

THE HYDRAULICS OF ROMAN AQUEDUCTS: WHAT DO WE KNOW? WHY SHOULD WE LEARN ?

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Abstract : The Roman engineers were at the forefront of science and their engineering heritage included some magnificent aqueducts, many of which are still standing. While some scholars suggested that Roman engineers did not know the basic principle of conservation of mass, the Roman aqueducts provide a clear demonstration of the high level of hydraulic engineering expertise. The successful design and operation of these outstanding systems were massive achievements by modern standards. The development of regulation basins, culverts and energy dissipators was far from obvious. It is the writer's opinion that the leading Roman hydraulic engineers involved with the major aqueducts in Gaul and North-Africa understood the concepts of continuity and momentum.

Keywords : Roman aqueducts, Hydraulic engineering, Energy dissipation, Conveyance, Design, Operation, Expertise.

INTRODUCTION

The Roman engineers were at the forefront of science during the Antiquity. Their engineering heritage included some magnificent bridges, roads and aqueducts, many of which are still standing (Fig. 1 and 2). Numerous aqueducts were used for centuries and some sections are still in use near Tunis and at Mons. Figures 2A and 2C shows the Roman aqueduct at Gier which was equipped by several large inverted siphon structures (Fig. 2D). These siphon structures were astonishing even by modern standards; yet we know very little of their design technique (Burdy 1996, 2002, Smith 2007). Despite such evidences, little is known on the engineering design techniques and hydraulic expertise of the Roman engineers who designed, built, operated and maintained the aqueducts (Hodge 1992). Some studies even suggested that the Romans did not know the basic principles of fluid mechanics, including continuity, momentum and energy principles (Garbrecht 1987, Hodge 1992, Levi 1995).

In this keynote lecture, the hydraulic engineering of Roman aqueducts is reviewed. The aqueduct hydraulics is discussed in the lights of modern standards and expertise. It is shown that the Roman engineers had a solid experience and expertise, and that the aqueducts were equipped with modern features implying some advanced knowledge.

WHAT IS AN AQUEDUCT ?

The Roman aqueducts were long subterranean conduits, following topographic contours lines. Some included major engineering structures like arcades, bridges, inverted siphons (Fig. 1), but the very-large majority of the water system was built at or below the natural ground level. Figure 2B shows the inside of a typical subterranean conduit section along the Brévenne aqueduct (Lyon, Fra.). The channel

followed the contour line of the hill slopes.

The aqueducts were built primarily for the public health and sanitary needs of towns and cities. These included the public fountains, public baths and *thermae*, toilets and latrines (Hodge 1992, Fabre et al. 2000). The aqueducts were always built after the town establishment, implying that they did not constitute the original drinking water supply. The aqueduct waters were used also in the sewer systems, and they assisted with the fight against fires.



(A) Nîmes aqueduct (Fra.) - Looking downstream at Pont-du-Gard and Gardon river



(B) Fréjus aqueduct (Fra.) - Looking upstream at the Arches de Sainte Croix, downstream of Château Aurélien - Note the slight bend in the aqueduct (background)

Fig. 1 - Photographs of Roman aqueducts



(A) Gier aqueduct (Lyon, Fra.) - Elevated channel and arcades du Plat de l'Air at Chaponost - The arcades are 55 m long and up to 15 m high and include 92 arches



(B, Left) Brévenne aqueduct (Lyon, Fra.) at Bitermay - Inside view of the subterranean conduit - The internal height of the conduit was about 1.7 m



(C, Right) Gier aqueduct (Lyon, Fra.) - Arcades of the bridge supporting the inverted siphon pipes at Beaunant (downstream of Chaponost)



(D) Gier aqueduct (Lyon, Fra.) - Inverted siphon structure of Beaunant downstream of the arcades du Plat de l'Air - The masonry structure supported 11 (or 12) lead pipes ($\varnothing_{\text{ext}} = 230 \text{ mm}$, $\varnothing_{\text{int}} \approx 162 \text{ mm}$), the maximum drop in elevation was 122 m and the total length of the siphon was 2660 m - Looking upstream at the 270 m long bridge supporting the pipes

Fig. 2 - Details of Roman aqueduct construction and design

Other aqueducts were built for irrigation purposes and to supply some industries: e.g., some silver and iron mines in the Western Alps, the Barbegal water mill factory near Arles. Further aqueduct channels were built for the drainage of low-lands and swamps: e.g., the Fucine Lake in Italy. Some large urban drains like the Cloaca Maxima in Rome were built with techniques similar to the aqueduct conduits. Altogether it was argued that an aqueduct was a show of power and wealth of the Roman civilisation.

