A Hydraulic Study of Roman Aqueduct and Water Supply *

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SUMMARY: Although some Roman aqueducts were built more than 2,000 years ago, little is known of their hydraulic performances. The study develops a hydraulic analysis of Roman aqueduct operation. It is shown that the existence of steep sections (i.e. bed slope up to 78%) implied the existence of both sub- and super-critical flows associated with hydraulic jumps. Three chute designs were used : smooth invert, stepped cascade and dropshaft cascade. The operation of steep chutes along an aqueduct was associated with some upstream and downstream regulation structures. It is believed that steep sections were design features of Roman aqueducts built under the supervision of experienced engineers.

NOTATION

d	flow depth (m) measured perpendicular to the channel bed
Fr	Froude number; for a rectangular channel : $Fr = V / \sqrt{g * d}$
g	gravity constant (m/s^2)
L	length (m)
Q	total volume discharge (m^3/s) of water
Q_{max}	maximum flow rate (m^3/s)
S_o	bed slope; $S_o = \sin\theta$
V	flow velocity (m/s);
ΔH	head loss (m) : i.e., change in total head
θ	bed (invert) slope

1 INTRODUCTION

The hydraulic expertise of the Romans contributed significantly to the advance of science and engineering in Antiquity. Aqueducts were built primarily for public health and sanitary needs: i.e., public baths, thermes, toilets. Many were used for centuries; some are still in use, for example at Carthage. [1] Magnificent aqueduct remains at Rome, in France, Spain and North Africa, for example, are still standing (e.g. [2,3,4]) (Figure 1). Aqueduct construction was an enormous task often performed by the army and the design was undertaken by experienced army hydraulicians. The construction cost was gigantic considering the small flow rates (less than 0.5 m^3/s) and was around one to three millions sesterces per kilometre on average (e.g. [5,6]) (^{1}).

Recent surveys have thrown new light on the longitudinal profiles of Roman aqueducts.[7] Most aqueducts consisted of very long flat sections with bed slopes around 1 to 3 metres per kilometre, and sometimes short steep portions in between. Despite arguments suggesting that Roman aqueducts operated with subcritical flows and that no energy dissipation device was required (^{2}), the writer demonstrates the existence of three types of steep sections: steep 'smooth' (^{3}) chutes followed by stilling basin(s), stepped channels, and dropshaft cascade (Figure 2, Table 1). The hydraulic features of steep chutes and dropshaft cascades are analysed and new conclusions on aqueduct design and operation are proposed.

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Figure 1a: Gier aqueduct (86km long, Q_{max} = 15,000 m^3/day) Brignais "La Gerle" looking upstream, arcades with with head tank of Garon siphon in foreground right (photograph taken in June 1998)

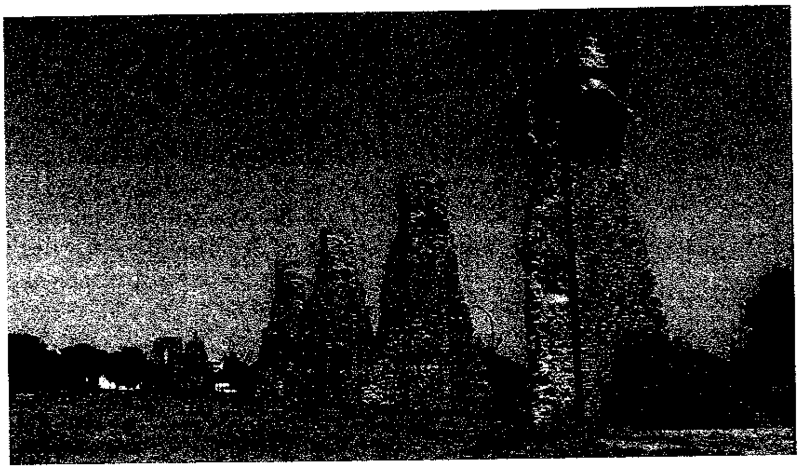

Figure 1b: Frejus aqueduct (36km long) (Courtesy of Didier Toulouze) Arcade near les Arénes

