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Hydraulics of Roman Aqueducts : Steep Chutes, Cascades and Dropshafts

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Abstract

This paper examines the archaeological evidence for steep chutes, cascades and drop shafts in Roman aqueducts. It also presents comparative data on steep descent water flow in aqueducts based on physical model tests. It is suggested that the Romans were aware of the hydraulic problems posed by supercritical water flows, and that the technological solutions they imposed were rudimentary but sound. For example, they understood the need for energy dissipation devices such as stilling basin and dropshaft.*

The Roman aqueduct remains one of the best examples of hydraulic expertise in antiquity. Many aqueducts were used, repaired and maintained for centuries and some, such as the aqueduct of Carthage (Tunisia), are still partly in use today.[1] Most aqueducts consisted of long, flat sections interspersed by shorter steep drops. Despite arguments suggesting that Roman aqueducts maintained a fluvial flow regime [2], the present study suggests that these steep drops produced supercritical flows requiring a technical response to ensure normal water flow. It is argued that the Romans employed three methods to address this problem: chutes followed by stilling basins, stepped channels, and dropshafts.

STEEP CHUTES AND STEPPED CASCADES : HYDRAULIC CONSIDERATIONS

A chute is characterized by a steep bed slope associated with torrential flow (fig. 1 and 2). This chute flow may be either smooth (fig. 2A) or stepped (fig. 2B). Roman designers used both designs as well as single drops along aqueducts (Tables 1 and 2). There are archaeological evidences of smooth chutes along the Brévenne, Cherchell, Corinth and Gorze aqueducts, and on the Anio Vetus, Claudia, Marcia and Anio Novus aqueducts at Rome (table 1).[3] Although there is less information on stepped channels, those at Andriake and Beaulieu are well-documented. Dam spillways also employed smooth and stepped chute designs. The oldest known stepped spillway was built around 1300 B.C. in Greece,[4] and the famous Marib dam (Yemen) was equipped with an unlined rock chute on the left bank to spill flood waters. Roman engineers also built several significant spillway systems.[5]

Appendix 1 provides some basic hydraulic calculations that I have applied to well-documented steep chutes. Tables 1 and 2 (column 4) summarize the results of these calculations. They were performed for “accepted” maximum flow rates (table 4) and demonstrate that high-velocity flows (velocities in excess of 8 m/s) occurred along several Roman aqueducts. The hydraulics of fluvial and torrential flows are distinguished by their fundamentally different behaviors. Torrential (supercritical) flows produce a much greater kinetic energy than fluvial flows. This value is normally expressed in terms of a “Froude number;”[6] i.e., the calculation of the properties of fluvial (lower energy) flows will produce a Froude number less than 1, while the properties of torrential flows produce a Froude number greater than 1. Supercritical torrential flow was consistently present along the entire channel of each investigated chute (table 1, column 4). Downstream of the chute, the transition to a slower flow motion took place as a hydraulic “jump,” characterised by strong energy dissipation (see appendix 1).

In modern engineering, hydraulic designers seek to avoid three types of hydraulic jumps: strong, oscillating, and undular jumps (fig. 3). Bed erosion and “scouring” is more likely whenever there is a strong hydraulic jump, abruptly increasing the scour potential of the water at any point. It is believed that Roman aqueduct mortar and concrete could never sustain the “uplift forces” that occur in the water just beyond these strong jumps.[7] Oscillating jumps present the risk that the position of the roller would be unsteady and fluctuate over great lengths. Further, the oscillating jump would be characterized by the unsteady propagation of the surge waves, highly undesirable in a narrow channel.[8] The third undesirable change in water flow pattern, the undular hydraulic jump, produces steady stationary free-surface waves of significant length[9] that have no formed roller pattern, and extend far downstream.[10] Thus, for a flow depth of 0.5m, these waves might extend for one kilometre or more. A similar wavy flow pattern may also occur with near-critical flows.[11] The waves generated by these undular and oscillating jumps can seriously interfere with the operation of the conduit downstream. Such problems in modern conduits include vibrations on downstream gates, disturbance of the discharge measurement devices, and changes in the way turbulent materials are dispersed within the channel.[12]

The free-surface profile at the downstream end of steep chutes is affected by both the high-speed chute flow and tailwater conditions. The latter are the flow conditions in the downstream canal.[13] Four flow situations may occur (fig. 4). With a supercritical tailwater depth, the flow remains supercritical after the change of slope and no jump occurs. When the tailwater depth is larger than the critical depth in the downstream conduit, a hydraulic jump takes place. Depending upon the chute and tailwater conditions, the jump may be located far downstream or close to the change in slope. For very high tailwater depths, the hydraulic jump becomes drowned and a plunging jet flow occurs at the change of slope.

For several of the Roman steep chutes (tables 1 and 5), the effects of tailwater conditions were investigated by performing backwater computations.[14] The results suggest that various types of jumps occurred, as well as plunging jet flows (table 5, column 3). These findings demonstrate that unfavorable flow conditions existed in these chutes, including oscillating hydraulic jump and undular flows which were unsuitable for a proper operation of the aqueduct unless structures were built to dampen the surge waves. A sensitivity analysis was further performed for several chutes and aqueducts: Table 5 contains a sample of the quantitative results for one of these. The study suggests no major change in backwater profiles for a broad range of discharge, from 30-120% of maximum flow rate.

Design of stilling basin downstream of steep chutes

In discussing the design of these basins it is necessary to consider their intended purpose, stilling basin design, and chute geometry.

Settling or stilling basins? The presence of basins along aqueducts (i.e. a short deeper section of the canal) often associated with inspection shafts and manholes has been well-documented.[15] But were they settling basins or stilling basins? Some studies have proposed that these were “settling basins” built to trap mud, sand and solid waste.[16]

Some basin systems, however, were clearly NOT designed to trap sediments. At Alepotrypes (Corinth), for example, the hydraulic power of the chute flow was about 9 kilowatts and the downstream cistern functioned primarily as a dissipation basin.[17] Three other, well-documented, basin systems were built downstream of steep chutes: at Sotizon, 2,410-m downstream of the Courzieu II chute (Brévenne), at Jouy-aux-Arches, downstream of the Moselle bridge-canal (Gorze), and in the case of at least five circular basins at Oudna (Carthage)[18] (fig. 5). Moreover, it appears that the basin dimensions are inadequate for purposes of trapping sediments. All of these aqueducts were covered and lined with mortar. The intake channel was the only possible point at which sediments could enter the system. Roman engineers were, even by modern standards, highly expert at building intake structures, and several of these were designed with a desilting device.[19] It is obviously most efficient to trap sediments directly at the point of entry rather than further downstream. Further the water velocity in the aqueduct channels was too slow to carry coarse sediments very far.[20]

The degree to which a sedimentation basin may effectively trap sediment is related to the inflow properties, depth and length (geometry) of the basin, and the properties of the sediment itself.[21] My calculations of maximum flow rates for the basins at Sotizon and Oudna suggest that sediment trap efficiencies were less than 50%. In addition, the basin volumes were small: 0.27 m^3 at Sotizon, 1.7 m^3 at Jouy and 0.176 m^3 per basin at Oudna. With inflow sediment concentrations as low as 0.02 to 0.19 kg/m^3, these basins would have been filled in one day at maximum flow rates. To clean the basins one had to stop the flow, making it improbable that cleaning would occur on a daily basis.[22] It is unlikely, in fact, that the aqueducts were stopped more than once a month, and the cleaning process would have taken several days to complete. Thus it appears to me most likely that at least four of these basins were in fact not sediment traps, but stilling devices.

Stilling basin designs: As the preceding discussion suggests, undulations and surge waves would create serious problems for the operation of an aqueduct. The purpose of the stilling basins was to dampen the wave energy. Calculations done of the backwater show the need for substantial energy dissipation at Alepotrypes and unfavourable flow conditions at Courzieu II (undular jump), Gorze bridge-canal (undular flow, $Fr = 0.88$) and at Oudna[23] (undular flow, $Fr = 0.7$) (table 5). At Sotizon, Jouy, and Oudna, the basins were primarily stilling basins to suppress downstream wave propagation (e.g. fig. 6). I believe that the Chevinay and Lentilly II chutes located downstream of the Sotizon basin were equipped with similar stilling devices although no trace of the basin has yet been found (table 5).

Stilling basins work best when the basin itself is deep and long. The minimum length of modern hydraulic jump stilling basins is about 3 to 6 times the downstream flow depth although, for oscillating hydraulic jumps, the basin length must be longer: a length-to-depth ratio of about 6:1.[24] At Sotizon this ratio is approximately 4:1. At Jouy it is approximately 10:1, while at Oudna it is closer to 3.8:1, although the basins at Oudna are circular in shape. Clearly, the Jouy basin had the most efficient design while that at Oudna was less than optimal. The circular shape of the Oudna basins, associated with a small volume, may have been intended to induce three-dimensional wave motion, associated with cross-waves, wave impact on the walls and wave reflection.[25] Consequently, a single basin will have been inadequate for dampening wave propagation. There are at least five basins at Oudna, and this quantity may represent an attempt on the part of the Roman designers to address this problem.

Chute geometry: In several instances, the design of the steep chutes differed from that of the main aqueduct channel. Some steep chutes were wider than the main channel, such as those at Chabet Ilelouine (Cherchell), and the Claudia aqueduct below D. Cosimato Cliff. It has been suggested that this design was introduced to maximize flow resistance.[26] Other steep chutes were narrower than the main channel. This is the case at Courzieu II (Brévenne), Lentilly II (Brévenne), and Hadrian’s Villa (Anio Vetus). Of interest, the chute outlet was often designed to be narrow at the point in which the water entered it, and gradually expanding in width. This is evident at Courzieu II (Brévenne), Lentilly II (Brévenne), Alepotrypes (Corinth), Jouy (Gorze), Hadrian’s Villa (Anio Vetus), and Fienile (Anio Novus). This corresponds to a transition from a cut-rock tunnel to an aqueduct bridge. In a few cases, the chute outlet design was a contraction: this occurs at the bridge at Mola si San Gregoria (Anio Vetus), and at the Claudia aqueduct below D. Cosimato Cliff. The gradual reduction in breadth seems related to the chute’s transition into a cut-rock tunnel. Modern hydraulics suggests that a channel expansion at the chute outlet assists in dissipating the energy of the flow.[27] This evidence could suggest that those who did the construction were not aware of the problem.

DROPSHAFT CASCADES

In some aqueducts Roman engineers built a series of dropshafts (called dropshaft cascades) along the aqueduct’s main branch. This technology is well-documented for the Cherchell, Cuicul, Köln, Montjeu and Yzeron aqueducts (table 3).[28] In Rome vertical dropshafts were used to connect aqueducts, particularly from newer, higher channels to older canals.[29] These shafts were sluice towers built primarily for water redistribution. It is believed that the design was probably a function of circumstances rather than a specific engineering feature of the newer aqueduct.

In modern hydraulics, there are at least three recognized purposes for designing dropshaft cascades. First, they may be used where the topography is especially steep. This is clearly the case for the Roman aqueducts at Recret and Grézieu-la-Varenne, Yzeron; Montjeu, and Autun (table 3, fig. 7 and 8). Up until now it has been believed that dropshafts were built to dissipate energy, and possibly also, as discussed above in the context of basins, to trap sediment.[30] Regardless of purpose, a dropshaft by design provides a connection between two flat conduits, located at different elevations along the (usually short) length of the shaft. In contrast, a steep chute would require a much greater horizontal distance for the same drop height. A second application of the dropshaft is the dissipation of the kinetic energy of the flow. Such a design is still used today.[31] To work well this design must account for three factors : i.e., drop height, shaft geometry and flow rate. If these are not properly considered, unacceptable scour and erosion may take place. A third application of the dropshaft cascade is the aeration (or, reoxygenation) of the flow. This occurs via air bubbles entrained by plunging jet action into the shaft pool.[32]

Hydraulics of Roman Dropshafts

In the Hydraulics Laboratory at the University of Queensland, we investigated the hydraulics of the Roman dropshaft using a 1/4th scale model of the Recret dropshaft on the Yzeron aqueduct (fig. 8A and fig.9). The results[33] highlighted several flow patterns with increasing flow rates. We expressed this in terms of d_C/L, which is the ratio of critical flow depth (the height of the drop, measured in meters) to the length of the dropshaft (also in meters).

