advanced expertise in hydraulic engineering. Classical landmark structures included some water aqueducts, dam reservoirs and irrigation and drainage networks. While some academics suggested that the Roman engineers did not know the basic principle of conservation of mass, the hydraulic expertise of the Roman engineers showed a clear demonstration of a high level of hydraulic engineering expertise. The successful design, operation and maintenance of these outstanding water systems represented some massive achievements by ancient and modern standards.*

Keywords: *hydraulic engineering; Roman period; aqueducts; hydraulic structures; engineering expertise*

1 . INTRODUCTION

The Roman engineering heritage encompasses a number of magnificent structures including bridges, roads, dams and aqueducts, with many still standing (Fig. 1 & 2). Among these, the aqueducts constitute a fine example of hydraulic engineering and many sections are still in use, in Tunisia, Spain and France for example. Surprisingly, relatively little is known on their engineering design nor the hydraulic knowledge of Roman engineers (Hodge 1992, Fabre et al. 2000). Some scholars suggested that the basic principles of fluid mechanics were unknown from the Romans (Garbrecht 1987, Hodge 1992,2002), but recent arguments showed the contrary (Chanson 2000,2002).

Herein the hydraulic design of several Roman aqueducts is re-analysed using modern hydraulic engineering knowledge. The operation of the aqueduct system is discussed and it is shown that the aqueducts were equipped with a number of hydraulic structures for flow control and energy dissipation. The design of these devices implied a solid expertise in open channel hydraulics and pipe flows. In turn, the Roman hydraulic engineers had some advanced technical expertise.

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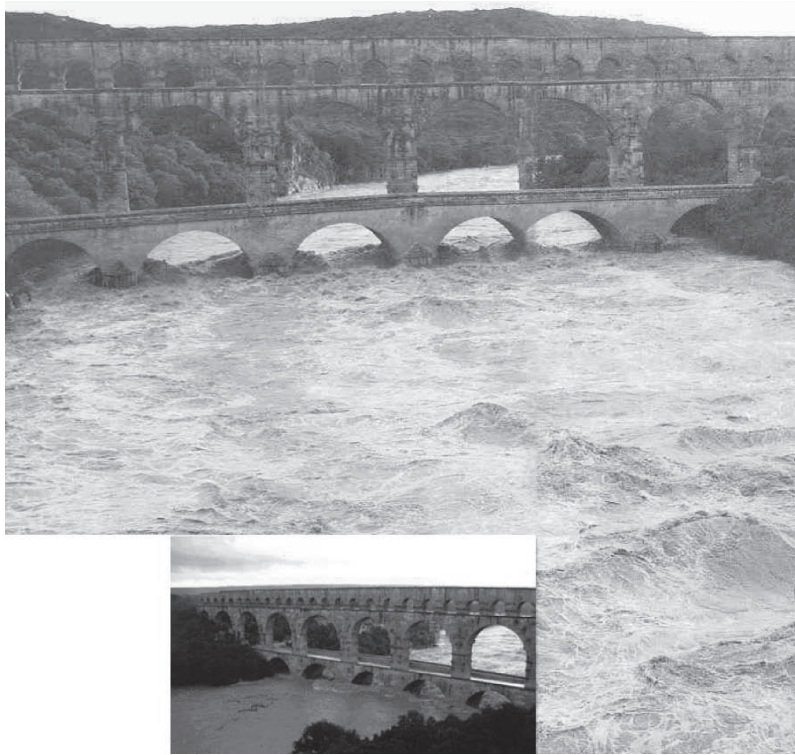


Fig. 1. Pont du Gard, Nîmes aqueduct (France) during a major flood on 9 Sept. 2002 (Courtesy of Bernard Wis). Looking upstream (Inset: looking downstream).



Fig. 2. Gorze aqueduct bridge across the Moselle River near Metz (France) on 6 May 2008 (Courtesy of Guy Bergé).

2. ROMAN AQUEDUCT: DESIGN AND CONSTRUCTION

The aqueducts were some long subterranean channels following the topographic contours lines. Figure 3 shows the cross-section of a typical subterranean conduit along the Gier aqueduct (Lyon, France). The very-large majority of the aqueduct was built at or just below the natural ground level. The channel invert and sidewalls were lined with mortar up to 0.5 to 1 m above the invert (Fabre et al. 2000, Burdy 2002). During operations, the waters were

flowing as open channel flow and the water depths ranged typically from less than 0.05 m and 1 m (Chanson 2002). The conduit was covered to reduce the contamination of the water by dirt and impurities. The roof internal height was usually between 1.1 and 2.1 m allowing regular access for maintenance. The role of repair and maintenance crews was critical to the operation of the aqueduct system as well as the quality of the waters.