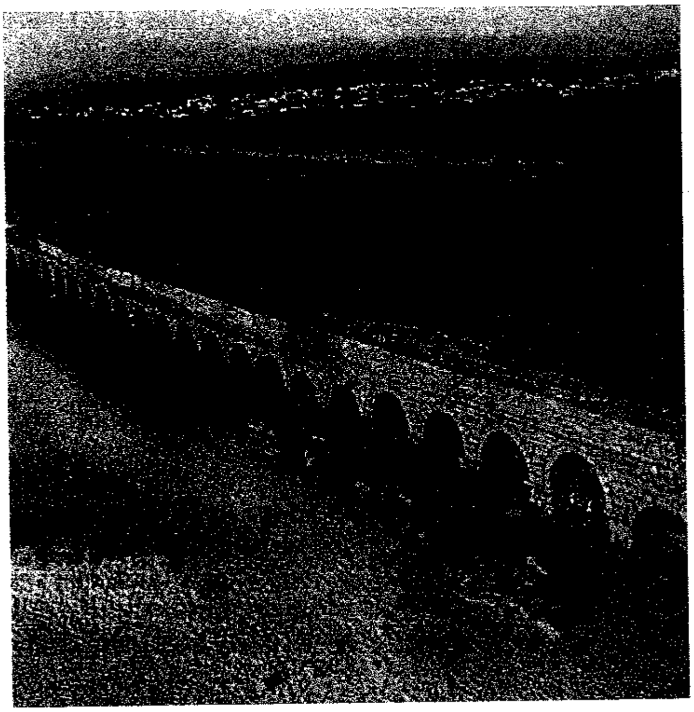

Figure 1c: The aqueduct in Caesarea (Courtesy of Israel Ministry of Foreign Affairs). Stretching North from Caesarea, the aqueduct once flowed with fresh spring water from Mount Carmel

Table 1
Well-documented steep sections of Roman aqueducts

Site, Aqueduct (Locations) (1)	**ΔH (m)** (2)	**L (m)** (3)	**$S_0 = \sin\theta$** (4)	**Q_{max} (m^3/s)** (5)	**Remarks** (6)
Smooth-invert chutes					
Gericomio, Marcia (Rome)	21	204	0.11	2.18	
Ponte dell'Inferno, Anio Novus (Rome)	26.4	--	0.011	2.20	
Mola di San Gregoria, Anio Vetus (Rome)	4.1	--	0.16	2.20	
Courzieu II, Brévenne (Fra.)	44		0.21	0.116	
Chevinay, Brévenne (Fra.)	87	~ 200	0.40	0.116	
Lentilly II, Brévenne (Fra.)	33	--	0.082	0.116	
Chabet Ilelouine, Cherchell (Alg,)	12.3	--	0.62	0.076	
Bord-Djedid, Carthage (Tun.)		--	0.37	--	Grandes citernes
Stepped cascades					
Beaulieu (Fra.)	37	--	--	--	Flat steps
Andriake (Turk.)	11	18	0.52	--	Pooled steps
Chabet Ilelouine, Cherchell (Alg,)	19	--		0.076	Downstream of Oued Bellah bridge
Dropshaft cascades					
Beaulieu (Fra.)	37	--	--	--	
Brisecou, Montjeu (Fra.)	140	770	0.13	--	24 rectangular shafts
Cerro de los Pinos, Valdepuentes (Spa.)	120	400	0.29	0.255	34 circular shafts
Chabet Ilelouine, Cherchell (Alg,)	12	32	0.36	0.076	4 circular shafts
Grand Thermes, Cuicul (Tun.)	3	85	--	--	4 circular shafts
Gunugu (Tun.)	20	--	--	--	4-5 circular shafts
Madinat-al-Zhara, Valdepuentes (Spa.)	200	--	--	0.255	
Recret, Yzeron (Fra.)	38	490	--	0.150	About 15 rectangular shafts
Vaugneray, Yzeron (Fra.)	22	375	0.058	0.058	About 8 rectangular chafts

Notes: L = chute length; Q_{max} = maximum flow rate; ΔH = total head loss; (--) = unknown

2 STEEP CHUTE DESIGNS

2.1 Smooth-invert chutes

A steep chute is characterised by supercritical flows and the kinetic energy of the flow is significantly larger than on a mild slope for the same flow rate. Energy dissipation must take place at the downstream end or in the downstream canal, and sometimes stilling structures must be introduced. The transition from high-velocity flow to a slower motion may take place as a hydraulic jump. In engineering practice, hydraulic designers want to avoid three types of jumps : undular, oscillating and strong hydraulic jumps. Strong hydraulic jumps are characterised by a high-potential for bederosion and scouring while wave propagation can affect the operation of the conduit downstream of undular and oscillating jumps (4). The latter may induce vibrations on downstream gates and perturbation of discharge measurement devices.