At low flow rates (d_C/L is less than or equal to 0.15), the free-falling nappe (the water surface) impacts into the shaft pool; we categorize this scenario as regime R1 (fig. 9A). In this flow, substantial air bubble entrainment occurs in the pool. In the downstream channel, the flow is supercritical in the absence of downstream backwater effect. In situations where the discharge rate is greater (the d_C/L is greater than 0.15 but less than 0.30), the upper nappe of the free-falling jet impacts into the downstream channel, flowing in between the inlet invert and obvert; we categorize this as regime R2 (fig. 9B). In R2 the rate of energy dissipation is smaller, the pool free-surface level increases significantly, and lesser air bubble entrainment is observed in the pool. At large flow rates (where d_C/L is greater than or equal to 0.30), the free-jet impacts onto the opposite wall, above the downstream conduit obvert (regime R3). The pool free-surface rises up to the downstream channel obvert and the water level in the pool fluctuates considerably. The third type of regime, R3, common in modern dropshafts, occurs only at large flow rates and was unlikely in Roman aqueducts.

Discussion

The analysis of the dropshaft model performances indicates that the optimum performances in terms of energy dissipation and flow aeration are achieved with a flow regime such as that illustrated in R1 (fig. 9A). The experiments show that the flow regime R2 is characterized by poor energy dissipation, little flow aeration and a high risk of scouring (figs. 9B and 10). In flow regime R2, extensive damage would occur very rapidly, typically in less than one day of operation. Most erosion would take place at the nappe impact and at the downstream conduit intake (fig. 10). The deterioration of modern concrete structures is well-documented[34] and worse damage would occur in Roman constructions. I suggest that, in fact, the dropshafts had to be overdesigned in order to prevent rapid and costly damage associated with the regime R2, and that the aqueduct dropshafts had to be built for an operation in a flow regime R1.

Table 6 summarizes the operation of well-documented dropshafts based on analytical calculations of the nappe trajectory and impact conditions.[35] At Cherchell, optimum performances (regime R1) were achieved for discharges less than 6,600 m^3/day.[36] This result challenges the accepted maximum discharge of 40,000 m^3/day.[37] For the Yzeron aqueduct, optimum operation (i.e. regime R1) occurred for flow rates up to 7,500 m^3/day in the Recret main section and 22,000 m^3/day in the Vaugneray branch. The Montjeu aqueduct dropshafts at Brisecou Forest could operate safely with flow rates up to 40,400 m^3/day. It is reasonable to assume that the Recret branch operated with a discharge less than 7,500 m^3/day, a figure consistent with an overall discharge of 10,000 to 13,000 m^3/day in the Yzeron aqueduct, assuming a flow rate of 5,000 m^3/day at Vaugneray.[38] However it was unlikely that either the

Vaugneray branch or the Montjeu aqueduct operated at 22,000 and 40,400 m^3/day respectively. It is more likely that these two series of dropshafts were oversized designs and that optimum operation of dropshaft was achieved in the setting outlined above as regime R1.[39]

DISCUSSION : CHUTE AND DROPSHAFT DESIGN

Although this study demonstrates the existence of steep sections along the aqueducts, certain questions remain. Were steep chutes and dropshafts an intentional design feature of Roman aqueducts ? Did the aqueduct designer (aquilex) understand the basic concepts of chute and dropshaft hydraulics ? Indeed it is plausible that some steep chutes were introduced as a functional solution to connect aqueduct sections that had been built by different gangs.[40] The construction of stilling basin and dropshaft was not (and is still not today) a simple job: it required the advice of an experienced engineer.

However, well-documented evidence of aqueduct chutes and cascades clearly exists (tables 1-3). These examples suggest that those who built them knew the problems that they faced and intentionally designed the chutes and dropshafts accordingly. The series of steep chutes at Brévenne were imposed by the topography of the valley. They included vertical drops of up to 87m (i.e. Chevinay/Plainet) which could not be a simple construction problem. These chutes were part of the original design of the aqueducts. At Montjeu, Cherchell and Yzeron (fig. 8), large series of dropshafts were installed: 24 dropshafts at Autun (ΔH = 140 m), at least 15 dropshafts at Recret and more at Vaugneray, and four dropshafts at Chabet Ilelouine. Clearly these were engineering design features of the aqueducts![41] In both Roman and modern times, the hydraulic design of chutes and dropshaft has been a highly specialized task; the engineering design of the Roman aqueduct would have been reserved for only those Roman engineers with the highest skills. Nonetheless, there is no written documentation to support this theory that the engineers understood the basic concepts of continuity and energy as used in modern hydraulics. Even modern calculations of aqueduct hydraulics are embryonic.[42]

Table 7 summarizes those observations of very steep gradients that are well documented. Here we find evidence of very steep gradients in short stretches, up to 78% at Cherchell Chabet Ilelouine. Steep chutes were found across a wide geographic range – in Italy, France, Algeria, and Turkey - suggesting that the steep-gradient design was not unique to Rome but also employed at aqueducts elsewhere in the empire. Secondly the steepest longitudinal slopes (not counting stepped spillway chutes) were smooth and stepped chutes but not a series of dropshafts. Supercritical flow took place in steep channels. Most Roman aqueducts had, overall, a mild slope that was associated with subcritical flows. The transition from the 'steep' chute flow to the subcritical flow was characterized by a hydraulic jump. Hence Roman engineers clearly had some experience of both supercritical flows and hydraulic jumps.

Thirdly, and conversely, the data in Table 7 highlights the fact that series of dropshafts were not used in the steepest topography, but rather for a range of longitudinal mean slopes up to 20% (table 7). This might suggest that dropshafts were not considered “safe” or “efficient” with very-steep gradients. Construction problems may have affected the choice of dropshafts or steep chutes. Further the dropshaft design might have been selected for purposes other than energy dissipation alone; the design may have been employed in some cases, for example, for re-aeration.

The Lyon aqueducts offer a useful example for a comparison between steep chute and dropshaft cascade design. At Lyon, the Yzeron and Brévenne aqueducts were both designed with steep longitudinal gradient sections (Burdy 1979, p.64). The older of the two, the Yzeron aqueduct, was equipped with a series of dropshafts (Recret, Vaugneray) while the aqueduct at Brévenne was equipped with steep 'smooth' chutes (e.g. Courzieu II, Chevinay, Lentilly II). Why ? At the Yzeron aqueduct, the overall drop of the two series of dropshafts was 38 m along 490 m at Recret, and 21.9 m along 375 m at Vaugneray, or 7.8% and 5.8%, respectively. In comparison, the overall gradient was about 4.8 to 5.4% at Beaulieu and about 15% in average at Montjeu (table 3).

These longitudinal gradients might seem small compared to the steep chute gradients along the Brévenne aqueduct - 22% at Courzieu II, 45% at Chevinay, and 8.2% at Lentilly II (table 1) - but the intervals between the steep chutes varied from about 7 to 16 km ! The overall drop in elevation from one chute intake to the next one was 65 m along 16.2 km at Courzieu II, 140 m along 11.2 km at Chevinay and 80 m along 7 km at Lentilly II (0.4%, 1.25%, and 1.1% respectively).

In summary, these figures suggest that the series of dropshafts of the Yzeron aqueduct were used for an overall gradient of 6 to 8%, while, at Brévenne, the longitudinal gradient of the aqueduct was only about 0.4 to 1.25%, including the steep chutes.

SUMMARY AND CONCLUSION

Roman aqueducts were equipped with short steep sections. For bed slopes ranging from 1% to 78%, three types of designs were used: the steep smooth chute followed occasionally by stilling basin(s) (fig. 6), the stepped cascade, and the series of dropshaft (fig. 7).

Steep chute flows were characterised by high velocity supercritical flows. Tailwater conditions were often subcritical and hydraulic jump flow conditions occurred at, or downstream of, the transition to the flat conduit. A complete backwater analysis has shown the presence of unfavourable conditions associated with these channels, in particular undular flows and oscillating hydraulic jumps. I suggest that stilling basins were sometimes introduced to dissipate the energy of the waters and to prevent downstream propagation of surge waves and undulations (fig. 6). These basins were found at Alepotrypes, Courzieu II, Jouy and Oudna. This implies that Roman hydraulic engineers observed flow instabilities along aqueducts and were capable of introducing devices to dampen the effects.

In a 1/4th scale laboratory model of a Recret shaft built specifically to investigate Roman dropshaft hydraulics, I observed three flow regimes. Optimum dropshaft operation occurred for the flow regime R1, characterized by low flows and nappe impact into the shaft pool. In regime R1, the dropshaft design was most efficient in terms of energy dissipation and air bubble entrainment, in particular compared to modern designs. Calculations suggest that dropshaft operation at Cherchell took place for lower-than-accepted flow rates, while two series of dropshafts, at Montjeu and Vaugneray, were equipped with oversized shafts.

The designs of dropshaft cascade, as well as steep chute followed by dissipation basin, show that the Roman aqueduct engineers were able to design specific features to cope with steep sections. It remains unclear whether they had some understanding of the hydraulic principles, or worked by observations and trial and error.

Most aqueducts were enclosed (covered) along their entire length, limiting the possibility for gas transfer at the free surface. Thus, the downstream waters were low in dissolved oxygen content unless reoxygenation devices were installed. I suggest that dropshafts may have been introduced in place of steep chutes in order to reoxygenate the water as well as to dissipate the energy of the flow. Aeration technology is commonly used today to reoxygenate depleted waters and to enhance the water quality. I recommend that further work by archaeologists focus on the excavation and survey of chutes and dropshaft to confirm this hypothesis.

APPENDIX 1 - HYDRAULICS OF OPEN CHANNEL FLOW : DEFINITIONS AND BASIC EQUATIONS

In open channel flows (for example fig. 1, a smooth chute), the critical depth d_c is the depth of flow producing maximum flow rate for a given specific energy. For a rectangular channel it equals : $\sqrt[3]{Q^2/(g*b^2)}$ where Q is the discharge, g is the gravity acceleration, and b is the channel breath. If the flow is critical, small changes in specific energy cause very large changes in depth. In practice, critical flows over a long reach of channel are unstable, characterized by large free-surface undulations. Such a flow pattern, called undular flow, is experienced with near-critical flows characterized by a Froude number greater than 0.3 but less than 3.0; $Fr = V/\sqrt{g*d}$, V is the flow velocity and d is the flow depth.[43]

Subcritical or tranquil flow occurs when the flow depth (d) is greater than the critical depth. As a channel becomes steeper, water tends to flow with greater velocity and shallower depth until, on steep sections, supercritical flow occurs and the rapid flow depth is less than the critical depth. Subcritical and supercritical flows are also called fluvial and torrential flows, respectively.

The transition back from supercritical to subcritical flow conditions creates a hydraulic jump, where the depth of flow suddenly increases. A hydraulic jump is undesirable because it leads to flow instability and possible surges, and thus has great erosive potential. Experimental observations highlighted different types of hydraulic jumps, depending upon the Froude number of the upstream flow. An undular hydraulic jump is observed at low Froude numbers (between 1 and 3). With increasing Froude numbers, other types of jumps include weak jump, oscillating jump (Froude number between 3.5 and 4.5), steady jump and strong jump (Froude number is greater than or equal to 10) (see, for example, fig. 3).[44]

Hydraulic calculations of steep chutes and cascades

In long prismatic chutes, the flow conditions in steep chutes may be calculated assuming uniform equilibrium flow conditions (i.e. normal flow) :

$$V_o = \sqrt{\frac{8 * g}{f}} * \sqrt{\frac{(D_H)_o}{4} * \sin\theta} \qquad (2)$$

where V_o is the uniform equilibrium flow velocity, $(D_H)_o$ is the hydraulic diameter[45] at uniform equilibrium, f is the Darcy-Weisbach friction factor and θ is the channel slope (fig. 1). The friction factor f is estimated from the Moody diagram for smooth chutes.[46] I computed f to be between 0.02 and 0.04 for Roman aqueducts with smooth mortar lining. For skimming flow over stepped cascades, f increases from 0.1 to 1 for bed slopes from 5 to 10 degrees and f equals about 1 for steeper slopes.[47]

There is a fundamental difference between smooth and stepped chutes: the kinetic energy of the flow is significantly larger in smooth chute flow that for a stepped one, for identical flow rate and chute properties. As a results larger energy dissipation must take place at the end of a smooth canal and sometimes stilling structures must be introduced.