The construction of an aqueduct was a huge task, sometimes performed by the army under the guidance of military hydraulic engineers. It was a public enterprise financed by the Emperor, the community, private citizens or a combination of these (Leveau 2004). The construction costs were extra-ordinary considering the relatively modest flow rate (less than $0.4 \text{ m}^3/\text{s}$). These were about 2 to 2.5 millions sesterces per kilometre in average for the large aqueducts of Rome (Février 1979, Leveau 1991, 2006). During the Augustan period (BC 33 to AD 14), one sesterce weighted about 1/336 of a pound of silver which would bring the cost of one kilometre of aqueduct to about US\$ 0.5 to 0.6 millions based on US\$ 0.18 per gram of silver ! For comparison, the construction of the Tarong water pipeline (Australia, 70 km long, $Q = 0.9 \text{ m}^3/\text{s}$) cost about US\$ 100,000 per km in 1994.

WHERE AND WHEN ?

The first major aqueducts were built to supply waters to the city of Rome. Eleven

large aqueducts were built between BC 312 and AD 226 with a cumulative length of 502 km (Table 1). Many more aqueducts were built in the Roman Empire using a similar technology. Aqueducts were found all around the Mediterranean Sea for example (e.g. Hodge 1992, Gebara et al. 2002, Amit et al. 2002). The longest system was the 132 km long Carthage aqueduct regarded as one of the marvels of the world by the Muslim poet El Kairouani. Several aqueducts were used for centuries and magnificent aqueduct remains are still standing, for example at Rome, in France, Spain and North Africa. Some sections of the Carthage and Mons aqueducts are still used today (Clamagirand et al. 1990, Valenti 1995).

Table 1-1 - Characteristics of Roman aqueducts

Name (1)	Location (2)	Construction (3)	Length (km) (4)
Arles	France	1st century AD	48.0
Athens	Greece	Hadrian	25.7
Brévenne	Lyon, France	AD 1-50?	70.0
Carthage	Tunisia	AD 160?	132.0
Cherchell	Algeria		> 45
Corinth	Greece	AD 125/160	85.0
Dougga	Tunisia		12
Gier	Lyon, France	AD 50?	86.0
Gorze	Metz, France	AD 100/200	22.3
Mons	Fréjus, France	AD 100/200?	39.4
Mont d'Or	Lyon, France	BC 40?	26.0
Montjeu	Autun, France		
Nikopolis	Greece	Augustus/Hadrian?	70.0
Nîmes	France	Claudian	50.0
Yzeron-Craponne	Lyon, France	BC 20-10?	40.0
Appia	Rome, Italy	BC 312	16.6
Anio/Anio Vetus	Rome, Italy	BC 272-269	81.0
Marcia	Rome, Italy	BC 144-140	91.3
Tepula	Rome, Italy	BC 125	
Julia	Rome, Italy	BC 33 or 40	15.4
Virgo	Rome, Italy	BC 19	20.9
Alsietima	Rome, Italy	BC 2	32.8
Claudia	Rome, Italy	AD 38-52	68.7
Anio Novus	Rome, Italy	AD 38-52	86.9
Trajana	Rome, Italy	AD 109	57.0
Alexandrina	Rome, Italy	AD 226	22.0

Notes : Augustus = BC 33 to AD 14 ; Claudian = period AD 41-54; Flavian = period AD 69-96; Hadrian = period AD 117-138;

It is believed that the Roman hydraulic expertise was developed through a combination of evolution and technology transfer. Some expertise was gained from the Etruscans on culverts, tunnels, water channels, from the Greeks on water

channels, dams and siphons, from Turkey, Egypt and Mesopotamia. However the Romans developed some expertise in construction and surveying techniques, including concrete technology and arch design, which were essential to the construction of an aqueduct system.