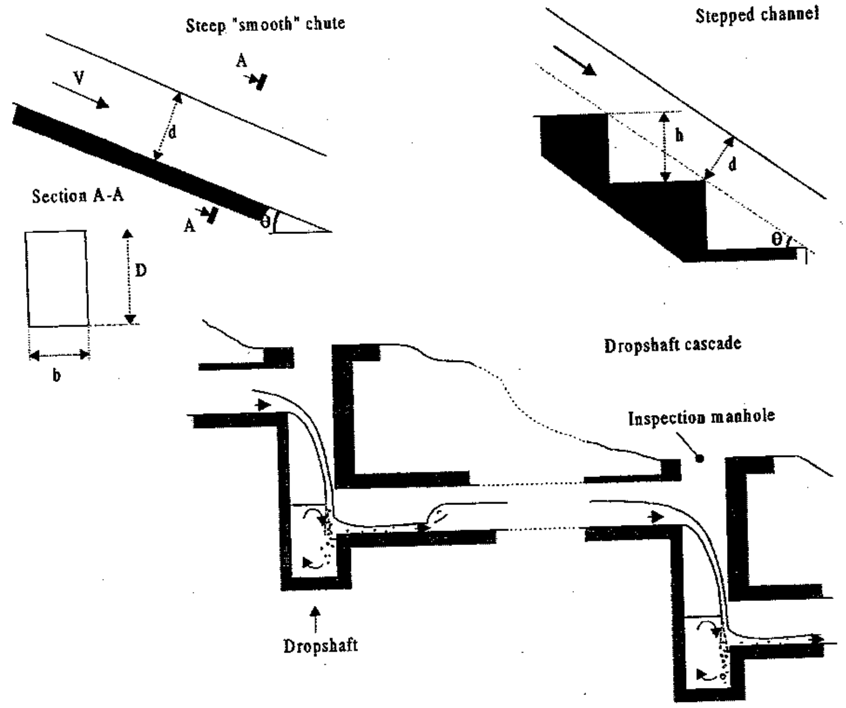

Figure 2: Sketch of steep chutes along Roman aqueducts

A complete 'backwater' analysis was conducted for several well-documented steep chutes (12, Table 1). The results highlight the existence of hydraulic jumps in some aqueducts and the occurrence of unfavourable flow conditions. Oscillating hydraulic jumps occur at the Brévenne aqueduct (one chute) and undular flows occur at the Brévenne (one chutes), Gorze (bridge), Carthage, Anio Vetus (one bridge), Anio Novus (two bridges) aqueducts. These flow conditions were unsuitable for proper operation of the aqueduct unless structures were built to dampen the surge waves.

Although several researchers have argued about the existence of 'settling basins' along aqueducts to trap sediments,[4,7,14] it is believed that several basins were 'stilling basins' (5) built downstream of steep chutes 12. At Alepotrypes (Corinth), the hydraulic power of the chute flow was nearly 9 kW and a downstream cistern acted as a dissipation basin. Three well-documented basin systems were built to damp waves: Sotizon downstream of the Courzieu II chute (Brévenne), Jouy-aux-Arches downstream of the Moselle bridge-canal (Gorze) and at least five circular basins at Oudna (Carthage).

2.2 Stepped cascades

Roman engineers used both single drops and stepped cascades along aqueducts (Table 1, Figure 3). The stepped chute design was also common with dam spillways. For example, the oldest known stepped spillway was built around BC 1,3000 in Greece and the Roman engineers built several significant stepped spillway systems.[15] (6)

What was the main purpose of the stepped cascade design ? At Beaulieu and Cherchell, the cascades were designed to dissipate the kinetic energy of the flow. At Andriake, the cascade is located at the downstream end of a series of arcades (Figure 3). Was the Andriake cascade built for energy dissipation purpose, to treat the water (re-aeration), for aquatic life (in the step pools) or a combination of the above ? The answer is as yet unknown. A related design is of course the watermill cascade at Barbegal in the South of France (Figure 4).

2.3 Dropshaft cascades

A dropshaft cascade consists of a series of dropshafts, each one being a low-head energy dissipator.[12] The design of Roman dropshafts included an unusual feature, namely a deep wide shaft pool. The pool of water acted as a cushion at the point of nappe impact preventing scour at the shaft bottom. The shaft pool facilitated further the entrainment of air bubbles by the plunging jet, maximising the bubble residence time and associated air-water gas transfer. The design contributed successfully to an enhancement of the dissolved oxygen (DO) content. Two dropshaft shapes were used : rectangular at Vaugneray, Recret and Montjeu (France), and circular at Cherchell (Algeria), Rusicade (Algeria) and Valdepuentes (Spain). It is possible that the latter shape was a design evolution.