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LIST OF SYMBOLS

A	cross-section area (m^2);
B	dropshaft width (m);
b	open channel width (m);
D	conduit height (m);
D_H	hydraulic diameter (m), or equivalent pipe diameter, defined as : $D_H = 4 * \frac{\text{cross-sectional area}}{\text{wetted perimeter}} = \frac{4 * A}{P_w}$
d	flow depth (m) measured perpendicular to the channel bed;
d_b	brink depth (m) : i.e., depth at the edge of a drop;
d_c	critical flow depth (m); in a rectangular channel : $d_c = \sqrt[3]{q^2/g}$;
d_o	uniform equilibrium flow depth (m) : i.e., normal depth;
d_{tw}	tailwater flow depth (m);
f	Darcy friction factor (also called head loss coefficient);
Fr	Froude number; for a rectangular channel : $Fr = V/\sqrt{g*d} = Q/\sqrt{g*d^3*b^2}$;
g	gravity constant (m/s^2);
H	total head (m);
h	1- step height (m); 2- invert drop (m) at a vertical dropshaft;
L	1- dropshaft length (m); 2- length (m) of stilling basin;
l	step length (m);
P	(shaft) pool height (m), measured from the shaft bottom to the downstream conduit invert;
P_w	wetted perimeter (m);
Q	total volume discharge (m^3/s) of water;
q	discharge per meter width (m^2/s); for a rectangular channel : $q = Q/b$;
V	flow velocity (m/s);
V_b	brink flow velocity (m/s);
V_o	uniform equilibrium flow velocity (m/s);

X	chute/cascade length (m);
x	horizontal Cartesian co-ordinate (m);
y	vertical Cartesian co-ordinate (m);

Greek symbols

ΔH	head loss (m) : i.e., change in total head;
Δz	change in bed (invert) elevation (m);
θ	bed (invert) slope;
$\varnothing$	diameter (m);

Subscript

c	critical flow conditions;
o	uniform equilibrium flow conditions;
tw	tailwater flow conditions;

Abbreviations

D/S (or d/s)	downstream;
U/S (or u/s)	upstream.

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Table 1 - Steep smooth chutes in Roman aqueducts

Steep Section (1)	Ref. (2)	Geometry (3)	Flow conditions (4)				Remarks (5)
			ΔH m	d_o m	V_o m/s	X m	
Brévenne aqueduct	[Co2]						
Courzieu II/La Verrière		b ~ 0.55 m, θ = 12.4°, mortar	44	0.05	4.24		Chute C1. 2.4 km upstream of the Bassin de Sotizon.
Chevinay/Plainet		b ~ 0.76 m, θ = 24.2°, paved stone	87	0.052	4.45		Chute C2.
Lentilly II/Les Molières-Montcher		b = 45 m, D = 0.8 m, θ = 4.7°, mortar	33	0.0795	3.25		Chute C5.
Limonest/La Bruyère		b ~ 0.53 m, mortar	8				Chute C6.
Cherchell aqueduct	[LP]						
Chabet Ilelouine		b = 1.3 m, θ = 38.0°	12.3	0.045	8		4 series of steep chutes followed by circular dropshaft.
Corinth aqueduct	[Lo]						
Alepotrypes		b ~ 1.1 m, θ = 1.72°, mortar		0.29	3.62		Upstream of a large stilling basin (40 × 11 m^2).
Gorze aqueduct	[Le]						
Bridge over Moselle		Two parallel canals, each : b ≈ 0.85 m, θ = 0.022°, mortar	4.3			1,100	Upstream calming basin (Ars-sur-Moselle) and downstream stilling basin (Jouy-aux-Arches).
				0.111	0.92		2 canals in operation.
				0.177	1.15		1 canal in operation.
Anio Vetus aqueduct							
Tivoli, Villa Hadrian	[VD]	b = 0.8 m, D = 1.25 m, θ = 11.6°, rocks and bricks	0.7	0.332	8,3		Short section. [VD, p. 40], [AS, pp. 63-64]
Bridge at Mola di San Gregoria	[AS]	b ~ 1.05 m, D ~ 2.37 m, θ = 9.3°	4.09	0.236	8.9		[AS, pp. 68-70]
Claudia aqueduct							

below D. Cosimato cliff	[VD]	b = 1.15 m, D = 0.9 m, θ = 26.6°, coarse concrete with rough reticulate	5.48	0.18	10.7		Upstream of bridge below Vicavaro. [VD, p. 196], [AS, p. 196]
<u>Marcia aqueduct</u>							
Casale Acqua Raminga, Gericomio	[Bl]	b = 1.15 m, θ = 8.9°, rough concrete	3.98	0.329	5.75	25.4	Upstream section. [AS, p. 115], [VD, p. 92]
		b = 1.15 m, θ ≈ 6.13°, rough concrete	31.9	0.374	5.05	204	Downstream section.
<u>Anio Novus</u>							
near Torrente Fiumicino	[Bl]	b = 1.25 m, θ ≈ 3.48°, brick work	6.8	0.315	5.58		[AS, p. 261], [VD, p. 280]
Ponte dell'Inferno to Ponte Scalino	[AS]	b ≈ 1.06 m, θ = 0.604°	26.37	0.765	2.71		Unlined rock tunnel. Cascades or steps ? [AS, p. 287]
Ponte Scalino to Ponte Amato	[AS]	b ~ 1 m, θ = 0.94°		0.686	3.21		Unlined rock tunnel. Cascades or steps ? [AS, p. 287]
Fienile	[AS]	b ~ 1 m, θ = 0.76°		0.747	2.95		Unlined rock tunnel. Cascades or steps ? [AS, p. 287]
<u>Carthage aqueduct</u>	[Ra]						
upstream of Oudna arcades		b = 0.865 m, θ ≈ 0.40°, mortar		0.157	1.47		Immediately upstream of Oued Miliane plain arcades.

Notes : d_o : normal flow depth; V_o : normal flow velocity; X : chute length; ΔH : total head loss. References[48].

Table 2 - Stepped cascades and drops in Roman aqueducts

Steep Section (1)	Ref. (2)	Geometry (3)	Flow conditions (4)		Remarks (5)
			ΔH m	X m	
STEPPED CASCADES					
Oued Bellah, Cherchell aqueduct	[LP]		37 18.6		Upstream of bridge. Cascade? Downstream of bridge.
Beaulieu aqueduct	[CQ]		37		Combination of steep chutes and dropshafts.
Petite cascade		5 steps : $h = 0.5$ to 0.5 m	2 to 2.5		Horizontal and inclined stepped faces.
Andriake, Lycia	[Mu]	Pooled steps : $h = 2.2$ m, pool height = 0.78 m, $b = 1.78$ m, $\theta = 31.4^{\circ}$	11	18	Series of 5 pooled steps.
Claudia aqueduct	[VD]	Single drop : $h = 1.1$ m			Near bridge below Vicavaro.
DROPS					
Brévenne aqueduct	[Co2]				
St-Pierre-La-Palud I		$b \sim 0.45$ m	30		
Lentilly II/Le Guéret-La Rivoire		$b \sim 0.45$ m	38		

Notes : b : channel width; X : cascade length; ΔH : total head loss. References[49].

Table 3 - Dropshaft cascades in Roman aqueducts

Steep Section (1)	Ref. (2)	Geometry (3)	Flow conditions (4)			Remarks (5)
			ΔH m	d_c m	X m	
Dougga aqueduct	[Ca]					
Oued Melah		B ~ 3.3 m b ~ 0.35 m (tunnel)	4 to 5			Located downstream of 200-m long bridge, upstream of tunnel..
Vaugneray, Yzeron aqueduct	[Co1]		21.9			Vaugneray branch of Yzeron aqueduct.
Puit du Bourg		Rectangular dropshaft : h = 2.55 m, b = 0.4 m, B = 1.14 m, L = 1.9 m		0.24		Downstream flow conditions : d ~ 0.35 m, V ~ 1.33 m/s
Recret/Grézieu-la-Varenne, Yzeron aqueduct	[Co1]	Rectangular dropshafts	38			Main branch of Yzeron aqueduct.
Puit Gouttenoire		Square dropshaft : h = 2.55 m, b = 0.55 m, B = L = 1.18 m, P = 1.12 m		0.197		
Puit-en-bas		Rectangular dropshaft : h = 2.5 m, b = 0.55 m, B = L = 1.17 m, D = 1.26 m, P = 1.35 m		0.197		Downstream flow conditions : d ~ 0.15 m, V ~ 1.9 m/s
Chabet Ilelouine, Cherchell aqueduct	[LP]		12.28			4 series of steep chutes followed by circular dropshaft.
Puit amont		Circular dropshaft : h ≈ 0.77 m, b ≈ 0.94 m, ∅ = L = 2.03 m, P > 1.75 m				Located downstream of steep smooth chute. Supercritical upstream flow : V ~ 8 m/s
Gunudu aqueduct			20			
Moulin Romain	[LP]	Circular dropshaft : h ~ 3.5 to 4 m, b ≈ 0.38 m, ∅ = L = 0.80 m				Upstream channel : 0.86-m wide.
Rusicade aqueduct	[Ve]	Circular dropshafts				
Beaulieu aqueduct	[CQ]		37			Combination of steep chutes and dropshafts.
Puit d'Olivari		Dropshaft : h = 6.2 m, b ~ 0.45 to 0.6 m				Rectangular or circular ? 147-m between dropshaft.
Puit du Château		Dropshaft : h ~ 8 m				Rectangular or circular ? 167-m between dropshaft.

Brisecou Forest, Montjeu aqueduct	[CQ, PR]	Rectangular dropshaft : h = 4.4 m, b = 0.8 m, B = 3.0 m, L = 2.4 m, D = 1.57 m, P > 0.8 m	140		770	A series of 24 dropshafts (possible combination with steep chutes).
		9 dropshafts (h = 4.4 m)				15 to 30-m between dropshaft.
		15 dropshafts (h = 4.4 m)				50 to 120-m between dropshaft.
Cuicul aqueduct	[Al]					
Grand thermes distribution line		Circular (?) dropshafts: h~1 to 0.4 m, b ≈ 0.45 m, ∅ = L = 0.80 m	3		85	Series of 4 dropshafts on an urban distribution line.
Köln aqueduct	[Gr]	Rectangular dropshaft : h = 0.35 m, b = 0.7 to 0.75 m, B = 0.9 m, L = 1.185 m, P = 0.2 m				Several dropshafts.

Notes : d_c : critical flow depth; X : dropshaft cascade length; ΔH : total head loss. References[50].

Table 4- Accepted flow rates and details of Roman aqueducts

Name (1)	Location (2)	Length km (3)	Discharge m^3/day (4)
Arles	France	48.0	8,000
Athens	Greece	25.7	
Beaulieu	Aix-en-P., France		
Brévenne	Lyon, France	70.0	10,000
Carthage	Tunisia	132.0	17,300
Cherchell	Algeria	> 45	40,000 / 6,600 (1)
Corinth	Greece	85.0	80,000
Cuicul	Algeria	5 to 6	
Dougga	Tunisia	12	
Gier	Lyon, France	86.0	15,000
Gorze	Metz, France	22.3	15,000
Gunugu	Algeria		
Köln	Germany	95.4	
Mont d'Or	Lyon, France	26.0	2,000 to 6,000
Montjeu	Autun, France		
Nikopolis	Greece	70.0	
Nîmes	France	49.8	35,000
Yzeron-Craponne	Lyon, France	40.0	13,000 (1)
Appia	Rome, Italy	16.6	73,000
Anio/Anio Vetus	Rome, Italy	81.0	190,080
Marcia	Rome, Italy	91.3	188,000
Tepula	Rome, Italy	17.7	18,000
Julia	Rome, Italy	22.9	48,000
Virgo	Rome, Italy	22.9	100,200
Alsietima	Rome, Italy	32.8	15,700
Claudia	Rome, Italy	69.7	190,900
Anio Novus	Rome, Italy	86.9	190,080
Trajana	Rome, Italy	57.0	114,000
Alexandrina	Rome, Italy	22.0	21,000

Notes : Column (4) = maximum discharges as estimated in some references below; (1) Present study. References[51].

