Hydraulics of Large Culvert beneath Roman Aqueduct of Nîmes

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Abstract: The Romans built ancient culverts beneath roads and aqueducts. The hydraulic operation of a large culvert, built around the 1st century A.D. beneath the Nîmes aqueduct, is described. The investigation shows the advanced design of an ancient multicell structure with a large discharge capacity equivalent to about 12 times the aqueduct maximum discharge capacity.

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Introduction

A culvert is a covered channel of relatively short length designed to pass water through an embankment, e.g., a road or a dam. Its purpose is to safely carry flood waters, drainage flow, and natural streams below the earthfill structure. Although the world's oldest culvert is not known, the Minoans and the Etruscans built ancient culverts in Crete and Northern Italy, respectively (Evans 1928; O'Connor 1993). Later the Romans built numerous culverts beneath their roads (Ballance 1951; O'Connor 1993). The construction of a culvert was favored for small water crossings whereas a bridge was preferred for longer crossings. Common culvert shapes were the arched design and the rectangular (or box) culvert (O'Connor 1993). The Romans also built culverts beneath aqueducts. Table 1 give a summary of well-documented drainage culverts and small bridges that supported aqueducts. Fig. 1 illustrates one example.

In the present study, the hydraulic design of a large box culvert built beneath the Nîmes aqueduct is presented. It is shown that the structure was an unique example of a Roman aqueduct structure, that the design was reliable, and that Roman engineers had sound drainage engineering skills.

Nîmes Aqueduct

The Roman aqueduct supplying the city of Nîmes (*Colonia Augusta Nemausus*) is one of the best documented aqueducts. Classical studies include those of Esperandieu (1926), Hauck (1988), Smith (1992–1993) and more importantly the multidisciplinary work of Fabre et al. (1991, 1992, 2000). The fame of the aqueduct is connected with its crossing of the Gardon river, i.e., the Pont du Gard, which is the most famous three-tier Roman bridge, is still standing (O'Connor 1993). Despite some discussion, it is believed that the aqueduct was in use from the 1st century A.D. up to the 4th or 5th century A.D. (Fabre et al. 2000).

The Nîmes aqueduct was 49,800 m long, and started at the Source de l'Eure at Uzès which drains a 45–50 km^2 catchment area. The total inverted drop was only 14.65 m from the source to the *castellum dividorum* (repartition basin) at Nîmes, which gives the aqueduct one of the flattest gradients among Roman aqueducts (Grewe 1992; Hodge 1992; Fabre et al. 2000). The aqueduct channel was typically 1.2 m wide and the maximum flow rate was estimated to be about 0.405 m^3/s (35,000 m^3/day). Fabre et al. (1991) showed, however, an important variability of the spring output at Uzès. During a period of study from July 1967 to May 1968 and January 1976 to December 1978, the average streamflow was 0.343 m^3/s (29,600 m^3/day), while the minimum flow rate was 0.125 m^3/s (10,800 m^3/day) in September 1976 and the maximum discharge was 1.66 m^3/s (143,400 m^3/day) in October 1976.

By its dimensions and capacity, the Nîmes aqueduct was among the largest aqueducts built in Roman Gaul. The list includes the 86-km long Gier aqueduct (at Lyon), the Gorze aqueduct (at Metz) with its 1,300-m long bridge across the Moselle River, and the Mons aqueduct (at Fréjus) with a maximum discharge capacity of 0.61 m^3/s (52,500 m^3/day). However the Nîmes aqueduct was smaller than the largest aqueducts in Rome: e.g., the Aqua Marcia and the Aqua Novus (Hodge 1992; Fabre et al. 1992).

Multicell Culvert at Vallon No. 6

Along the Nîmes aqueduct, a large box culvert was recently excavated at Vallon No. 6, located 17 km downstream of the Pont du Gard between the Combe de la Sartanette and Combe Joseph in the Bois de Remoulins two valleys in the Remoulins Forest (Fabre et al. 1992, 2000) (Table 1). (Prior to excavations, the culvert cells were blocked; the structure was covered by dirt and storm water flowed over the aqueduct.) The culvert was designed to allow passage of storm water beneath the aqueduct in a small valley, locally called a *combe* (Figs. 1 and 2). (Note that the