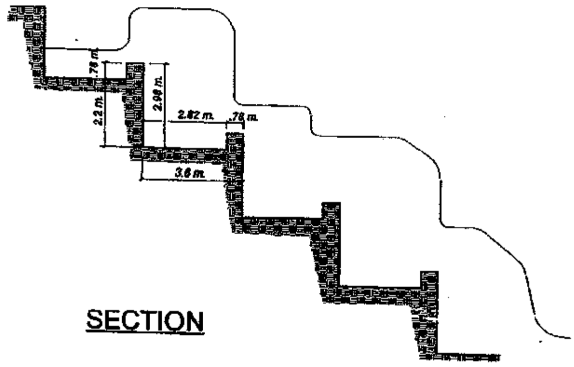

Figure 3: Andriake cascade (Courtesy of Dennis Murphy)

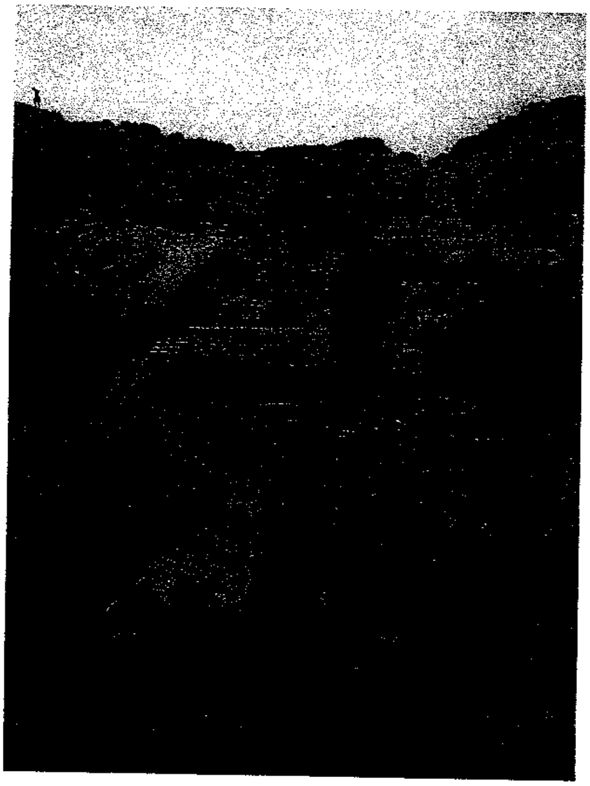

Figure 4: Barbegal water mills (Photograph taken in June 1998): ΔH = 20m, L = 60m. View from downstream. The inflow channel arrived at the top of the hill through a man-made cut into the rock. The mill was equipped with 2 series of 8 water wheels (ΔH = 20m, L = 60m, $Q_{max} = 0.26 m^3/s$)

For large drops in bed elevation, dropshaft cascades were built : e.g., a series wiht an overall drop of 200m at Valdepuentes (Madinat-al-Zhara, Figure 2). Such a design had an excellent reliability record and was used for centuries (7). It must be understood that the design was not obvious: a dropshaft cascade was a complex hydraulic structure that included the construction of numerous shafts and interconnection channels in difficult topographic conditions.

3 DISCUSSION: AQUEDUCT DESIGN AND OPERATION

3.1 Presentation

Short steep sections were introduced to connect aqueduct sections built by different gangs, as a remedy for misalignments (8). However the writer has also found well-documented evidence of aqueduct chutes and cascades. The series of steep chutes at Brévenne were imposed by the topography of the valley and they were part of the original design (Table 1). Large dropshaft cascades were installed at Montjeu, Cherchell, Valdepuentes and Yzeron (Table 1). These were also basic design features of the aqueducts !

The design of an aqueduct was a difficult task.[7,18] The designer or *librator* (9) was often an experienced army engineer.[5,19] The hydraulic design of steep chutes was a highly specialised task. The construction of stilling basins, stepped cascades and dropshafts was not (and is still not today) a simple job: the advice of an experienced engineer was required. The librator had to have experience, if not expertise, with sub- and super-critical flows, hydraulic jumps, stilling basin and dropshaft designs. 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 (10). Hero understood the principle of continuity, and probably those of momentum and energy, and he impressed Italian scientists for many centuries, including Galileo.[20] It is most likely that he also influenced the Roman hydraulicians of the 1st, 2nd and 3rd centuries AD.

3.2 Design and operation

Although Vitrivius recommended the installation of regulatory devices at regular intervals (e.g. [7], p. 165), little information is known of the regulation of aqueduct flow. Few remains have been found or studied so far. Table 2 lists some excluding the *castella* (11) built near the cities. The existence of steep sections (Table 1) associated with supercritical flow motion implied the use of both upstream and downstream control structures. Supercritical flows must be controlled from upstream while subcritical flows are best controlled from downstream.[8,9] Regulation devices had to be installed upstream and downstream of the chutes; for example, a downstream castellum could never control the steep chute flow.