HOW WERE THE AQUEDUCTS DESIGNED AND OPERATED ?

The aqueduct construction was an enormous task and the design was undertaken by experienced army hydraulicians. Skilled engineers included the *aquilex* (hydraulics and hydrology engineer), *architectus* (survey engineer, design architect) and *librator aquae* (civil and hydraulic engineer). The construction of an aqueduct involved hundreds of workers and it took several years: e.g., 3 years for the Anio Vetus in Rome, 14 years for the Aqua Claudia and Anio Novus in Rome about 300 years later, 15 years for the Nîmes aqueduct. The costs were enormous. The Romans used three main types of conduits : (a) open channels (*rivi per canales structiles*), (b) lead pipes (*fistuli plumbei*) and (c) earthenware pipes (*tubuli fictiles*) (Leveau 2006). The open channels were built in masonry or cut in the rock and the flows were driven by gravity, while the lead pipes were used for pressurised conduits including inverted siphons (Fig. 2).

Little is known on the hydraulic engineering of Roman aqueducts, their design procedure and the design engineers. But a re-analysis of the aqueduct hydrology and hydraulic engineering brings new lights on the level of expertise of the Roman hydraulic engineers.

HYDROLOGICAL CONSIDERATIONS

No information is known on the flow rates of the aqueducts. Some answers may derive from the studies of the catchments. A recent comparison between the Gorze, Mons and Nîmes aqueducts is relevant. The water supply systems were equipped with relatively wide channels and were supplied by natural springs with similar catchment areas (Chanson 2002). The springs are still used today, and Figure 3 presents the average daily streamflows of the Gorze, Mons and Nîmes aqueduct springs. Table 2 summarises the basic hydrological statistics. The data shown in Figure 3 suggest that a modern aqueduct could not operate at maximum flow rates for more than few months per year. During the dry periods, the water supply was reduced by the source output and the ratio of the maximum to minimum daily flow rates was between 10 to more than 1,000 (Fig. 3B). Valenti (1995) detailed 13 years of spring outflows for the source of La Siagnole at Mons (period 1981-1993). The lowest daily flow was zero while the highest record was 17.9 m³/s. The flow rate was less than 0.07 m³/s, or less than 1/16th of the average daily flow, for 25% of the study period, during the summer typically.

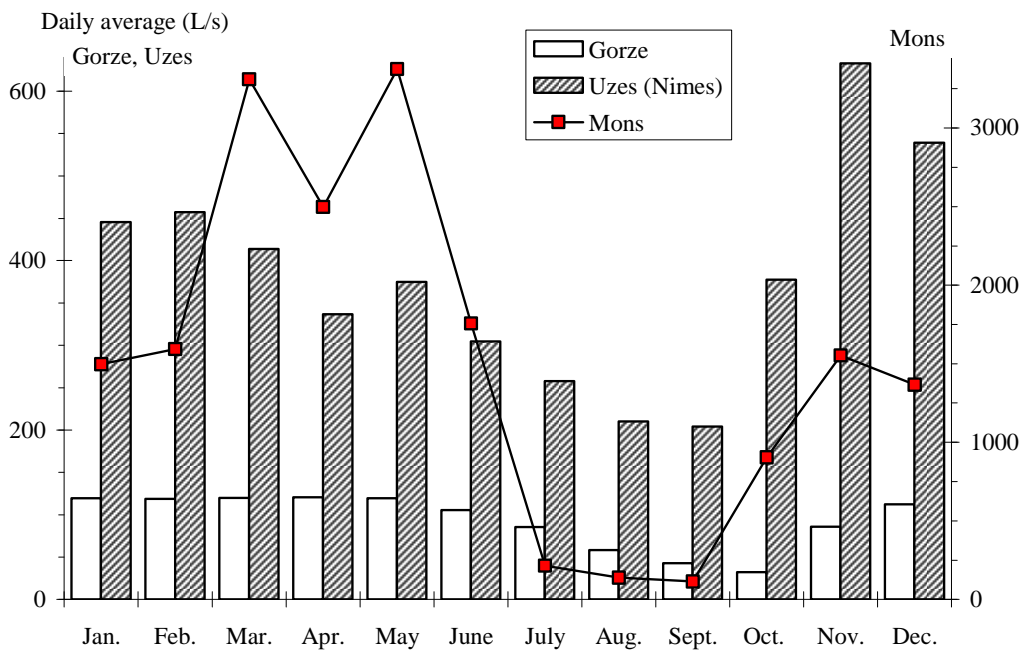
Ancient flow rates are unknown and there is little information on the ancient climate. Nonetheless, the present discharge data provide some qualitative information on the water supply variability. During the 20th century, the minimum daily flow rate of the aqueducts was one to three orders of magnitude smaller than the maximum daily flow rate. Within a given month, the variations of the daily discharge were within one to three orders of magnitude. It is believed that such discharge variability was likely to