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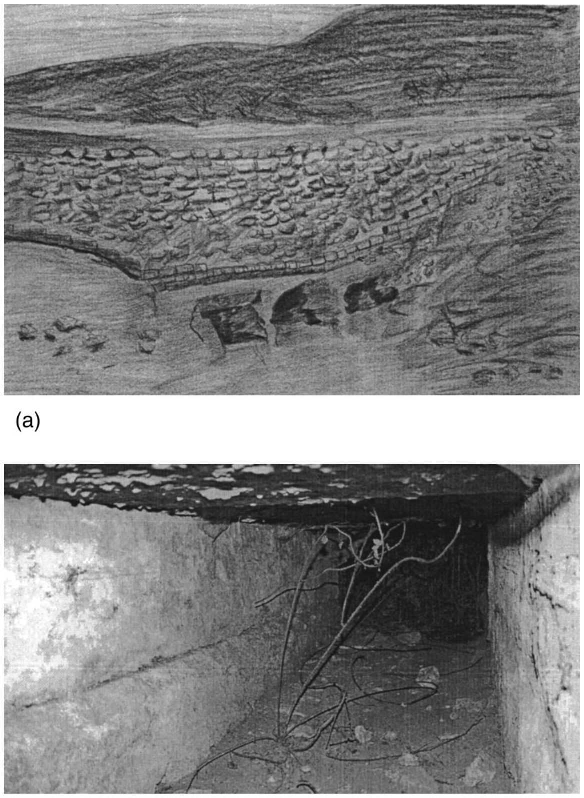
Table 1. Culvert and Small Bridges beneath Roman Aqueducts

Location	Type[a]	Barrel/throat characteristics	Remarks
Small bridges			
Small bridge near Vollem, Cologne aqueduct	Arched bridge	1 passage: 1.1 m wide, 1.1 maximum height Cross-sectional area: $\sim$1 m^2 Barrel construction: single rib segmental arch[a] supported by large stone block walls	Meternich-Vollem, upstream end of aqueduct. Grewe (1986, pp. 64–67)
Pont Amont at Roc-Plan, Nîmes aqueduct	Arched bridge	3 arches (3.4 m high, 2.8 m wide, 5.4 m long) with 4 buttresses Aqueduct invert elevation: 66.398 m NGF	37.8 km upstream of Nîmes. Fabre et al. (2000, pp. 75–76)
Pont de la Combe Pradier, Nîmes aqueduct	Arched bridge	Single arch (original design) Aqueduct invert elevation: 64.691 m NGF	30.3 km upstream of Nîmes. Fabre et al. (2000, p. 93)
Culverts			
Vallon No. 6 culvert, between Combe de la Sartanette and Combe Joseph, Nîmes aqueduct	Box culvert	3 rectangular cells: 0.5×0.65 m^2, 0.8×0.65 m^2, 0.6×0.65 m^2 Cross-sectional area: $>$1.24 m^2 Barrel construction: large limestone blocks; cut water design of dividing wall upstream end Aqueduct invert elevation: 64:858 m NGF	31.9 km upstream of Nîmes. Downstream of the Pont du Gard. Fabre et al. (1992), present study
Pont Aval at Roc-Plan, Nîmes aqueduct	Arched culvert	3 biased cells (1.7 m high, 1.15 m wide, 5.4 m long) Aqueduct invert elevation: 66.381 m NGF	37.7 km upstream of Nîmes. Fabre et al. (2000, pp. 75–76). The barrel cells were partly cleared in Oct. 1988 during a violent storm which caused major damage of Nîmes
Culvert of the Vallon de Coste Belle, Nîmes aqueduct	Box culvert	4 rectangular cells (5.5 m long) Total width of opening: 1.1 m Construction: stone slabs Aqueduct invert elevation: 66.180 m NGF	36.9 km upstream of Nîmes, between Pont Bornègre and Pont du Gard. Fabre et al. (1992, 2000, pp. 77–78). Possible siphoring of the aqueduct above the culvert
Culvert, Combe Pradier, Nîmes aqueduct[b]	Box culvert	Single rectangular cell Aqueduct invert elevation: 64.691 m NGF	Stage 2 after filling the arch for reinforcement 30.3 km upstream of Nîmes. Fabre et al. (2000, p. 93)
Culvert of Les Escaunes, between La Perotte tunnel and Les Cantarelles tunnel, Nîmes aqueduct	—	Aqueduct invert elevation: 64.1 m NGF	22 km upstream of Nîmes. Fabre et al. (2000, p. 97)
Culvert near Burg Dalbenden, Cologne aqueduct	Arched culvert	1 cell: 0.9 m wide, 0.7 m maximum height Cross-sectional area: $\sim$0.6 m^2 Barrel construction: single rib segmental arch[a]	Kall–Urft, upstream end of the aqueduct. Grewe (1986, pp. 42–46)
Series of culverts, Brévenne aqueduct, Lyon	—	Location: Chevinay across Le Plainet stream; at Sourcieux, etc.	Burdy (1993, p. 152), present study
Series of culverts, Gier aqueduct, Lyon	—	Location: primarily in the upstream section	Burdy (1993, pp. 225–229)