Table 5 - Tailwater flow conditions downstream of steep chutes

Steep Section	Q m^3/day	Tailwater flow patterns
(1)	(2)	(3)
Brévenne aqueduct		
Courzieu II/La Verrière	28,000	***Undular jump*** 15.4-m d/s of change in slope (d_{tw} = 0.418 m).
	10,000	Undular jump 8.5-m d/s of change in slope (d_{tw} = 0.197 m).
	7,000	Undular jump 6.4-m d/s of change in slope (d_{tw} = 0.154 m).
	5,000	Undular jump 4.6-m d/s of change in slope (d_{tw} = 0.123 m).
	3,500	Undular jump 3.4-m d/s of change in slope (d_{tw} = 0.097 m).
Chevinay/Plainet	28,000	***Undular jump*** 13-m d/s of change in slope (d_{tw} = 0.434 m).
	10,000	Undular jump 7.2-m d/s of change in slope (d_{tw} = 0.204 m).
	7,000	Undular jump 5.4-m d/s of change in slope (d_{tw} = 0.154 m).
	5,000	Undular jump 3.8-m d/s of change in slope (d_{tw} = 0.127 m).
	3,500	Undular jump 2.8-m d/s of change in slope (d_{tw} = 0.10 m).
Lentilly II/Les Molières-Montcher	28,000	Steady jump immediately d/s of change in slope (d_{tw} = 0.586 m).
	10,000	***Oscillating jump*** 1.5-m d/s of change in slope (d_{tw} = 0.268 m).
	7,000	Oscillating jump 1.2-m d/s of change in slope (d_{tw} = 0.208 m).
	5,000	Oscillating jump 1-m d/s of change in slope (d_{tw} = 0.165 m).
	3,500	Oscillating jump 0.7-m d/s of change in slope (d_{tw} = 0.130 m).
Gorze aqueduct	15,000	***Undular flo***w in bridge-canal (Fr = 0.88). (Identical flow pattern for operation with one and two canals.)
Carthage aqueduct		
Oudna, start of Oued Miliane plain arcades	17,300	***Undular flow*** d/s of change in slope : Fr = 0.7 (d_{tw} ~ 0.228 m).
Corinth aqueduct		
Alepotrypes	80,000	Plunging jet flow.
Anio Vetus aqueduct		
Tivoli, Villa Hadrian	190,080	Steady jump at sudden enlargement (d_{tw} ~ 1.7 m).

Bridge at Mola di San Gregoria	190,080	Plunging jet flow (d_{tw} ~ 1.8 m). Risk of ***undular flow*** in d/s conduit.
Claudia aqueduct		
below D. Cosimato cliff	190,900	Steady jump at change in slope (d_{tw} ~ 2.2 m).
Marcia aqueduct		
Casale Acqua Raminga, Gericomio	188,000	Weak jump 9.1-m d/s of steep chute (d_{tw} = 1.32 m).
Anio Novus		
near Torrente Fiumicino	190,080	Critical flow in downstream conduit (Fr = 1.03, d_{tw} = 0.668 m).
Ponte dell'Inferno to Ponte Scalino	190,080	Sub-critical backwater effect in steep chute associated with ***undular flow***.
Ponte Scalino to Ponte Amato	190,080	Plunging jet flow (d_{tw} ~ 1.4 m). Risk of ***undular flow*** in d/s canal.
Fienile	190,080	Plunging jet flow (d_{tw} ~ 1.0 m). Risk of ***undular flow*** in d/s canal.

Note : d_{tw} = tailwater normal depth; results based on backwater calculations (CH98); ***bold italic*** : unfavourable flow conditions.

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Table 6 - Summary of aqueduct dropshaft operation

Aqueduct (1)	Flow regime (2)	Flow conditions (3)	Remarks (4)
Cherchell			
Chabet Ilelouine	regime R1	$Q \le 6{,}600$ m^3/day	Supercritical inflow.
	regime R2	$Q > 6{,}600$ m^3/day	
Yzeron			Subcritical inflows.
Vaugneray	regime R1	$Q \le 22{,}000$ m^3/day	
	regime R2	$22{,}000 < Q \le 52{,}000$ m^3/day	
	regime R3	$Q > 52{,}000$ m^3/day	Assuming D = 1.26 m.
Puit Gouttenoire	regime R1	$Q \le 7{,}500$ m^3/day	
	regime R2	$7{,}500 < Q \le 19{,}500$ m^3/day	
	regime R3	$Q > 19{,}500$ m^3/day	Assuming D = 1.26 m.
Puit-en-bas	regime R1	$Q \le 7{,}500$ m^3/day	
	regime R2	$7{,}500 < Q \le 20{,}000$ m^3/day	
	regime R3	$Q > 20{,}000$ m^3/day	
Montjeu			Subcritical inflows.
Brisecou Forest	regime R1	$Q \le 40{,}400$ m^3/day	
	regime R2	$40{,}400 < Q \le 74{,}700$ m^3/day	
	regime R3	$Q > 74{,}700$ m^3/day	

Table 7 - Summary of longitudinal slopes of steep Roman chutes, cascades and dropshaft cascades

Steep section type (1)	Bottom slope tanθ (in %) (2)	Location (3)
AQUEDUCTS		
Steep chute	1.1 %	Anio Novus (Ponte dell'Inferno to Ponte Scalino tunnel)
Steep chute	1.3	Anio Novus (Ponte dell'Inferno to Ponte Scalino tunnel)
Steep chute	1.6	Anio Novus (Ponte Scalino to Ponte Amato tunnel)
Steep chute	3.0	Corinth (Alepotrypos, upstream of stilling basin)
Dropshaft	4.1	Beaulieu (Puit d'Olivari)
Dropshaft (circ.)	4.8	Beaulieu (Puit du Château)
Dropshaft (circ.)	5.1	Cuicul (Series of 4 dropshafts along therms, distribution line)
Dropshafts	5.2	Montjeu, Autun (series of 24 dropshafts)
Dropshafts (rect.)	5.8	Yzeron (Vaugneray, Puit du Bourg)
Steep chute	6.1	Anio Novus (Torrente Fiumicino)
Dropshafts (sq.)	7.8	Yzeron (Recret/Grézieu-la-Varenne cascade)
Steep chute	8.3	Brévenne (Lentilly II/Les Molières-Montcher)
Steep chute	10.7	Marcia (Gericomio)
Steep chute	15.7	Marcia (Gericomio)
Steep chute	16.4	Anio Vetus (Bridge at Mola di San Gregoria)
Drops or chutes ?	19.0	Brévenne (Lentilly II - Le Guéret-La Rivoire)
Dropshafts (rect.)	19.6	Montjeu, Autun (9 dropshafts)
Drops or chutes ?	20.0	Brévenne (St-Pierre-La-Palud I)
Steep chute	20.6	Anio Vetus (Tivoli, Villa Hadrian)
Steep chute	22	Brévenne (Courzieu II/La Verrière)
Steep chute	45	Brévenne (Chevinay/Plainet)
Steep chute	50	Claudia (below D. Cosimato cliff, upstream of bridge below Vicavaro)
Stepped chute	61	Andriake, Lycia
Steep chutes	78	Cherchell Chabet Ilelouine
Dropshafts + chutes	38.4	Cherchell, Chabet Illelouine (combination of dropshafts and chutes)
SPILLWAYS		
Stepped chute	122 to 164 %	Oued Guergour dam
Stepped chute	167	Oued Bou Mazouz dam
Stepped chute	229	Kasserine dam

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FIGURE CAPTIONS

Figure 1 - Sketch of steep chute, dropshaft and stepped cascade observed in Roman aqueducts

Fig. 2 - Photographs of chute flows in operation

(A) Smooth chute flow, $Q = 0.075$ m^3/s (6,480 m^3/day), $\tan\theta = 7\%$, $b = 0.5$ m, $d \sim 0.035$ m, $V \sim 4.3$ m/s

View from downstream (flow from top to bottom)

(B) Stepped chute flow, $Q = 0.033$ m^3/s (2,850 m^3/day), $\tan\theta = 20\%$, $h = 0.1$ m, $b = 0.4$ m

View from downstream (flow from top to bottom)

Fig. 3 - Sketch of undular, oscillating and strong hydraulic jumps

Fig. 4 - Sketch of different tailwater flow conditions and associated backwater effects

Fig. 5 - Stilling basins in Roman aqueducts

(A) Basin of Sotizon and a typical cross-section of Brévenne aqueduct (after LYON-BR)

(B) Oudna, at the start of Oued Miliane plain arcades (Carthage aqueduct) (after Rakob 1974)

(C) Jouy-aux-Arches downstream of the Moselle bridge-canal, Gorze aqueduct (after Lefebvre 1996)

Fig. 6 - Sketch of stilling basin operation in Roman aqueduct

Fig. 7 - Dropshaft cascade in Roman aqueduct

Fig. 8 - Dimensioned drawings of dropshafts

(A) Recret Puit en bas, Yzeron aqueduct

(B) Brisecou forest, Monteu aqueduct

(C) Puit du Bourg, Vaugneray, Yzeron aqueduct (Vaugneray branch)

(D) Köln aqueduct

Fig. 9 - Photographs of the Recret dropshaft model in operation

(A) Regime R1, $Q = 0.00104$ m^3/s, $h/L = 1.68$, $D/L = 0.83$, $d_c/L = 0.0582$

Side view. Flow from the left to the right - High speed photograph (~ 50 μs)

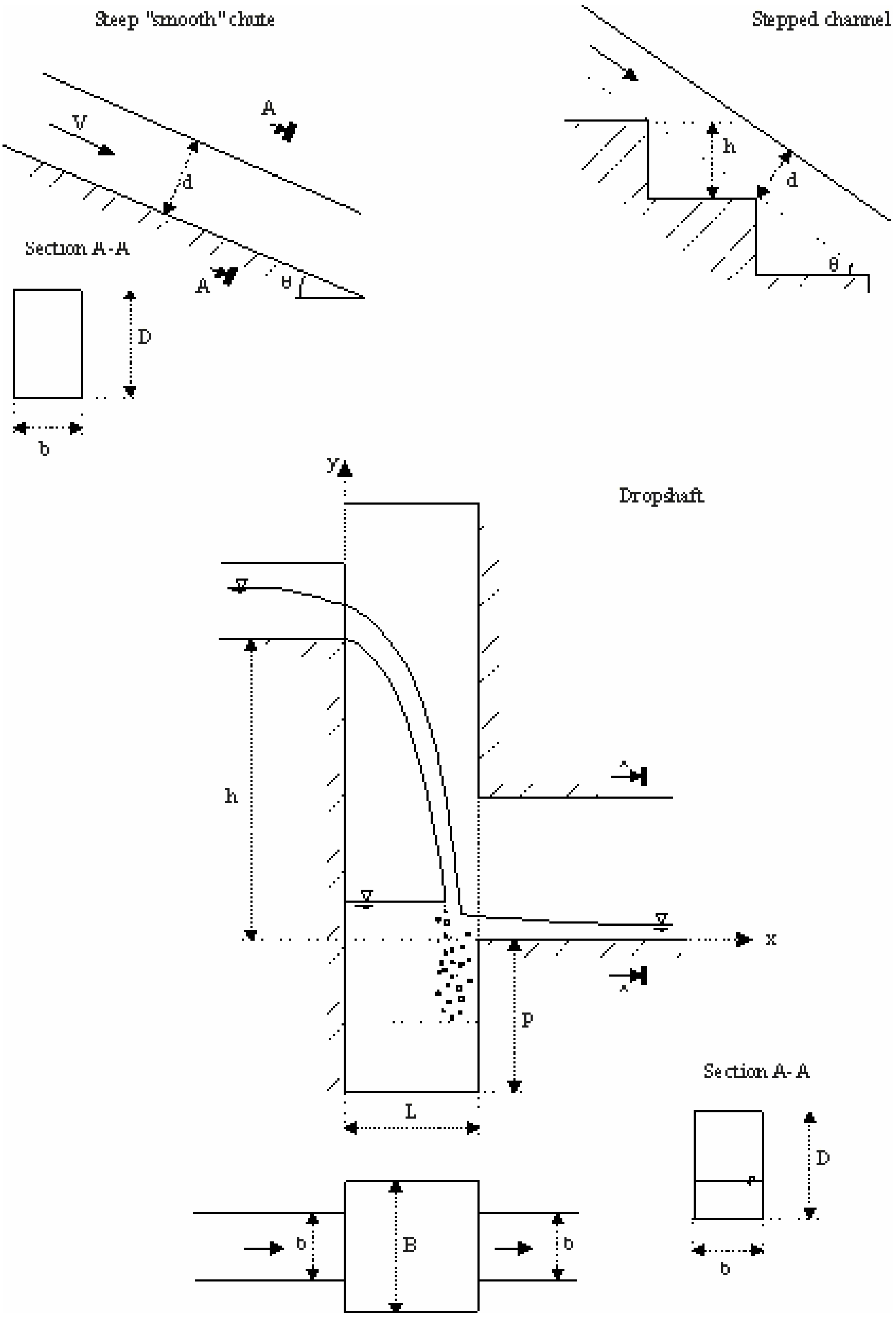
(B) Dropshaft model in operation (Regime R2)

Q = 0.00975 m^3/s, h/L = 1.68, D/L = 0.83, d_c/L = 0.259

Side view, flow from the left to the right - High-speed photograph (~ 50 μs)

Fig. 10 - Risks of scour and damage at a dropshaft operation with a flow regime R2

Figure 1 - Sketch of steep chute...