Table 2

Control/regulation systems installed along Roman aqueducts

Regulator/Control system (1)	**Description** (2)	**Remarks** (3)
Segovia (Spa.)	Rectangular basin. Overflow on left. Gate(s) regulating the overflow (and possibly the canal).	'Caseta frente' located upstream of aqueduct bridge.[18]
Ars-sur-Moselle, Gorze (Fra.)	Rectangular basin (4.2m by 3.3m, 1.3m deep) upstream of 1,300m long bridge over Moselle river. Basin invert 0.4m deeper than aqueduct invert. Overflow canal (gated) on left side, Gates regulating the dual bridge-aqueduct canal.	Location: about 9km upstream of *Divodurum* (Metx). Note the bridge aqueduct unusually equipped with two 0.85m wide channels.[22]
Pont-du-Gard, Nimes (Fra.)	Rectangular basin (1.9m by 2.1m basin invert at canal invert elevation). Overflow opening (gated) on the left side. Gate regulating the bridge-aqueduct canal.	Located upsstream of Pont-du-Gard, about 34km upstream of *Nemausus* (Nimes). [19,23]
Barbegal, Arles (Fra.)	Rectangular basin (3.3m by 2.3m). Convergence of two aqueduct branches upstream of 350m long arcades feeding the water mills.	[24]
Dureze siphon head tank, Gier (Fra.)	Rectangular chamber (6.4m by 2.25m) upstream of Dureze siphon. Overflow opening on left wall.	Also called Saint-Genis de Gouttenoire. Location: about 53km upstsream of *Lugdunum* (Lyon). [25 pp105,203]
Manahole R34, Gier (Fra.) (?)	Rectangular chamber (0.95m long by 0.89m wide, 0.9m high), associated with a manhole, to instll a wooden gate (?).	Location: 26km upstream of *Lugdunum* (Lyon). Hypothesis by (7, p104) critisised by (26, p219).

Notes: Left = left when looking downstream; Right = right when looking downstream

The regulation of the flow was a necessity to prevent overflows and unsatisfactory aqueduct operations during wet seasons while providing optimum flow conditions (minimum energy losses and maximum flow rates) to supply the city satisfactorily during low-flow seasons. The writer believes that sluices and control structures were installed upstream of steep sections to regulate the aqueduct operation.

In pipes, valves and taps are the most common types of regulatory devices while gates are more appropriate in open channels. The two most common types are the undershoot and overshoot gates (Figure 5). With an *undershoot* or underflow gate, the outflow is delivered underneath the gate edge. At an *overshoot* or overflow gate, the water discharges over the upper edge of the gate. There is a major difference between undershoot and overshoot sluices: the relationship between the flow rate and the upstream water level satisfies respectively:

$$Q \infty \sqrt{d_1} \qquad \text{Undershoot sluice (1)}$$

$$Q \infty \sqrt{d_1^3} \qquad \text{Overshoot sluice (2)}$$

where d_1 is the upstream water depth (Figure 5). With an overshoot gate, a small variation of the upstream level induces a large change in outflow. At an undershoot gate, a change in upstream water level is associated with a smaller variation in discharge. In practice the overflow gate is commonly used for spillway design and overflow systems. An underflow sluice is better used to control the downstream flow rate (i.e. as a regulation device). It is believed that gates installed in the main aqueduct channel were undershoot sluices while the gates of overflow canals and diversions were an overflow gate type.

3.3. A standard steep chute design ?

A summary of well-documented very-steep gradients is presented in Figure 6. Steep sections were found in several countries suggesting that the de-