Note: — indicates no information.
[a]Terminology used by O'Connor (1993).
[b]After second refurbishment (stage 2).

catchment area was very small: 0.028 km^2.) While the aqueduct crossings of the Combe de la Sartanette and Combe Joseph were bridges (Table 2), the culvert was a multicell structure equipped with three rectangular cells with a total cross-sectional area in excess of 1.2 m^2 (Fig. 2). The cells were made of large limestone blocks placed on supporting pillars, or dividing walls, and were founded on worked bedrock [Fig. 1(b)]. The upstream end of each dividing wall was cut into a chamfer and formed cut waters (Fig. 2). Note that the Bornègre Bridge on the Nîmes aqueduct, located between Uzès and the Pont du Gard, was composed of three arches (Table 2) with two center piers equipped with upstream cut waters. The writer visited both the multicell culvert and the



(a)

(b)

Fig. 1. Vallon No. 6 culvert (Nîmes aqueduct) between Combe de Sartanette and Combe Joseph. (a) Sketch made from a photograph taken during the 1980s excavations: the aqueduct flows from left to right; the three cells are visible underneath the *specus*; note the rubble masonry construction of the aqueduct. (b) Inside view of the main culvert cell looking upstream (photograph taken in September 2000); note the soffit made of one large limestone block (ashlar masonry).

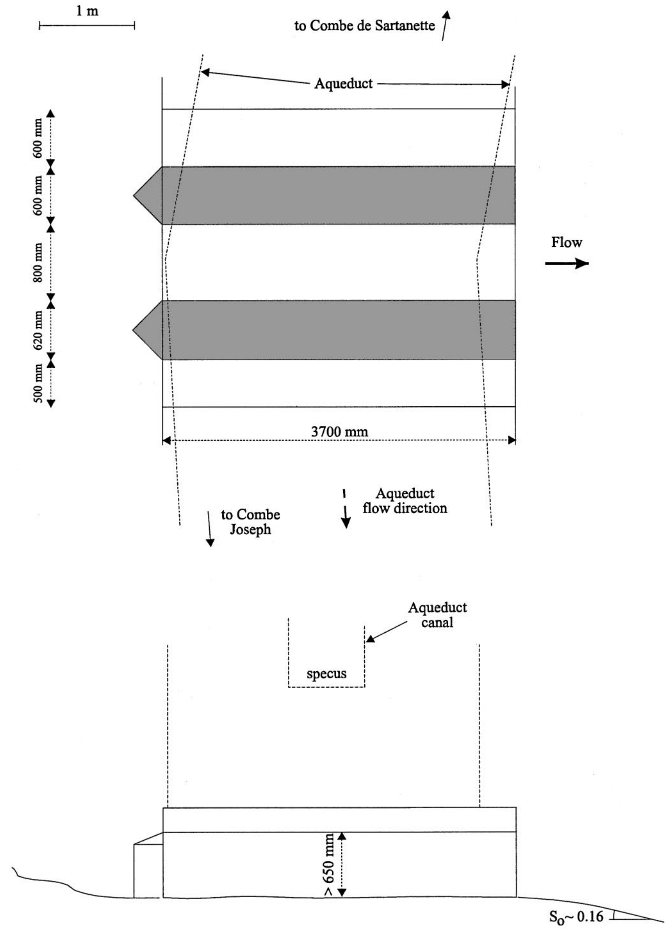


Fig. 2. Vallon No. 6 multicell culvert (Nîmes aqueduct); dimensioned sketch.

Bornègre Bridge sites in September 2000. He believes that the cut waters of the culvert were better shaped. (The cut waters of the Bornègre Bridge were sturdier and less profiled that those of the multicell culvert, i.e., a 60° convergence angle at Bornègre and 45° at the culvert.)