occur in Roman times, and these must have had implications on the water distribution.

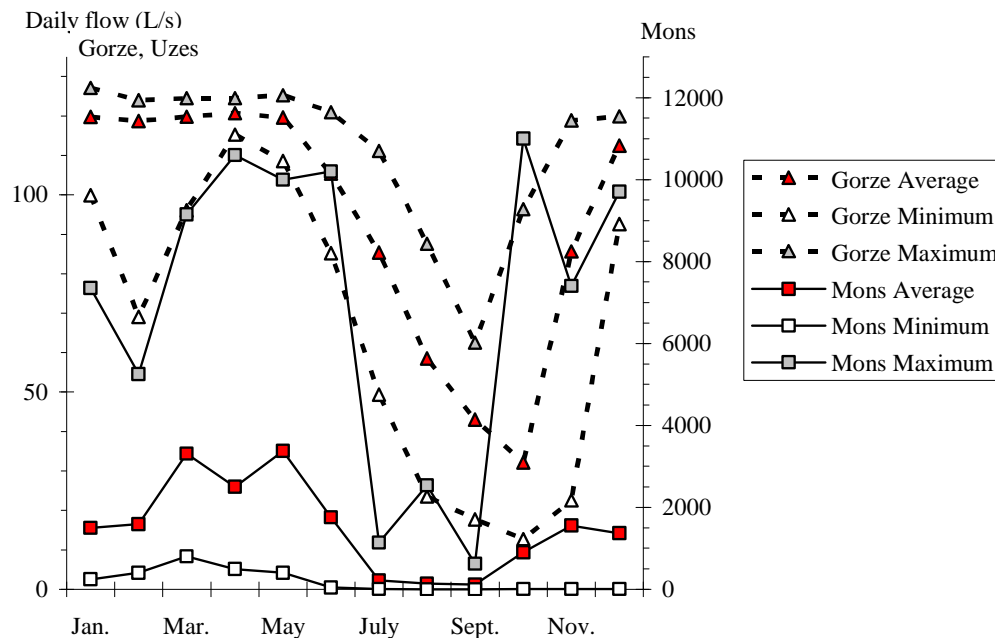
Table 2 - Modern hydrological data of Roman aqueduct water supplies

	<u>Gorze</u> (Metz)	<u>Nîmes</u>	<u>Mons</u> (Fréjus)	<u>Remarks</u>
Aqueduct length (km)	22,300	49,800	39,400	
Catchment area (km ²) :	58	50	52 / 130	
Spring(s) :	Les Bouillons	L'Eure (Uzés)	La Siagnole	
Study period:	199-98	1976-78	1984-86	
Average daily discharge (m ³ /s):	0.093	0.38	1.53	
Standard deviation (m ³ /s):	0.034	--	2.0	
Maximum daily discharge (m ³ /s):	0.127 (*)	--	11.0	(*) spills.
Upper quartile (m ³ /s):	0.120	--	2.25	
Median daily discharge (m ³ /s):	0.116	--	0.68	
Lower quartile (m ³ /s):	0.065	--	0.050	
Minimum daily discharge (m ³ /s):	0.013	--	0	

Note: The Gorze spring flow rate data excluded spills and overflow.