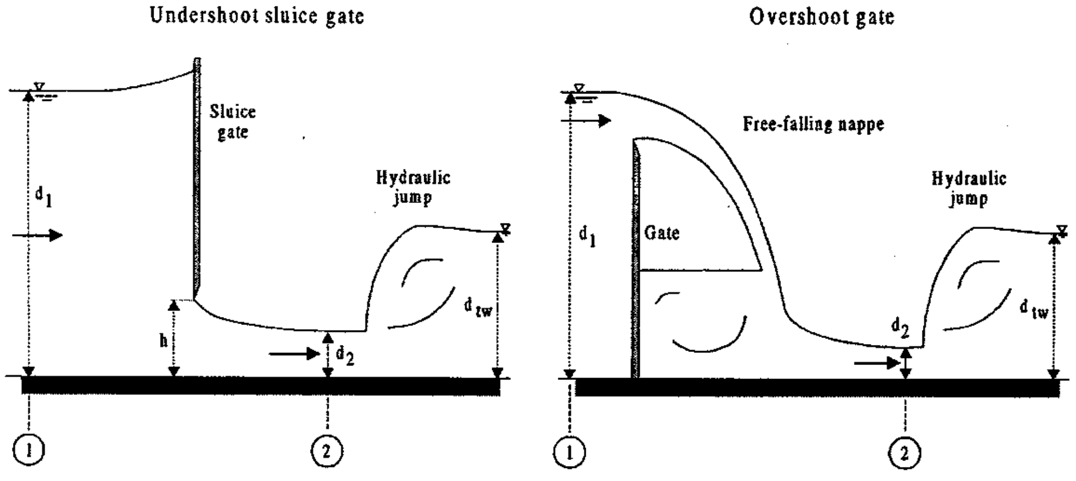

Figure 5: Overshoot and undershoot gate operation

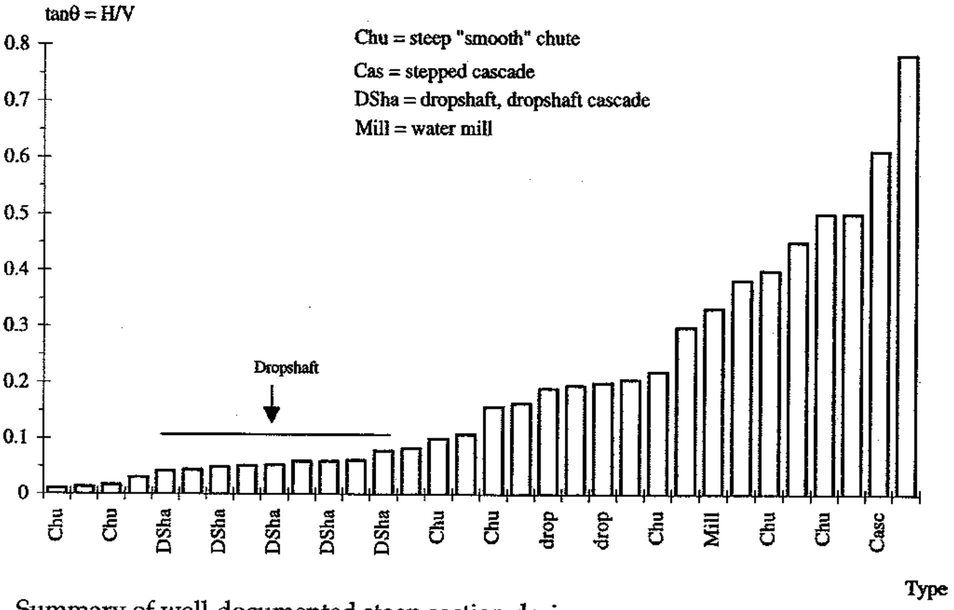

Figure 6: Summary of well-documented steep section designs

sign was not unique to a colony but in use in all the empire. Figure 6 would suggest that smooth chutes were used for the steepest gradients, but the examples of the Yzeron and Brévenne aqueducts at Lyon are enlightening (Table 1). The older canal at Yzeron was equipped with dropshaft cascades while Brévenne was equipped with 'smooth' chutes. At Yzeron the dropshaft cascades were used for an overall gradient of 6 to 8%, while the longitudinal gradient at Brévenne was only about 0.4 to 1.25% including the steep chutes. The writer is convinced that the dropshaft cascade was the standard design for long steep sections (e.g. Valdepuentes, Spain) while the chutes and cascades were restricted to specific and shorter sections : e.g., Andriake, Cherchell.

4 SUMMARY AND CONCLUSION

The study demonstrates the existence of steep sections along Roman aqueducts (Table 1, Figure 6). A hydraulic analysis shows the existence of supercritical flow conditions, sometimes associated with hydraulic jumps. The Roman engineers used three designs: the smooth chute, stepped cascade and dropshaft cascade. It is believed that the latter was standard for long steep sections. Smooth and stepped chutes were used for shorter portions.

The conception and construction of these hydraulic structures were specialised tasks. The design engineer had to have a solid experience with supercritical flow, hydraulic jumps, stilling basins, stepped cascades and dropshafts. Further the satisfactory operation of an aqueduct equipped with steep chutes implied the use of upstream regulation devices as well as downstream control structures.

Altogether the writer demonstrates the positive outcome of a multi-disciplinary research project involving archaeologists, historians, surveyors as well as engineers.

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ENDNOTES

1 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$ 23 to 69 millions (based on US$485.5 per ounce of silver on 25 November 1998) ! By comparison the pipeline for the Tarong power station (70-kin long, 0.9 m3/s) in Queensland costed AUD$ 0.2 millions per kin (Courier Mail 3 Dec. 1994, p. 13).