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View from downstream (flow from top to bottom)

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(B) Stepped chute flow, Q = 0.033 m^3/s (2,850 m^3/day), tanθ = 20%, h = 0.1 m, b = 0.4 m

View from downstream (flow from top to bottom)

Fig. 3 - Sketch of undular, oscillating and strong hydraulic jumps

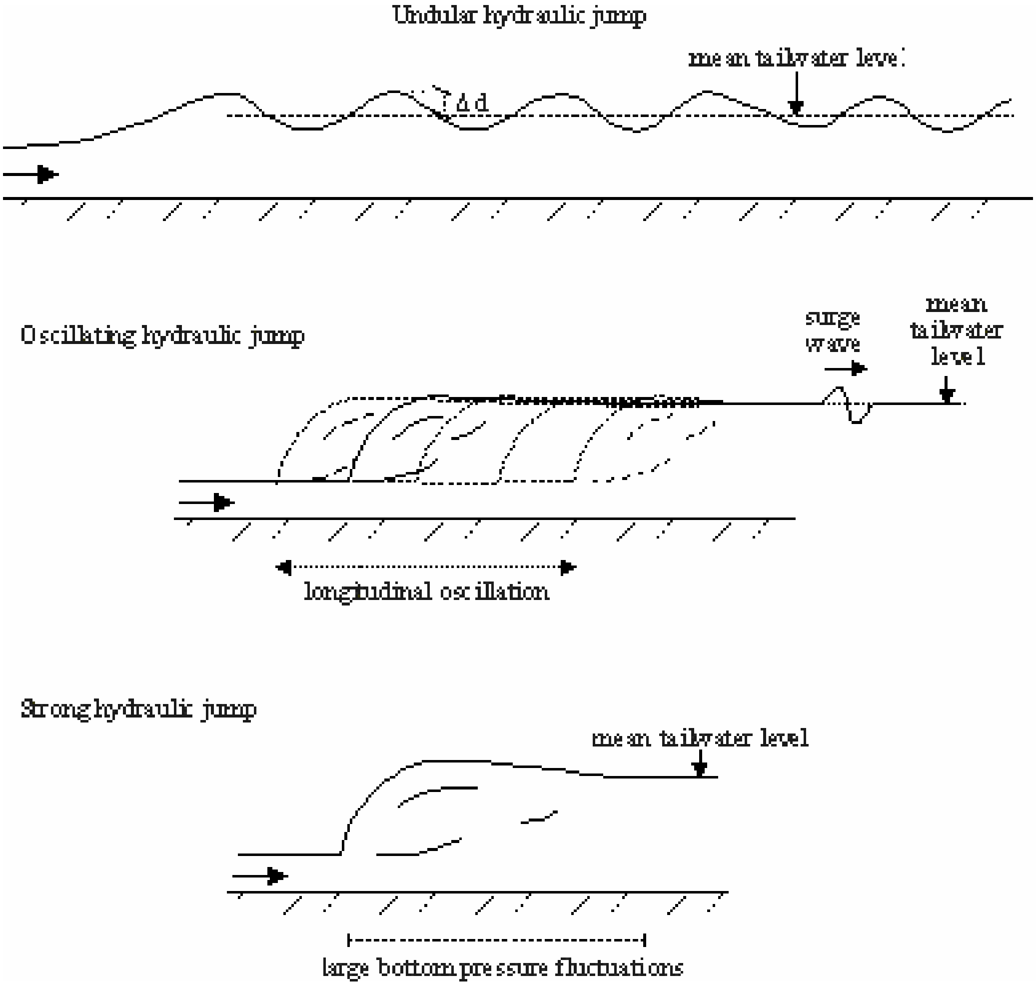


Fig. 4 - Sketch of different tailwater flow conditions and associated backwater effects

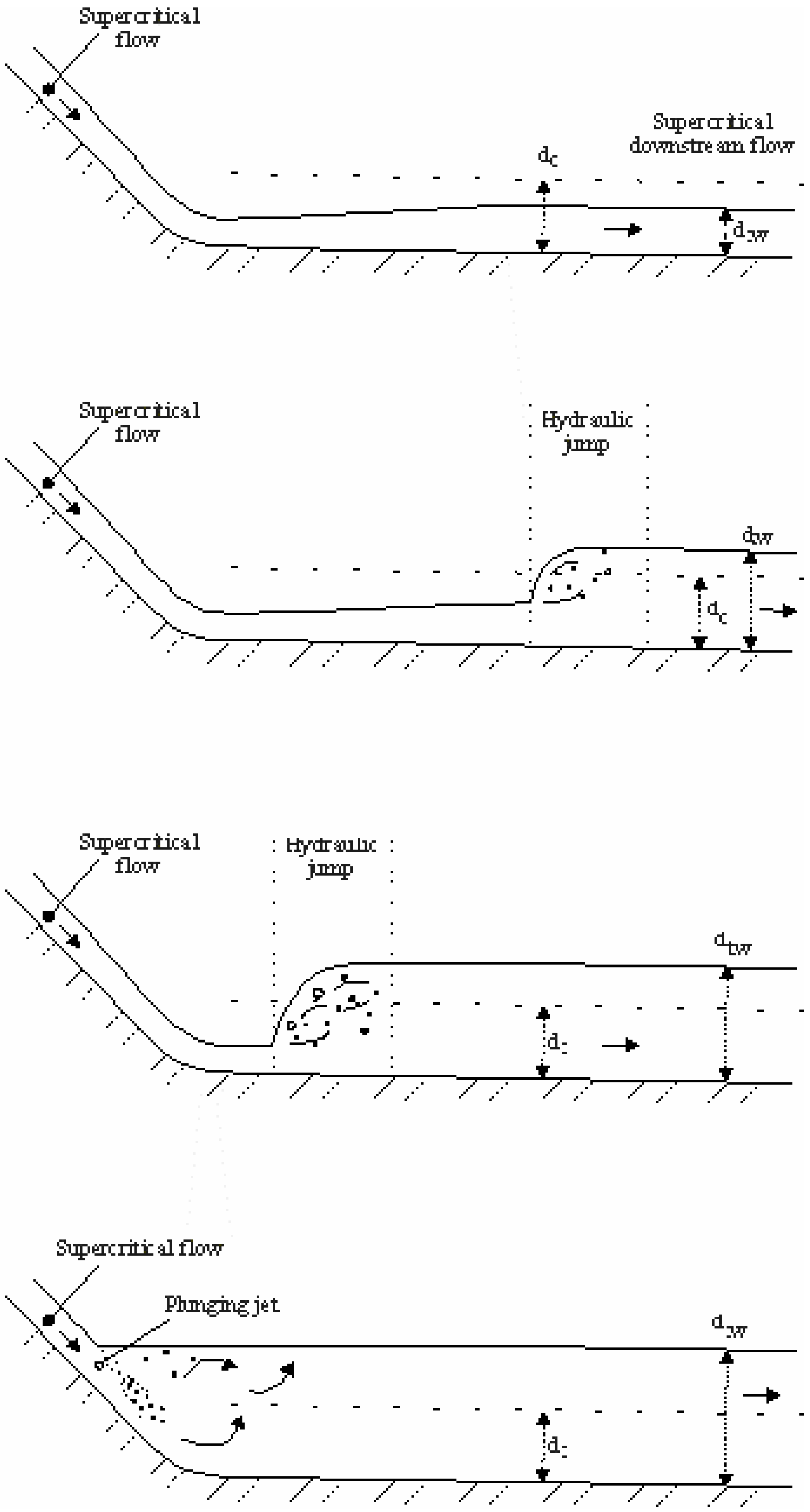


Fig. 5 - Stilling basins in Roman aqueducts

(A) Basin of Sotizon and a typical cross-section of Brévenne aqueduct...

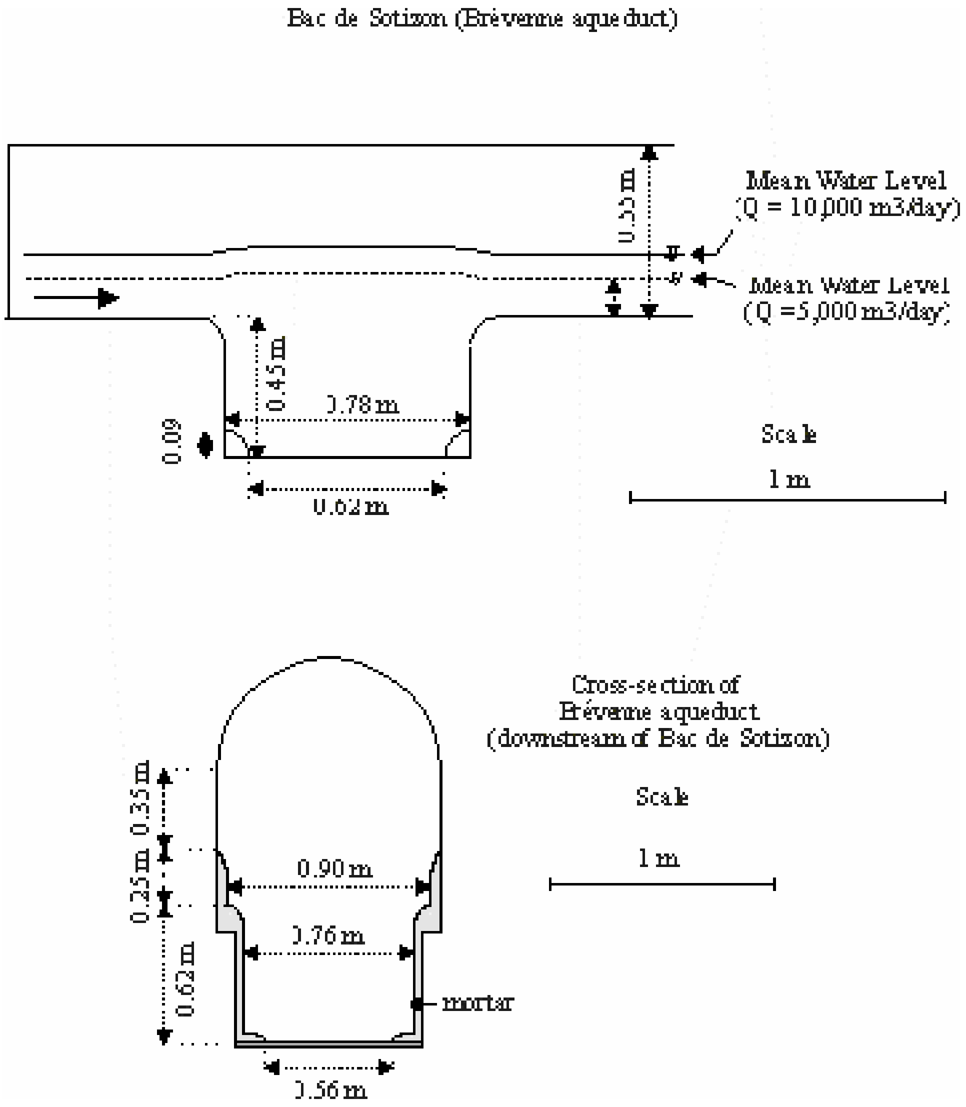
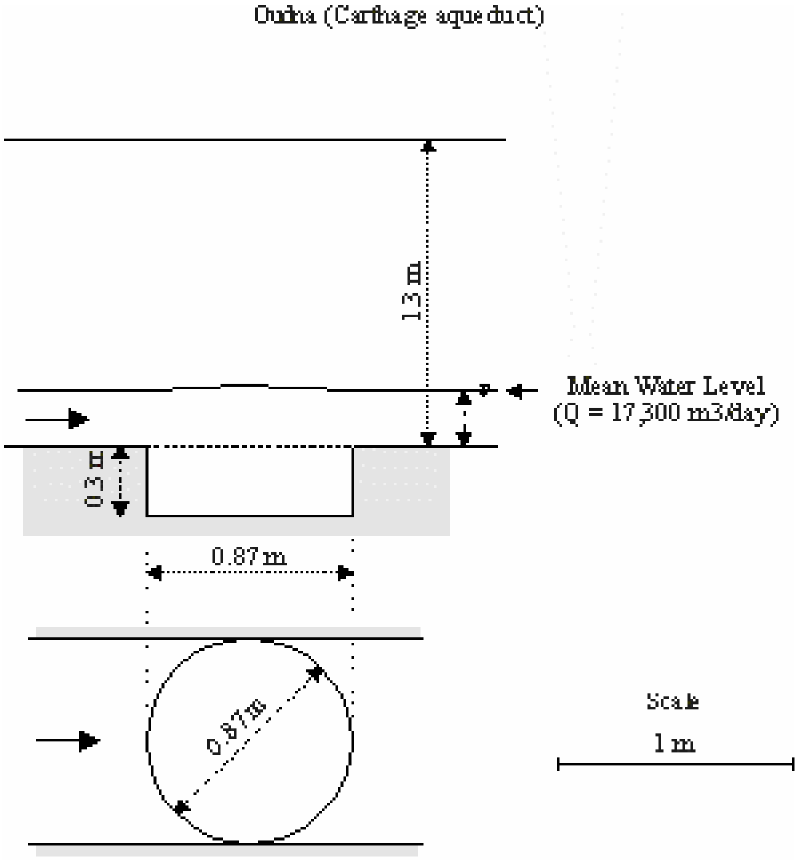


Fig. 5 - Stilling basins in Roman aqueducts

(B) Oudna, at the start of Oued Miliane plain arcades (Carthage aqueduct) ...