The construction of aqueducts was a gigantic task often conducted the supervision of military engineers. The construction was a public enterprise financed by the Emperor, the community, private citizens or a combination of these (Leveau 2004). The Nîmes aqueduct (Fig. 1) was financed by both the Emperor and the city, while Figure 4 illustrates the water system of a private villa. The construction costs were huge considering the modest flow rates: about 2 to 2.5 millions sesterces per km for the aqueducts of Rome and a water discharge less than 0.4 m³/s (Février 1979, Leveau 1991,2006). Based upon the silver contents of sesterce during the Augustan period, the cost would be today 1.6 to 2.1 millions US\$ per km based on US\$0.61 per g of silver! For comparison, the Tarong water pipeline construction in Australia costed US\$100,000 per km in 1994, and the pipeline delivered 0.9 m³/s.

The construction of the aqueduct system was a gigantic project and the design required a range of engineering skills including hydrology, surveying, civil and hydraulic engineering, and construction management. The construction site involved hundreds of workers and it took several years to complete the aqueduct: from 3 years for the Anio Vetus in Rome to 15 years for the Nîmes aqueduct, and possibly more for some. The engineers used three types of conduits: open channels, lead pipes and earthenware pipes (Leveau 2006). The canals were built in masonry and sometimes cut in the rock and the flow motion was driven by gravity. The lead pipes were used for pressurised sections including the inverted siphons (e.g. Aspendos, Lyon).



Fig. 3. Gier aqueduct at Mornant near Lyon (France) in June 1998.



Fig. 4. Hot water channels to heat the Villa Montcaret (France) in June 2009 (Courtesy of Mr and Mrs J. Chanson). The private Roman villa was equipped with a heating system (hypocaust), a swimming pool (natatio) and thermal baths (thermae).

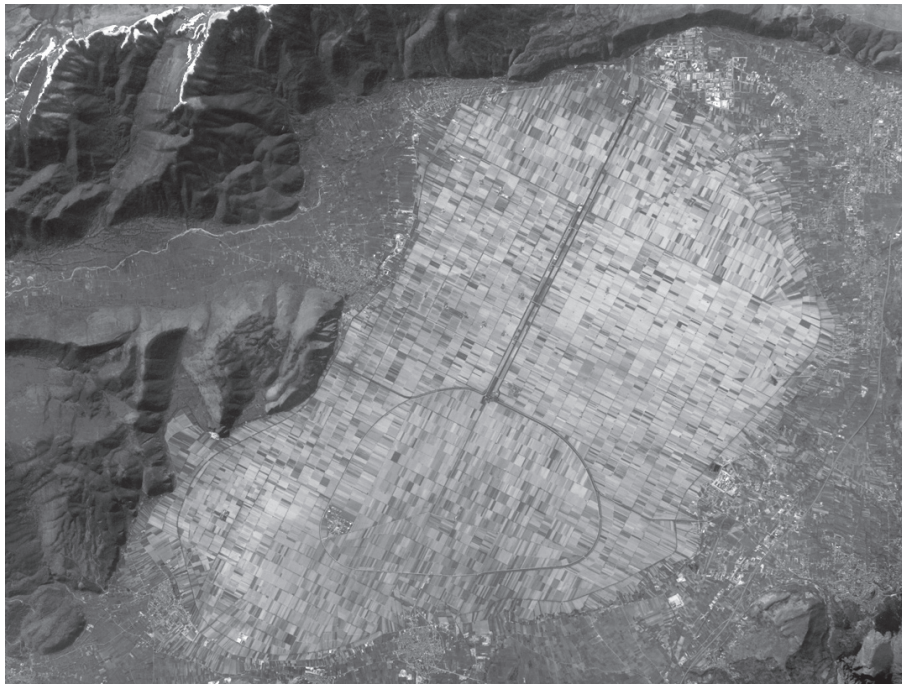


Fig. 5. Lake Fucine (Italy) on 26 Feb. 2008 (Courtesy of NASA Earth Observatory). In Roman times, the drainage outlet of the basin was a tunnel located next to the town of Avezzano (top right).

The Roman aqueducts were built for the public health and sanitary requirements of the cities. These needs encompassed the public fountains, public baths, and toilets (Hodge 1992, Fabre et al. 2000) (Fig. 4). The aqueducts were built after the town establishment, and did not constitute the original drinking water supply. The aqueduct water delivery was used further in the sewer system and assisted with the fight against fires (e.g. in Rome). Some aqueducts were built for irrigation purposes and to feed the industries (e.g. mines, flour mills). A number of aqueducts were built for the drainage of swampy areas such as the Fucine Lake in Italy (Fig. 5). Altogether it was argued that an aqueduct was a show of power and wealth of the Roman civilisation (Fevrier 1979, Leveau 1979).