(A) Monthly-average daily flow rates



(B) Monthly minimum, averaged and maximum daily flow rates at Gorze and Mons
 Fig. 3 - Daily flow output at Gorze (Period 1997-1998), at Mons (Period 1984-86) and at Uzès (Nîmes) (Period 1976-1978) (Data: Société Mosellane des Eaux, SRAE Côte d'Azur, Fabre et al. 2000)

Reservoirs and cisterns had to be used to regulate the water distribution in town: evidences were found, for example, at Cuicul (Alg.), at Autun (Fra.), at Rome and Carthage, and in Israel. Despite arguments suggesting that the aqueduct flow was not regulated, Vitruvius recommended to install regulatory devices at regular intervals (Hodge 1992, p. 165), while recent studies demonstrated the existence of in-stream regulation systems (Fabre et al. 2000, Bossy et al. 2000, Chanson 2002). These were large basins equipped with sluice gates. The operation of two aqueducts was analysed recently. It was demonstrated that the regulation of the flow was a necessity : (a) to prevent overflows and unsatisfactory aqueduct operations during wet seasons, (b) to provide optimum flow conditions (minimum energy losses and maximum flow rates) during low-flow seasons, (c) to regulate the outflow and (d) for maintenance (Chanson 2002). These control structures were equipped with vertical sluices, and their operation required gate openings less than 0.07 to 0.1 m at Gorze and less than 0.1 to 0.12 m at Nîmes. For larger openings, the flow was not affected by the presence of gate.

A basic regulation method On-Off was required for regular maintenance works, including cleaning and repairs. Frontinus mentioned the maintenance crews (117) and he stressed the needs for prompt actions (121). His text proved that the flow rate could be stopped, at least at Rome. Another regulation technique was the dynamic regulation, commonly used today in open channel systems. Such a technique regularised the flow rate to satisfy the users' needs during day times and to store water in the aqueduct during night times. Both Bossy et al. (2000) and Chanson (2002)

argued that the Romans used such a dynamic regulation technique, on a daily and possibly weekly basis, to store water at night and during low-demand periods. The storage capacity of an aqueduct could be significant: about 20,000 m³ and 50,000 m³ at Gorze and Nîmes respectively. Note that the usage of the aqueduct for storage would yield water levels in the channel much higher than the normal depth.

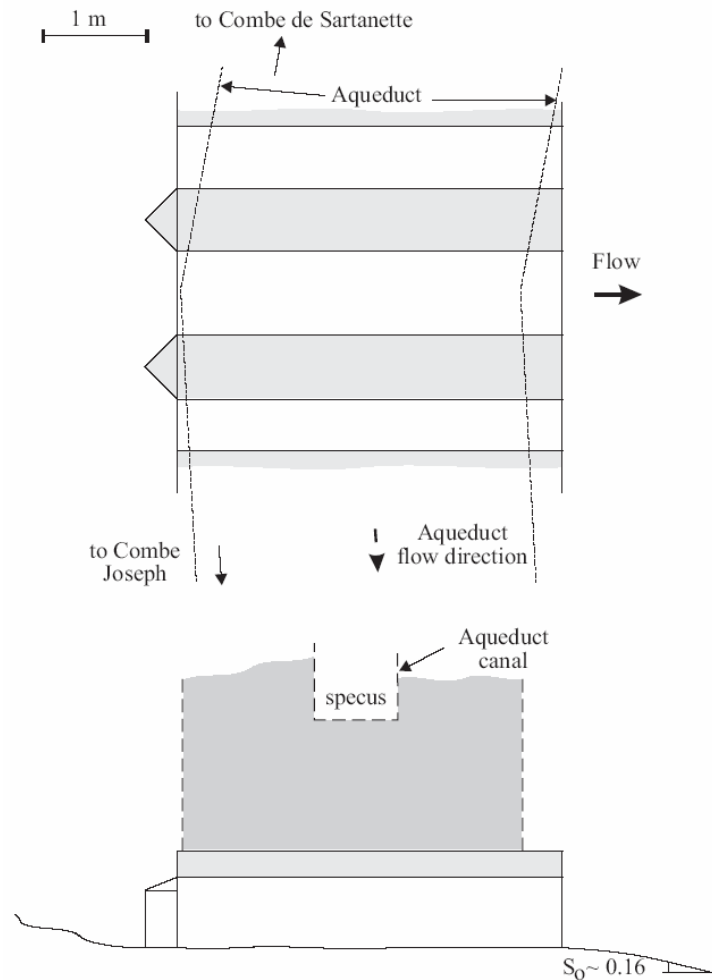


Fig. 4 - Dimensioned sketch of the Vallon No. 6 multi-cell culvert beneath the Nîmes aqueduct (Fra.)