2 Modern calculations of aqueduct hydraulics are embryonic. The present study suggests however that the current misunderstanding' of aqueduct hydraulics derives from the 'ignorance' of historians and archaeologists. Most hydraulic calculations are feasible by undergraduate engineering students, provided that accurate information on the channel dimensions and flow rate are available 8,9.

3 The word 'smooth' is used in contrast to 'stepped' (i.e. stepped cascade).

4 "This type [of oscillating jump] has a pulsating action [...]. [It] is one of the most difficult [types of jump] to handle" (10, p. 1401-22). The same researchers highlighted specific problems in confined channels :"In narrow structures, such as canals [and aqueducts], waves may persist to some degree for miles. Structures in this range of Froude numbers are the ones which have been found to require the most maintenance" p. 1404-2).

5 The concept of stilling basin was known prior to the Roman era. In Priene, Greece, a large stilling basin (3.23-m long, 0.8-m wide, 0.8-m deep) was built at the downstream end of the sewer system during the 5-th century B.C. 13. The maximum discharge was probably about 0.425 m3/s before spillage.

6 Roman dams equipped with drop spillways included Harbaka (AD 200-300?, Syria). Examples of stepped spillways included Kasserine dam (Tunisia AD 100?), Oued Guergour dam (Tunisia AD 100?), Qasr Khubbaz (Syria AD 100-200), and Tareglat dam (Libya AD 200-300).

7 For example, the dropshaft cascades of the Valdepuentes aqueduct were later re-used by the Muslims 13.

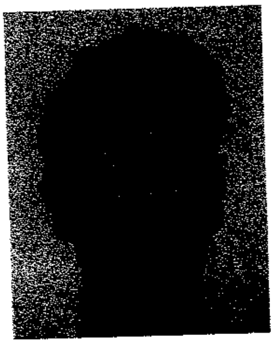
8 For the techniques of construction and the problems associated with connecting different sections, see 5,17,18.

9 A librator was a military engineer and expert surveyor: e.g., Nonius Datus who designed the Saldae aqueduct (Algeria). An aquilex was a water seeker, expert in finding water (e.g. in a desert). An architectus was simply responsible for the harmony of the monument. It is believed that the aquilex was a hydrologist, the architectus was probably a structural engineer, while the librator was a true hydraulician.

10 Greek mathematician (I st century A.D.) working in Alexandria, Egypt. He wrote at least 13 books on mathematics, mechanics and phys-

ics. He designed and experimented the first steam engine. His treatise "Prieurnatica" described Hero's fountain, siphons, steam-powered engines, a water organ, and hydraulic and mechanical water devices. It influenced directly waterworks design during the Italian Renaissance.

11 The *castellum divisorium* is a distribution structure, often located at the outskirst of a city: e.g., Nimes, Pompeii, Fr6jus, Arles. At Tebourda (Thuburbo Minus, Tun.), the castellum was a rectangular basin, 2.8-m long, 1.5- wide and 1.5-m deep, distributing the water into three separate directions (2 1, pp. 108-109).



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Hubert Chanson is a senior lecturer in fluid mechanics, hydraulics and environmental engineering at the University of Queensland since 1990. His research interests include design of hydraulic structures, experimental investigations of two-phase flows, coastal hydrodynamics, water quality modelling, environmental management and natural resources. He is the author of three books : "Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways" (Pergamon, 1995), "Air Bubble Entrainment in Free-Surface Tuton DC) and at the Workshop on Flow Characteristics around Hydraulic Structures (Nihon University, Japan 1998). He gave an invited lecture at the International Worshop on Hydraulics of Stepped Spillways (ETHZijrich, 2000). He lectured several short courses in Australia and overseas (e.g. Taiwan).

Discussion on

A Hydraulic Study of Roman Aqueduct and Water Supply

H Chanson
The University of Queensland

Paper No.W20/503, AJWR Vol4. No.2, 2000

Discussion by Dr J Davies FIEA
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The author presents an interesting topic and introduces the Australian hydraulic fraternity to Roman hydraulics, perhaps for the first time.

The comments which follow hopefully will draw out important points, perhaps not adequately explained in the paper itself.

In standard texts (eg [1]) a hydraulically steep slope is defined as one in which the critical depth of flow is greater than the uniform depth of flow. Similarly, a hydraulically mild slope is one for which the critical depth is less than the uniform depth of flow. The use of these definitions in the paper would perhaps have led to greater clarity.