3. ROMAN AQUEDUCT: HYDRAULICS AND OPERATION

A number of aqueducts were fed by natural springs. Some springs are still in use today: e.g., those of the Gorze, Mons and Nîmes aqueducts (Chanson 2002,2008), and their operation provide some interesting data. The modern hydrological records suggest that a water supply system cannot operate at large flow rates for more than a couple of months per year at best. During the dry seasons, the aqueduct discharge was limited by the spring output, and recent hydrological data yielded a ratio of maximum to minimum daily flow rates between 10 to more than 1,000 (Chanson 2008). For example, the spring of La Siagnole at Mons yielded between zero to 17.9 m³/s for the period 1981-1993; the daily discharge was less than 0.07 m³/s for 1/4th of the study period, typically during the summer; within a given month, the daily discharge varied within one to three orders of magnitude (Valenti 1985). While the ancient flow rates are unknown, it is thought that a similar discharge variability occurred during in the Roman period.

In response to the discharge variability, the Roman engineers devised a number of remedial measures. These included the construction of reservoirs and cisterns at the aqueduct downstream end: e.g., at Cuicul (Algeria), at Autun (France), at Rome and Carthage (Fig. 6). Another method consisted in some dynamic regulation of the aqueduct itself. Vitruvius recommended the installation of regulation devices (Hodge 1992), and a number of recent studies presented several in-stream regulation systems (Fabre et al. 2000, Bossy et al. 2000, Chanson 2002). The regulation of the aqueduct was a basic requirement to prevent overflows and spillages during the wet seasons, to provide an optimum operation with minimum energy losses and maximum flow rates during the dry periods, to regulate the water outflow and for maintenance. A dynamic regulation allowed a regulated water supply in response the city needs during the day time and some water storage in the channel sections during the night periods (Bossy et al. 2000, Chanson 2002,2008). For a relatively large aqueduct (e.g. Gorze, Nîmes), the aqueduct conduit could store about 20,000 m³ and 50,000 m³ of water, corresponding to 1 to 3 weeks of water supply depending upon the population and the water restrictions.

The successful operation of the aqueducts required some solid expertise in open channel hydraulics and hydraulic structure designs. For example, some advanced stormwater systems were designed and built to protect the aqueduct from runoff water, including multi-cell culverts and bridges (Chanson 2002b, 2008). Figure 1 shows a recent flood of the Gardon River beneath the Pont du Gard. The stream is an impetuous river characterised by spectacular floods locally called 'gardonnades'; 123 major floods took place between 1463 and 2003: that is a major flood every 4 to 5 years; the maximum instantaneous discharge is about 3,100 m³/s for a 1-in-20 years flood event.



Fig. 6. Water cisterns of La Malga in Carthage (Tunisia) in 2010 (Courtesy of Dr Michel Royon).

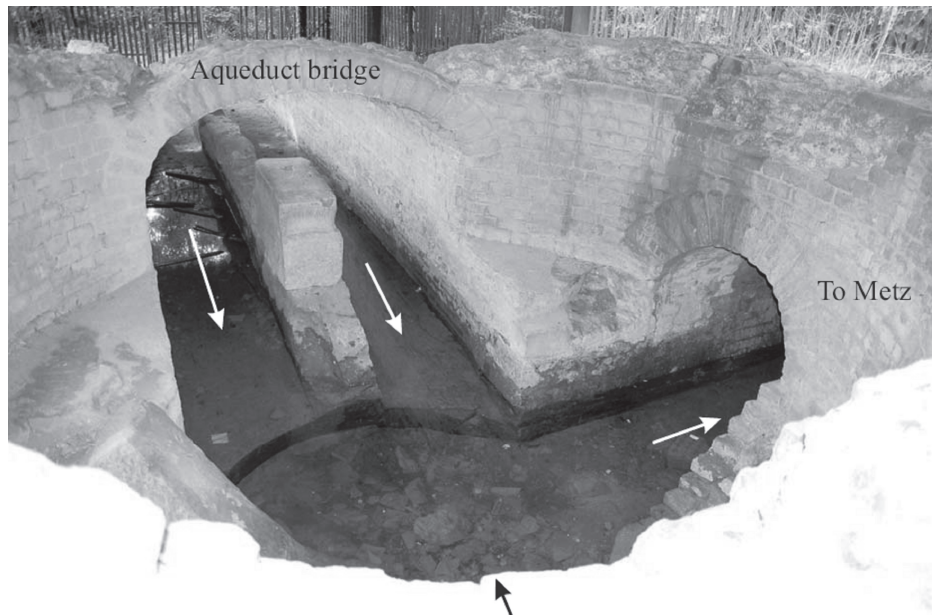


Fig. 7. Bassin de Jouy-aux-Arches, downstream of the Gorze aqueduct bridge (France) on 6 May 2008 (Courtesy of Guy Bergé).