An unusual stormwater system

The knowledge of the catchment hydrology was essential to select a suitable water supply as well as to design the stormwater drainage systems protecting the stability and integrity of the aqueduct system. Along the Nîmes aqueduct, a large box culvert was recently excavated (Fabre et al. 1992, Chanson 2002c). The structure was designed to allow storm water passage beneath the aqueduct (Fig. 4). The culvert was a multi-cell structure equipped with 3 rectangular parallel cells. The upstream end of each dividing wall was cut in a pointed shape to form cut-waters.

The Romans used several culvert designs beneath their roads, the most common

designs being the arched culvert and the rectangular (or box) culvert. But few culverts were built beneath aqueducts and this structure showed unusual features: (a) a box culvert of large dimensions, (b) a multi-cell structure, and (c) a modern and sound design from a hydraulic perspective (Chanson 2002c). Detailed hydraulic calculations showed that the culvert operated with free-surface inlet flow conditions for flow rates up to $2 \text{ m}^3/\text{s}$ and it could pass up to $4.2 \text{ m}^3/\text{s}$: i.e., more than 12 times the aqueduct maximum flow rate. While many studies highlighted the hydraulic expertise of the Romans for small to medium discharges, the writer believes that the sound hydraulic design of this multi-cell culvert, including its large discharge capacity and modern design, demonstrates some hydraulic experience, if not knowledge, in dealing with large stormwater runoff and its conveyance beneath a major structure (¹).

ENERGY DISSIPATION

The aqueducts consisted of long, flat sections although a number were equipped with steep sections with up to 78% slopes (Ashby 1935, Hodge 1992). The existence of steep invert implied that the flow became supercritical and that some hydraulic devices were required to dissipate the kinetic energy of the flow along the steep section and at its downstream end when the channel connected to a flat section (Chanson 2000). The energy dissipation system was essential to ensure normal downstream flow operation and to prevent scour and damage to the structure. Three types of structures were used : (a) a smooth steep chute followed by some hydraulic jump dissipator, (b) a stepped chute, and (c) some dropshaft or dropshaft cascade (Chanson 2000, 2002b).

Short sections had a steep stepped invert gradient (Fig. 5). The Roman engineers used both single drops and stepped cascades. The Brévenne aqueduct included a number of steep chutes. At Chevinay, the steps were made of rockfill covered by stone slabs, with dimensions similar to modern precast concrete block systems developed by the Russians (Chanson 2001). Another large cascade was found at Andriake in Turkey. Different step geometries were used : flat horizontal step (e.g. Beaulieu), inclined downward flat step (e.g. Chevinay) and pooled step (e.g. Andriake) (Fig. 5). Such a wide range of designs suggests that the Roman engineers had a strong experience, and possibly expertise, in stepped chute design. Pooled step and inclined downward step designs are indeed unusual even by modern standards (Chanson 2001).

Other steep sections were equipped with unusual dropshaft structures (Fig. 6). Chanson (2000, 2002b) presented the first documented survey of Roman dropshaft structures. It showed the existence of single dropshaft construction as well as complex cascades (or series) of dropshafts. Some of the best documented dropshaft cascades were located on the Valdepuentes aqueduct at Cordoba (²) with at least three major dropshaft cascades : i.e., at Cerro de los Pinos upstream of the Valdepuentes bridge, at Madinat-al-Zhara, and at Cortijo los N., downstream of junction with Veneros branch junction (Lopez-Cuervo 1985, Villanueva 1993, 1996). The total drop in elevation at Cerro de los Pinos and Madinat-al-Zhara dropshaft cascades was

¹ Another example was of course the Pont-du-Gard above the Gardon river (Fig. 1A).