For example, figure 2 shows cross section sketches of a steep smooth chute; a stepped channel and a dropshaft cascade. Illustration of critical and uniform flow depth together with a water surface profile would have assisted in illustrating the sub and super critical flow regimes.

Also in figure 2 the dropshaft cascade water surface profile indicates super critical flow downstream of a dropshaft, followed by a hydraulic jump. Could the author please explain why there should be super critical flow on the downstream side of the dropshaft, which presumably is in a region of mild slope?

In Section 2.1 the statement "the transition from high velocity flow to a slower motion may take place as a hydraulic jump .... "may understate the situation. The reality is perhaps that while a smooth transition between sub critical and super critical flow is possible, the reverse is not the case; the transition back from super critical to sub critical flow has to occur through a hydraulic jump - a smooth transition is impossible.[1]

Figure 2 for a stepped channel appears to show a water surface profile at constant depth above each step, which may occur at flows in excess of the design capacity when the structure is effectively drowned out. The structure would presumably operate for most of the time with super critical flow over the end of the step, with a hydraulic jump on the step below. As with figure 2, perhaps figure 3 could be redrawn to show the interaction of the water surface profile with critical and uniform flow depths.

The paper presents the case for Roman understanding of open channel hydraulics including sub critical, super critical flow and hydraulic jumps.

The author discusses the possibility that steep sections were introduced to connect aqueduct sections built by different gangs, as a remedy for misalignments. This interpretation does not however assist when the misalignment is one requiring a step upwards rather than downwards! It seems more likely that by trial and error the Romans would have gradually developed an appreciation of the massive structures required to adequately dissipate energy, without hydraulic failure by erosion, and that mild slopes were generally employed to keep velocities sufficiently low to prevent erosion also.

In Section 3.2 it is stated that "super critical flows must be controlled from upstream ...." This treatment of the subject appears to depart from the traditional treatment in which super critical flow itself is considered as a hydraulic "control"; that is, it determines the stage discharge relationship in the upstream section.[1]

While table 1 documents surviving examples of steep Roman aqueduct sections, it does not of itself demonstrate any particular theoretical basis, rather perhaps only an experience gained through trial and error.

REFERENCE

1 Henderson FM. Open channel flow. MacMillian Company, New York USA. 1966.

Response

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The writer thanks the discusser for his interest in the topic and his discussion.

The writer is aware of the basic definitions of steep and mild slopes.[1] He used the technical terminology in the paper[3] as per basic undergraduate textbooks.[1,2] The dropshaft cascade sketched in[3, fig 2] is based upon the Recret cascade (Yzeron, France) which was built with mild-slope connecting conduits between shafts. The Romans built dropshaft cascades with either mild or steep slope conduits between vertical shafts. For example, mild slopes at Recret, Vaugneray and Montjeu (France); steep slopes at Valdepuentes (Spain). Physical model tests,[4,5] showed that supercritical flow may occur downstream of the shaft until a hydraulic jump is induced by the tailwater conditions (ie. mild slope).

In [3, fig.2] the stepped cascade is sketched for a skimming flow regime. A skimming flow takes place for small step heights or large flow rates: ie, when the ratio of critical depth to step height is greater than 1.2.[6] While some cascades were built with large step heights (eg. Andriake (Turkey)[4]), others were designed with small step heights implying a skimming flow as sketched in [3, fig.2]: eg. Kasserine (Tunisia), Qasr Khubbaz (Syria).[6]

The discusser suggested that Roman engineers built the aqueducts by trial and error. This is untrue and there is a solid bibliography suggesting the contrary. For a review, see [3,4]; for the dropshaft cascades of the Valdepuentes aqueduct, see [7,8].

Lastly there seems to be some confusion on the terminology "hydraulic control".[1:40-43] defined clearly a control as a location where critical flow occurs, while [2:44-46] used specifically the term "hydraulic control". The paper [3] followed the same terminology. At a location where critical flow conditions occur, the flow properties (ie. depth and velocity) are deduced from the continuity equation and from the definition of minimum specific energy, independently of momentum and energy consideration. Henderson wrote: "at any feature which acts as a control the discharge can be calculated once the depth is known".[1:43] Chanson stated: "at a control section critical flow conditions take place and that fixes a unique relationship between depth and discharge in the vicinity".[2:521]

In summary, the discusser seek some clarification which was developed above. References [3,4] demonstrated that Roman aqueducts operated with both sub- and super-critical flows implying that the Romans had experience, if not expertise, in open channel hydraulics. The construction and long-lasting operation of several dropshaft cascades showed a solid experience in difficult hydraulic structures. The operation of regulation systems highlighted further some sound hydraulic practice, an issue that was presented independently in reference [9].

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