Along the aqueducts, the regulation basins included some control gates and overflow devices. Figure 7 presents an example of regulation basin at the downstream end of the Moselle aqueduct bridge. The control gates would be undershoot sluices while the overflows would be controlled by overshoot gates. The operation of vertical sluice gates along the Gorze and Nîmes aqueducts were estimated (Chanson 2002): a proper operation required some gate openings less than 0.07 to 0.1 m at Gorze and less than 0.1 to 0.12 m at Nîmes. In other water systems, some overflow weirs were used to regulate the flow. For example, Figure 8 shows a broad-crested weir at the downstream end of a water channel. The successful operation of regulation devices required further some sound prediction of the free-surface profile along the aqueduct channel to ascertain: the optimum location of the devices, and their optimum characteristics. Did the Roman engineers use some small size (laboratory) models? Today any

such water supply system would be modelled physically or numerically during the design stages.

The aqueducts were equipped with a few steeper sections as well as some overflow devices that required the introduction of energy dissipation systems. The dissipation of the kinetic energy was critical for a proper downstream operation, to prevent scour of the channel bed and damage to the aqueduct structure itself. Some recent studies showed at least three designs: that is, a steep smooth chute followed by a hydraulic jump, a stepped cascade, and a dropshaft system (Chanson 2000,2002). Figure 9 shows a small hydraulic jump stilling basin. One major dissipation structure was located along the Valdepuentes aqueduct at Cordoba (Spain) with a series of three dropshaft cascades yielding a total drop of more than 350 m. The operation of these energy dissipation structures was complex, including by modern standards, and required some advanced hydraulic expertise.



Fig. 8. Water cascade at Perge (Turkey) in Sept. 2002 (Courtesy of Dennis Murphy). Right: looking upstream. The right photograph shows the details of the overflow weir with its broad-crest followed by a steep chute (flow direction from right to left).

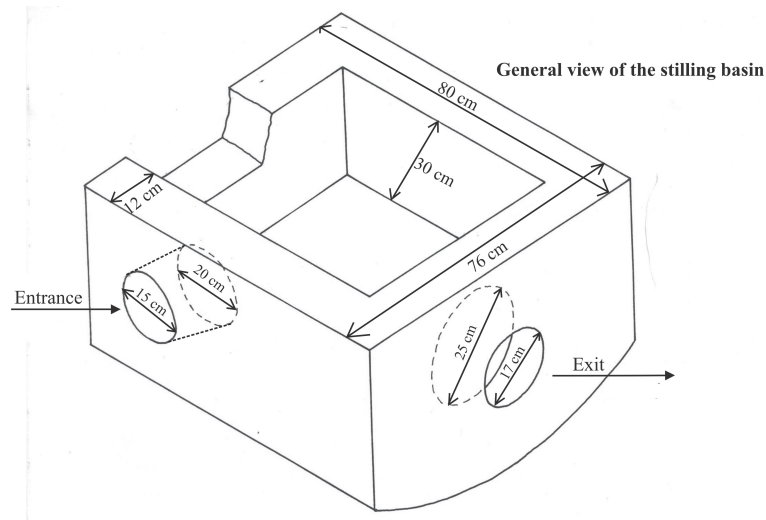


Fig. 9. Small stilling basin along an aqueduct supplying a Roman fort in Potaissa Turda (Romania) (Courtesy of Dr Fodorean Florin).

4. CONCLUSIONS

The Roman aqueducts operated successfully for centuries and their design constituted some major achievement including by modern standards. Although the aqueducts were long subterranean channels following the hillslope contour lines, they were equipped with a number of hydraulic structures including regulation devices, stormwater systems and energy dissipators. These successful design and operation of these devices required some advanced knowledge in fluid mechanics and hydraulic engineering. Indeed the complexity of basic fluid mechanics is linked with the non-linearity of the governing equations. The Roman aqueducts represent a superb illustration of successful civil engineering designs, covering hydrology, hydraulics, structural engineering, surveying and project management.

This contribution yields many questions. Who were the Roman engineers? How did they design the aqueduct system? How did the engineers predict the free-surface profiles and determine the needs for regulation devices and energy dissipators? Was physical modelling or prototype tests conducted? The author believes that the Roman engineering expertise was limited to a handful of engineers; these were the precursors of the French Ingénieurs du Corps des Ponts, British Royal Engineers, and US Army Corps engineers.

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