²Also called Aqua Vetus. The aqueduct was used for several centuries, by the Romans and later by the Muslims.

respectively 120 m and 200 m. The Cerro de los Pinos dropshaft cascade was very steep (total drop of 120 m over a 400 m long distance) and an unusual *spiramina* design was used. It consisted of three 90-degree dropshafts. This is the only documented dropshaft design of this type. Some 90-degree shafts were possibly parts of the Montjeu aqueduct although it is uncertain whether these were dropshafts, inspection shafts or simple bends.

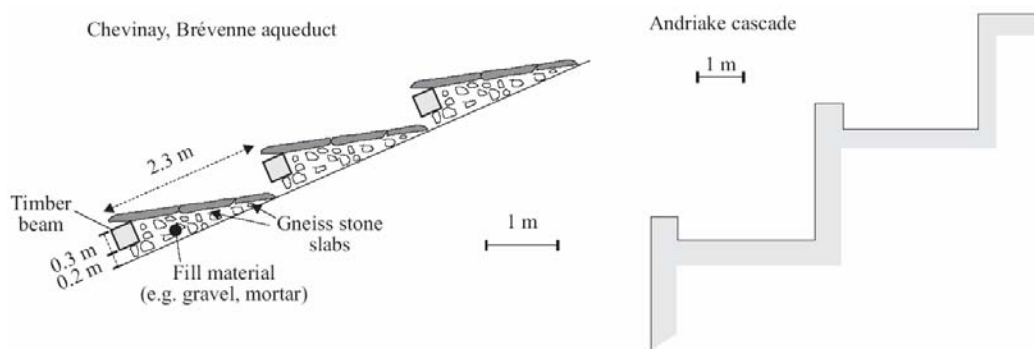


Fig. 5 - Example of stepped cascades in Roman aqueducts



Fig. 6 - Full-scale hydraulic model of the Recret dropshaft, Yzeron aqueduct (Lyon, Fra) - Model flow rate: $Q = 0.044 \text{ m}^3/\text{s}$

Historical records on dropshafts were found to be unreliable. Observations of Roman

shafts included wells, cisterns, inspection shafts and dropshafts without distinction. Most studies on the Montjeu aqueduct dropshafts at Autun relied on the original work of Roidot-Del age (1879?). The drawings of Jean Roidot-Del age (1794-1878) showed 24 "puits" (shafts) along the Montjeu aqueduct, but the term "puit" was used for both dropshafts ("puits de rupture") and inspection shafts ("regards") (Fig. 7). The writer inspected parts of the aqueduct in September 2000. The path of the aqueduct is relatively flat but for two short steep sections in the For t de Brisecou and at Pierre de Couhard ⁽³⁾ (Fig. 7). Further the dimensions of the shafts were not identical contrary to some erroneous belief. Near the source of the A n Nadour branch of the Hippo Zarite aqueduct (Tun.), Gauckler (1902) observed the presence of circular shafts (1 m diameter, 2.5 m deep). Only four shafts located on a steep slope were likely to be dropshafts.



Fig. 7 - 19th century drawing of the Montjeu aqueduct steep section at Brisecou, Planche 65, Roidot-Del age (1879?)

The hydraulics of Roman dropshafts was recently investigated (Chanson 2002b, 2004, 2007). Figure 6 shows the full-scale model of a rectangular dropshaft installed on the Yzeron aqueduct at Recret. The hydraulic performances of a dropshaft cascade differed from those of a single dropshaft. The operation of a cascade was characterised by hydraulic interference between adjacent dropshafts (Chanson 2002b). In particular the geometry and slope of the connecting channels (in-between dropshafts) did affect the operation of the dropshaft cascade. For flat connecting channels (e.g. Vaugneray), a hydraulic jump took place downstream of each dropshaft. The hydraulic jump was a very energetic process associated with scour beneath the roller and possibly wave propagation further downstream (Chanson 2007). With steep connecting channels (e.g. Cerro de los Pinos, Valdepuentes), the flow between dropshafts was supercritical or torrential. Lesser energy dissipation took

³ It is the writer's opinion that the only dropshafts were the "puits" No. 18, 19, 20, 21, 22 (Fig. 7), and 24 (at Pierre de Couhard), and possibly the "puits" No. 10 and 23.

place at each dropshaft.