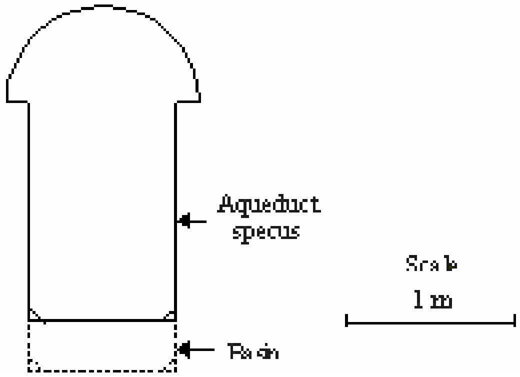


Fig. 5 - Stilling basins in Roman aqueducts

(C) Jouy-aux-Arches downstream of the Moselle bridge-canal, Gorze aqueduct ...

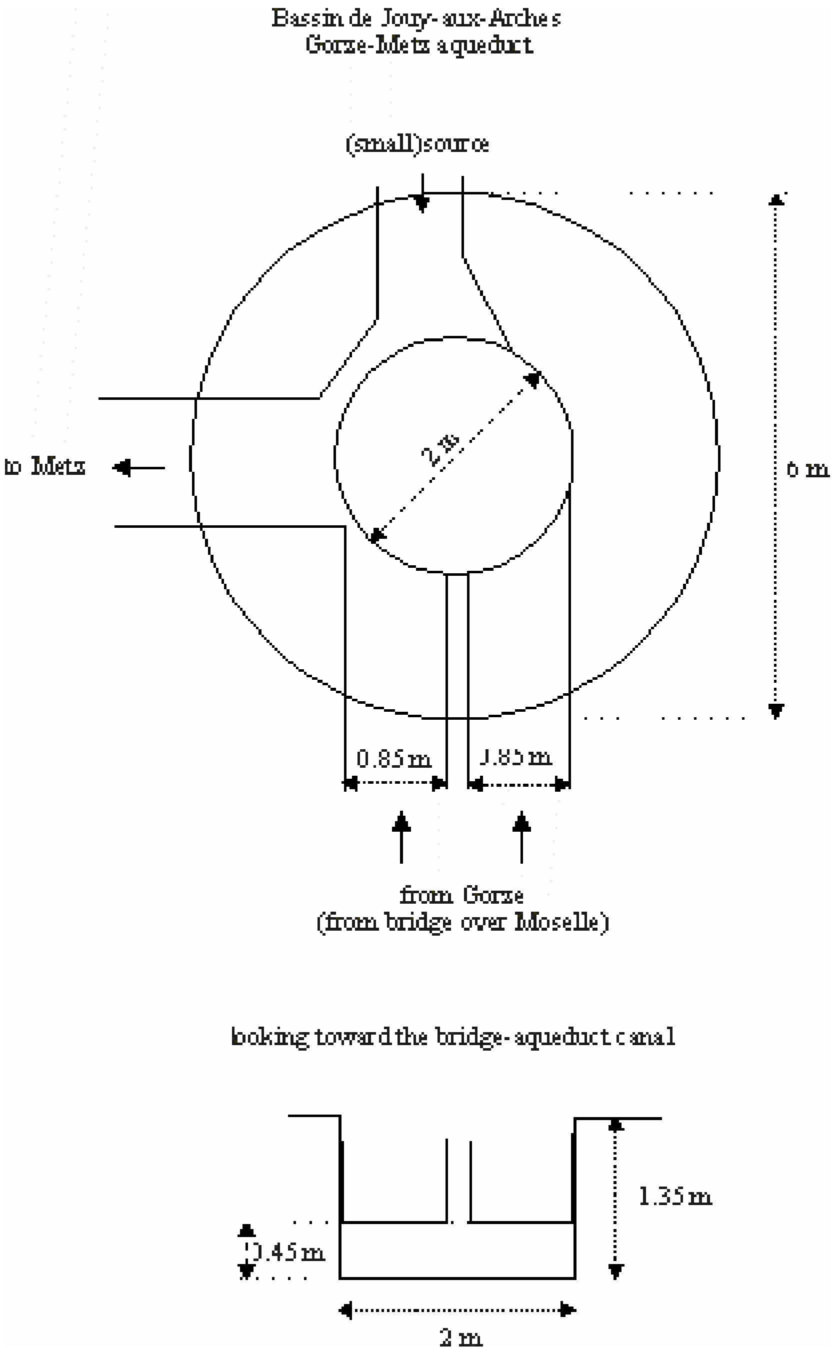


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Fig. 6 - Sketch of stilling basin operation in Roman aqueduct

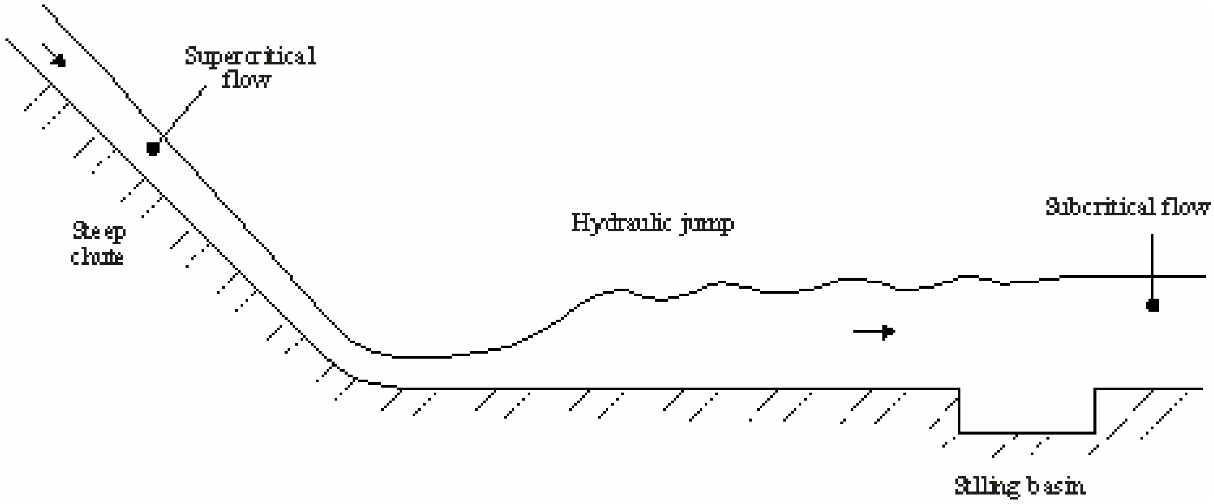

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Fig. 7 - Dropshaft cascade in Roman aqueduct

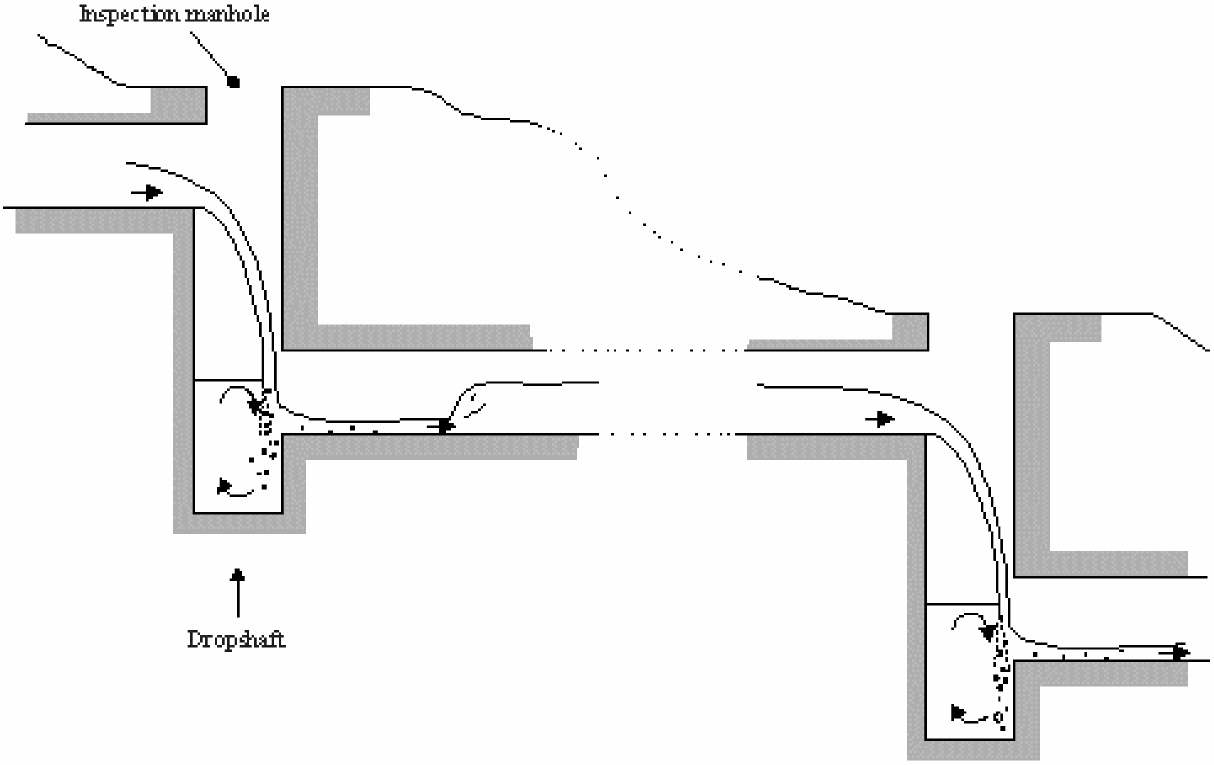

Fig. 8 - Dimensioned drawings of dropshafts

(A) Recret Puit en bas, Yzeron aqueduct

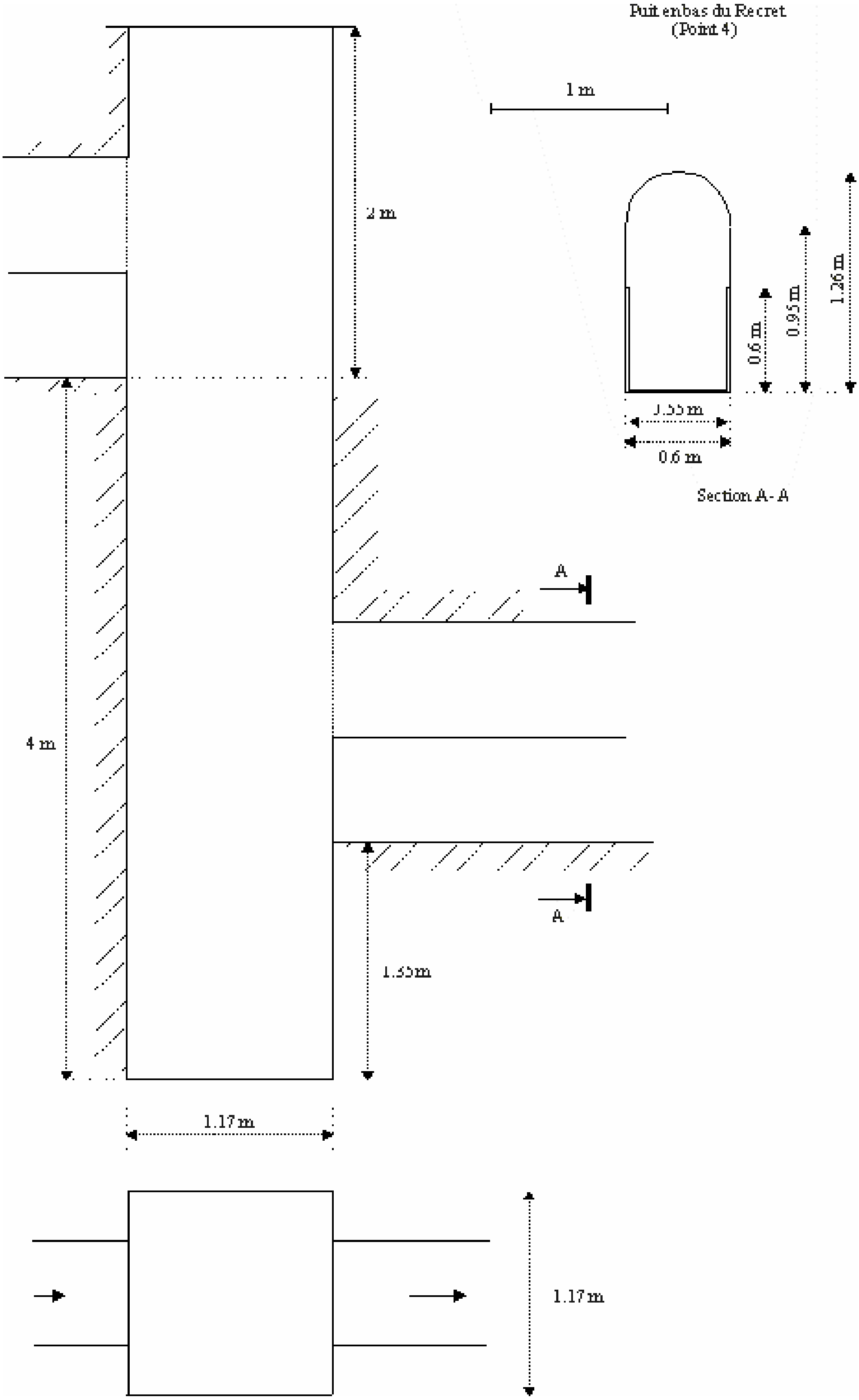

Fig. 8 - Dimensioned drawings of dropshafts

(B) Brisecou forest, Monteu aqueduct

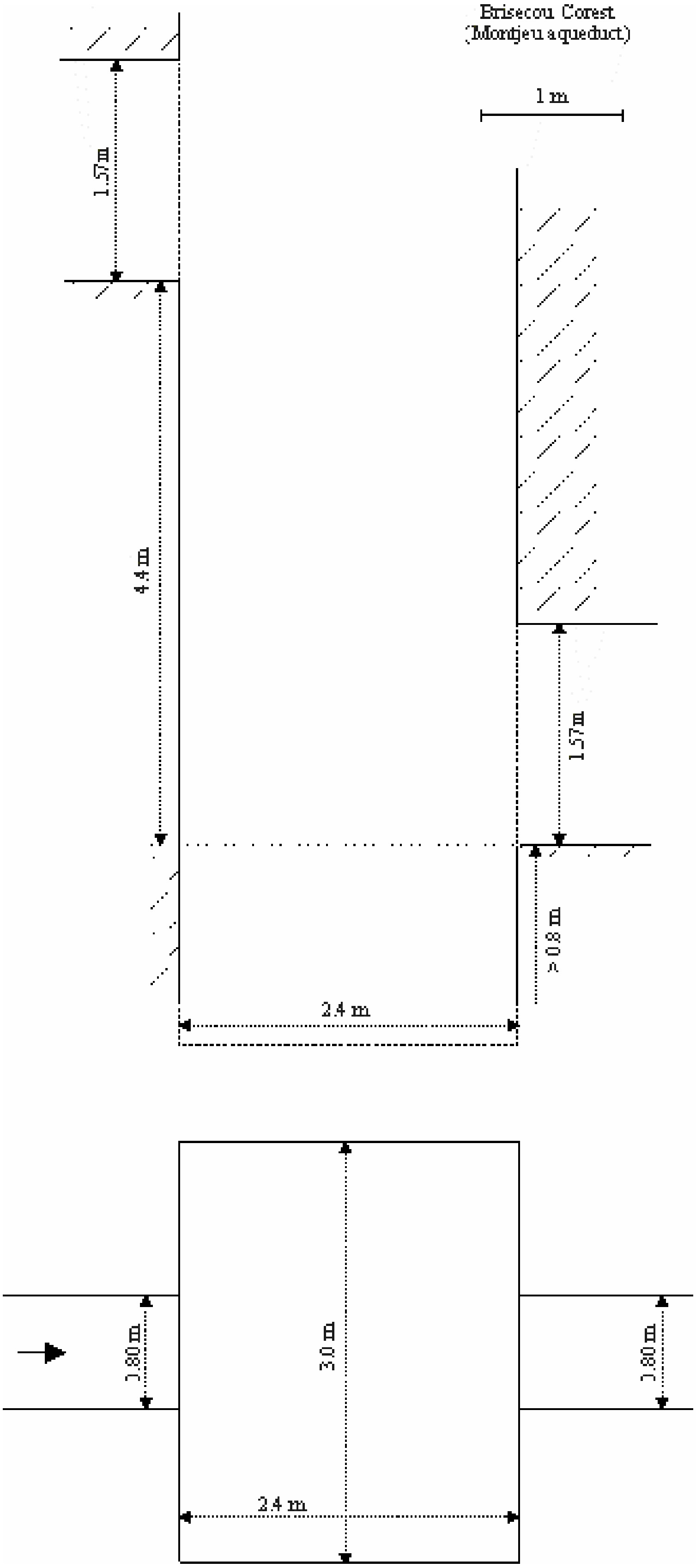

Fig. 8 - Dimensioned drawings of dropshafts

(C) Puit du Bourg, Vaugneray, Yzeron aqueduct (Vaugneray branch)

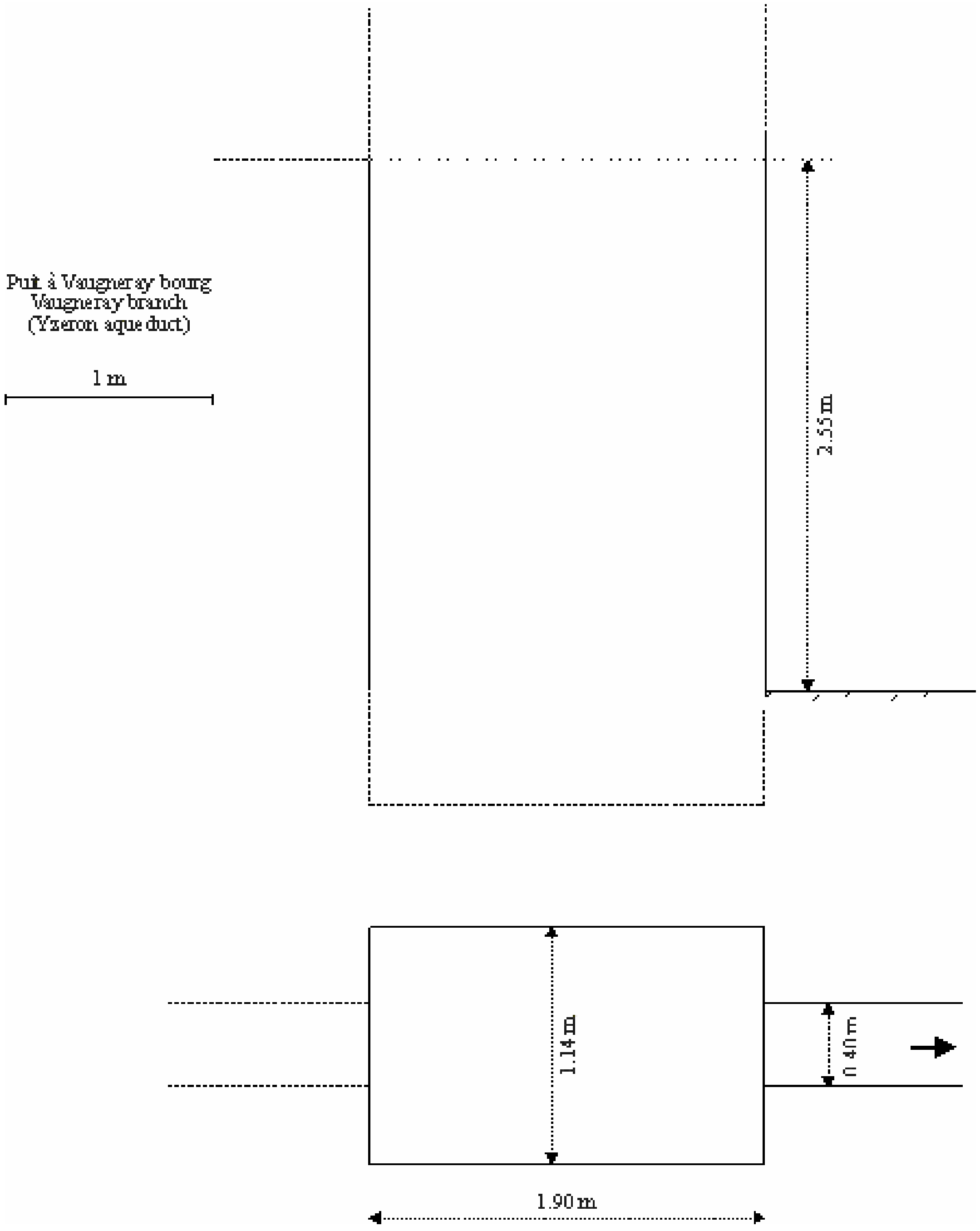

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Fig. 8 - Dimensioned drawings of dropshafts

(D) Köln aqueduct

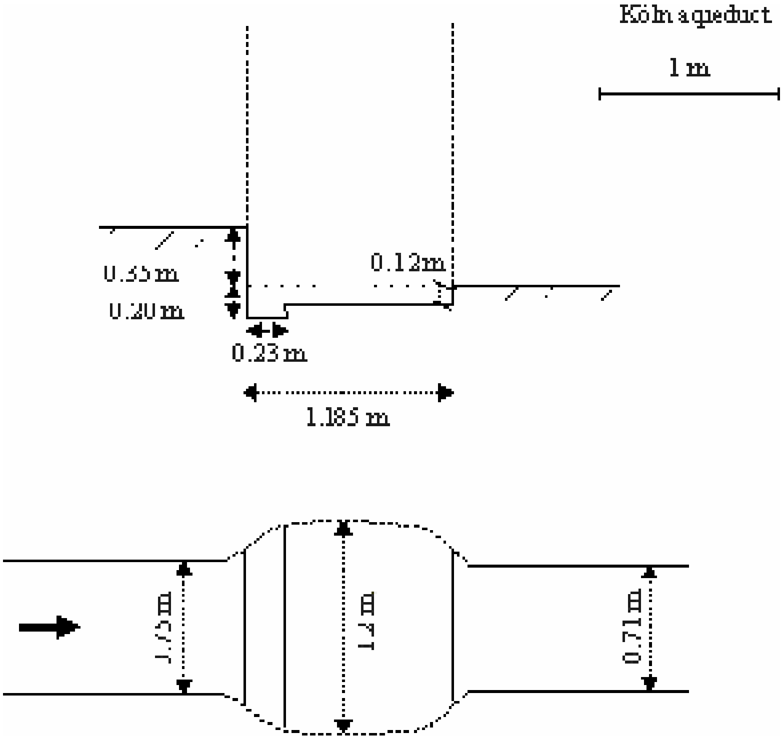

Fig. 9 - Photographs of the Recret dropshaft model in operation

(A) Regime R1, $Q = 0.00104$ m^3/s, $h/L = 1.68$, $D/L = 0.83$, $d_c/L = 0.0582$

Side view. Flow from the left to the right - High speed photograph (~ 50 μs)

CHANSON, H. (2000). "Hydraulics of Roman Aqueducts : Steep Chutes, Cascades and Dropshafts." *American Jl of Archaeology*, Vol. 104, No. 1, Jan., pp. 47-72 (ISSN 0002-9114).