The results of these investigations highlighted that the operations of both single dropshaft and dropshaft cascade designs were complex even by modern standards. Today, the design of dropshaft is restricted to a handful of experienced engineers and usually verified by extensive physical modelling.

WHAT CAN WE LEARN FROM THE ROMAN ENGINEERS AND THEIR AQUEDUCTS ?

The design of an aqueduct was a difficult task. Grewe (1992), Hodge (1992) and Leveau (2006) elaborated on the difficulties facing the Roman engineers. Several aqueducts included hydraulic systems (regulation basins, dropshaft, stepped chutes, culvert) that required advanced hydraulic engineering knowledge. In particular the hydraulic design of stepped chutes, dropshafts and multi-cell culverts is not today a simple job (Chanson 2002, 2002b). This is a highly specialised task and the advice of an experienced engineer is required. For example, dropshaft hydraulic calculations are among the most difficult hydraulic engineering calculations. Even research on dropshaft hydraulics is limited : i.e., there are only 9 international refereed journal articles on dropshaft design listed in Science Citation Index, the Web of Science® for the period 1985-2007.

Further the construction of an aqueduct required some solid hydrological expertise; not only to select the suitable spring(s) but also to ensure a safe operation of the aqueduct system during rain storms. The latter involved the design of overflows in the in-stream regulation systems, and also the construction of culverts and bridges at stream and gully crossings. At Nîmes, both the Pont-du-Gard and the Vallon No. 6 multi-cell culvert were evidences of a high level of expertise in storm water hydraulics. Let us remember that the Gardon river is an impetuous river characterised by spectacular floods ("gardonnades"). At Anduze, 30 km upstream of Pont-du-Gard, 123 major floods were recorded between 1463 and 2003 and the maximum water depth exceeded 8.5 m above the river bed with an estimated discharge over 3,700 m³/s. For comparison, the average annual discharge for 1970-1984 was 35.5 m³/s at La Baume, 8 km upstream of Pont-du-Gard, where the maximum instantaneous discharge is about 3,100 m³/s for a 1-in-20 years flood event (Banque Hydro.eaufrance.fr 2007).

The writer believes that the hydraulic engineering expertise in Roman times was restricted to a handful of engineers. Who were they ? Although there is no written proof that the engineers understood the basic concepts of continuity and energy, as used in modern hydraulics, they were contemporaries of Hero of Alexandria who understood the principle of continuity, probably those of momentum and energy (4). It is believed that he also influenced the Roman hydraulicians of the 1st, 2nd and 3rd centuries AD, and possibly the designers of the Nîmes, Mons, Montjeu and Valdepuentes aqueducts.

In any case, the aqueduct engineers designed very reliable energy dissipation structures and storm water floodways, used for centuries. For example, the dropshaft

⁴Hero designed the first steam turbine and he impressed Italian scientists for many centuries including Galileo (Levi 1995).

cascades of the Valdepuentes aqueduct were later re-used by the Muslims (Villanueva 1993, 1996), and the Pont-du-Gard is still standing after the record water levels observed in September 2002 and December 2003. The sound design implied a great deal of engineering experience.

CONCLUSION

While some scholars suggested that Roman engineers did not know the principle of conservation of mass, the Roman aqueducts provide a clear demonstration of the high level of hydraulic engineering expertise of the Roman engineers. The successful design and operation of these magnificent systems were massive achievements even by modern standards. The development of regulation basins, culverts and energy dissipators, including dropshaft cascades and stepped chutes, was far from obvious, even for today's engineers. The complexity of basic fluid mechanics is linked with governing equations characterised by non-linearity. It is the writer's opinion that the leading Roman hydraulic engineers involved with the major aqueducts in Gaul and North-Africa understood the concepts of continuity and momentum, and were influenced by Hero of Alexandria. Hero knew the continuity and momentum equations; he built the first steam turbine and he was contemporary to Frontinus.

The Roman aqueducts constitute a superb example of "real-world" hydraulic engineering. They were successful civil engineering designs encompassing hydrology, fluid dynamics, structural engineering, soil mechanics, surveying and water management. Such projects form the backbone of our civil engineering profession, and the writer believes that many university students, professionals and academics could learn a lot from the real-world success stories that are the Roman aqueducts.

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