(B) Dropshaft model in operation (Regime R2)

Q = 0.00975 m^3/s, $h/L = 1.68$, $D/L = 0.83$, $d_c/L = 0.259$

Side view, flow from the left to the right - High-speed photograph (~ 50 μs)

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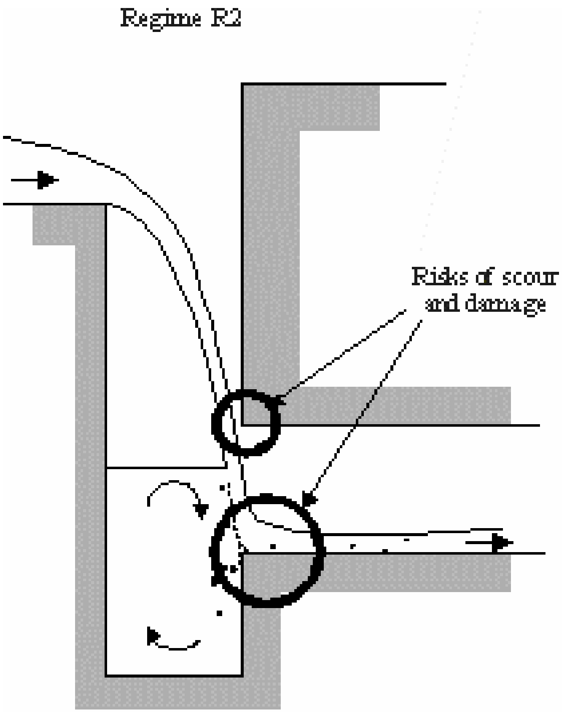
Fig. 10 - Risks of scour and damage at a dropshaft operation with a flow regime R2



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Notes

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[1] Clamagirand et al. (1990) 423-31.

[2] That is, a tranquil flow regime such as the flow Froude number is less than unity (e.g. Chanson 1999).

[3] The Carthage aqueduct has a moderate slope (0.7%) upstream of the Oudna arcades, but the channel is technically termed “steep” because the flow was considered torrential.

[4] The overflow stepped weir in Akarnania, Greece, built around B.C. 1,300, is an earthfill embankment, 10.5-m high with a 25-m long crest (KNAUSS 1995, CHANSON 1997). The downstream slope is stepped (14 steps) with masonry rubbles set in mortar. The weir was used for several centuries. It is still standing and flash floods spill over the stepped chute. See also Chanson 1997; Knauss 1995.

[5] Roman dams equipped with chute spillway included Cornalvo (Spain, 2nd century AD), Al Khums (Libya, 3rd century AD). Examples of drop spillway included Harbaka (Syria, 3rd century AD). Examples of stepped spillway include the Kasserine dam (Tunisia) Oued Guergour dam (Tunisia, 1st century AD), Qasr Khubbaz (Syria, 2nd century AD), and Tareglat dam (Libya, 3rd century AD) (Chanson [1995a] 23-37).

[6] The Froude number is defined as the ratio of the velocity to the square root of the gravity acceleration times the flow depth : i.e., $Fr = V/\sqrt{g*d}$ for a rectangular channel.

[7] This comment is based upon my experience (associated with site inspections of several aqueducts) in several hydraulic studies related to concrete deterioration. I have discussed the issue of concrete resistance with world-known concrete experts and historians, who suggested similar results in Roman concrete and 19th century concrete.

[8] "This type [of jump] has a pulsating action ... [It] is one of the most difficult [types of jump] to handle" (Bradley and Peterka [1957a] 1401-22). Bradley and Peterka’s work also 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" (Bradley and Peterka [1957b] 1404-1402).

[9] e.g., $X/d \geq 2,000$ where X is the longitudinal extent of the undular flow and d is the flow depth.

[10] Chanson and Montes 1995.

[11] Chanson 1995b.

[12] For more complete reviews, see Chanson [1995b] 1-1 to 1-4; for undular flows, see Montes and Chanson 1998; for oscillating jumps, see Bradley and Peterka 1957a and 1957b.

[13] Assuming a long prismatic downstream conduit, the downstream flow depth or tailwater depth is the uniform equilibrium flow depth in the downstream conduit.

[14] Standard step method, distance calculated from depth (e.g. Henderson 1966; Chanson 1999. See Chanson 1998 for further details on the calculations.

[15] For example, Hodge [1992] 103-105, and Chanson [1999] c-1. Examples of inspection shafts and manholes include Cap Blanc at Hippo Zarite (0.3-m square shaft, P = 0.4 m) (Gauckler [1902] 129), Grand'Croix at Gier (0.9-m×0.87-m rectangular shaft, P = 0.32 m) (Conseil Général du Rhône [1996] 209), and Oudna at Carthage (Rakob [1974] 49-50). Gauckler (1897) 176 illustrated an aqueduct at Ksar Soudane (Tunisia) with circular manholes, possibly acting as basins. At Hippo Zarite (near Bizerte), the Aïn Nadour branch (B = 0.2 m wide, P =

0.3 m) had several circular basins (∅ = 1 m, P ~ 2.5 m ?) (Gauckler [1902] 126). Gauckler's father, Philippe Gaspard Gauckler (1826-1905), was a French hydraulic engineer and member of the French 'Corps des Ponts-et-Chaussées'. He re-analysed the experimental data of Darcy and Bazin (1865), and in 1867 he presented a flow resistance formula for open channel flows (Gauckler-Manning formula) sometimes called improperly the Manning equation (Gauckler 1867).

[16] For example, Rakob 1974, Rakob 1979, Hodge 1992, and Burdy 1996.

[17] The concept of a stilling basin was known prior to the Roman era. In Priene, Greece, a large stilling basin was built at the downstream end of the sewer system during the 5-th century B.C. (Ortloff and Crouch 1998). The basin was about 3.23-m long, 0.8-m wide and 0.8-m deep and the maximum discharge was probably about 0.425 m^3/s before spillage.

[18] Sotizon is also called “Bac de Sotizon” or “Bac de nettoyage de Sotizon à En Triaume” (Conseil Général du Rhône 1993). For the Mosell bridge-canal see e.g. Lefebvre 1996. The role of the basin was recognized early as a stilling device to calm the flow: “un espece de puits, afin que les eaux y puissent tournoyer et prendre ensuite plus facilement leur direction” (Francois and Tabouillot [1769] 146). The five circular basins at Oudna were separated by 25 to 50-m at the start of the aqueduct arcades across Oued Miliane plain (Rakob [1974] pl. 36 and 37; fig. 11). Although further basins were found near Carthage and within Carthage, it must be noted that none existed upstream of the Oued Miliane plain arcades.

[19] For example, the Gier aqueduct intake at Saint-Chamond (Conseil Général du Rhône 1996).

[20] A complete set of calculations were developed in Chanson (1998) appendix E.

[21] For example Fair et al. 1971.

[22] Rakob (1979) 40 commented on the frequent cleaning task of the Carthage aqueduct basins. Lefebvre (1985) similarly mentioned the rate of sediment filling at Gorze.

[23] At the start of Oued Miliane plain arcades.

[24] See, e.g., U.S. Department of Interior (1965) and Novak et al. (1996).

[25] A similar cross-wave pattern is experienced in undular hydraulic jumps and near-critical flows (Chanson and Montes 1995; Chanson 1995b).

[26] Leveau and Paillet 1976.

[27] For example, Hager 1992; Novak et al. 1996.

[28] It may also be suggested by construction details in the Beaulieu, Dougga, Gunudu and Rusicade aqueducts.

[29] In Rome, vertical dropshafts were used also to interconnect aqueducts, particularly from newer higher channels to older canals. At Grotte Sconce (also spelled 'Grotte Sconcie'), a branch of the Anio Novus aqueduct lead to a circular dropshaft and into the Claudia aqueduct, and a second rectangular dropshaft lead to the Marcia aqueduct (Ashby [1935] 277-79 and fig. 31; Van Deman [1934] 212-13 and 302-303). At San Cosimato Gorge, a side channel connected the Claudia to the Marcia aqueducts through a 9.2-m deep rectangular dropshaft (Ashby [1935] 101-102 and fig. 7; Van Deman [1934] 76-77. Other examples of 'interconnection shafts' included a square dropshaft from Claudia to Vetus at Voltata delle Corrozze (Van Deman [1934] 213) and a rectangular shaft from Anio Novus to Claudia near the Fosso Arcese bridge (Ashby [1935] 275).

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[30] Conseil Général du Rhône (1991) 80; Gauckler (1902) 129. Although there is some uncertainty whether the shafts at Hippo Zarite were dropshafts or inspection holes, Gauckler (1902) mentioned specifically that the shafts were designed with an invert drop of 0.4-m to trap impurities.

[31] For example, Apelt 1984; Rajaratnam et al., 1997.

[32] For example, Ervine and Ahmed 1982; Chanson 1998.

[33] Chanson 1998.

[34] For example, U.S. Department of the Interior 1965; Chanson (1995a) 198-201; Novak et al. 1996.

[35] The calculations are based on the nappe trajectory equation and shaft geometry (Chanson 1998). The results were validated successfully with the physical experiments.

[36] The Cherchell dropshafts were preceded by steep chutes and the inflow conditions of the shaft were torrential (supercritical). Although Equation (1) is not applicable, Chanson (1998) 4-16 developed a complete analytical solution of the problem which gave an maximum flow rate of 6,600 m^3/day (for optimum performances).

[37] Leveau and Paillet 1976.

[38] For the Yzeron discharge, ses Conseil Général du Rhône 1992. Estimate of the Vaugneray branch flow rate is based on the catchment in absence of further information.

[39] In mathematical terms, for aqueducts equipped with dropshafts operating with subcritical inflow, the flow rate must satisfy :

$$Q < 0.1292 * \sqrt{g} * b * \frac{L^3}{h^{3/2}} \qquad \text{Regime R1} \quad (1)$$

where b is the dropshaft inflow width, L is the shaft length and h is the invert drop (fig. 1).

[40] For the techniques of construction and the problems associated with connecting different sections, see Fevrier 1979 and Leveau 1979.

[41] At Cuicul (Djemila, Algeria), the location of the dropshaft cascade is most unusual : it was on a distribution branch in an urban environment rather than on the main line. The construction of the cascade was a major civil engineering work. Its underground location within the city might suggest that it was built prior to the surrounding buildings (e.g. therms) and that careful urban planning was made at Cuicul. Alternately the city expansion might have taken place in stages and the cascade was out of town in an early stage.

[42] The present study suggests that the current 'misunderstanding' of aqueduct hydraulics derives from the 'ignorance' of most historians and archaeologists. The hydraulics calculations are feasible easily by undergraduate engineering students, provided that accurate information on the channel dimensions and flow rate are available (Chanson 1999; Henderson 1966).

[43] For near-critical flows, see Chanson 1995b.In rectangular flat channels, The Froude number is unity at critical flow conditions : i.e., Fr = 1 for $d = d_c$ (critical flow depth).

[44] This classification is valid only for hydraulic jumps in rectangular horizontal channels (e.g., Henderson 1966; Chanson 1999).

[45] The hydraulic diameter is defined as four times the cross-section area (of the flow) divided by the wetter perimeter : $D_H = 4 * A/P_w$.

[46] Moody 1944.

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[47] Chanson (1995a) 87-88.

[48] References : [AS] ASHBY; [Bl] BLACKMAN (1978); [Co2] LYON-BR; [CQ] COQUET (1966); [Le] LEFEBVRE (supra No. F.17); [LP] LEVEAU and PAILLET (supra No. 28); [Lo] LOLOS (1997); [Ra] RAKOB (supra No. 2); [VD] VAN DEMAN.

[49] References : [Co2] LYON-BR (1993); [CQ] COQUET (supra No. 47); [LP] LEVEAU and PAILLET (Supra No. 28); [Mu] MURPHY (1998); [VD] VAN DEMAN.

[50] References : [Al] ALLAIS (1933); [Ca] CARTON (1899); [Co1] LYON-YZ; [CQ] COQUET (supra No. 47); [Gr] GREWE (1986); [LP] LEVEAU and PAILLET (Supra No. 28); [PR] PINETTE and REBOURG (1986); [Ve] VERTET (1977).

[51] References : CARTON (supra No. 50), ASHBY, VAN DEMAN, LEFEBVRE (1996, supra No. 19); LEVEAU and PAILLET (supra No. 28), BLACKMAN (1979), FABRE et al. (1992), HODGE, LOLOS (supra No. 47), Conseil Général du Rhône (1987), Conseil Général du Rhône (1996, supra No. 20), LYON-YZ, LON-BR.