Discussion

Historians and archaeologists have no doubt that the multicell culvert was built in the early stages of the aqueduct (i.e., the 1st century A.D.). The excavation work showed no sign of refurbishment. Fabre et al. (2000, pp. 419–420) reported however that the culvert cells were progressively blocked during aqueduct operation. (But they did not elaborate on the causes of blockage, e.g., siltation, debris, man-made obstruction, etc.) During his site inspection, the writer noted that the culvert barrel was properly located at the trough of the valley and aligned with the *combe* axis. The cells had similar dimensions compared to modern precast concrete box culverts.

Culverts were seldom used beneath aqueducts and the Vallon No. 6 culvert downstream of the Pont du Gard is an unique example. Its unusual features included a box culvert design of large dimensions, a multicell structure, and modern, sound design from a hydraulic perspective (see Hydraulics of the Culvert).

Hydraulics of Culvert

The hydraulic performance of the multicell culvert was estimated using modern culvert design calculations (see e.g., work by Chanson 1999). Modern box culverts are optimally designed for the smallest barrel size to allow inlet control operation. Hence calculations were conducted assuming inlet control operation and this is consistent with the steep upstream and downstream bed slopes (i.e. $S_o \sim 0.16$) and relatively short barrel length. For an internal barrel height of 0.65 m, the culvert operated at free-surface inlet flow conditions for flow rates up to 2 m^3/s, corresponding to upstream water depth of 0.78 m. For greater upstream flow depths, the barrel inlet was submerged. The calculations are summarized in Fig. 3(a), which shows the relationship between the discharge Q in the barrel and the upstream water depth d_1. Fig. 3(b) shows a typical free-surface pattern for submerged inlet conditions.

The results demonstrate a large discharge capacity. Considering a maximum acceptable upstream water depth of 2 m, the culvert could pass up to 4.2 m^3/s (363,000 m^3/day). (Note that this is more than 12 times the aqueduct maximum flow rate.) As a comparison, the larger Bornègre Bridge has experienced flash floods over 5 m^3/s in modern times (Fabre et al. 2000), although its catchment area was much larger (Table 2, column 3). (For upstream water depths greater than 2 m, the reservoir formed upstream of the aqueduct would induce a large pressure force on the structure with a high risk of it overturning and sliding.) Dur-

Table 2. Comparative Drainage Characteristics of Four Crossings of Nîmes Aqueduct (with Nonperennial Streams)

Crossing	Description	Catchment area (km^2)	Maximum flood flow (m^3/s)	Remarks
Pont Bornègre	Three segmental arches (ashlar masonry); total span ~17 m	0.6–0.8	5[a]	Located 6,745 m downstream of the Eure source and 9,061 m upstream of the Pont du Gard
Combe de la Sartanette	One arch (course rubble); Span: 4.08 m (2.23 m after refurbishment)	0.27	—	Located 1,394 m downstream of the Pont du Gard; also called Pont de la Baume–Sartanette
Vallon No. 6	Three rectangular cell culvert (big limestone blocks); cross-section area: 1.24 m^2	0.028	4.2[b]	Located 1,728 m downstream of Pont du Gard
Combe Joseph	One arch (rubble masonry) Span: 4.05 m	0.14	—	Located 2,473 m downstream of Pont du Gard

Note: — indicates no information.

[a]Recent observations.

[b]Calculated.

ing floods, the barrel operated at relatively high flow velocities. For example, the mean barrel velocity was in excess of 2.5 m/s for a 3 m^3/s flow rate.

Discussion

In Table 2, the characteristics of four crossings beneath the Nîmes aqueduct are summarized. Each crossing is characterized by a nonperennial stream in a karstic catchment (Cretaceous limestone). The catchment area and the maximum flood flow (if known) are listed in columns 3 and 4, respectively. At Vallon No. 6, the culvert could pass an intense storm event corresponding to a maximum effective rainfall intensity of nearly 540 mm/h which is consistent with observed maximum rainfall intensity of 800–900 mm/h in the nearby Cévennes range.

As a comparison, the mean annual rainfall near Nîmes has been about 700–800 mm for the last 50 years. During the same period, recorded intense rainfalls included 430 mm in 7 h (61 mm/h) on October 3, 1988 and 250 mm on October 12, 1990 (Fabre et al. 2000, pp. 160–161).

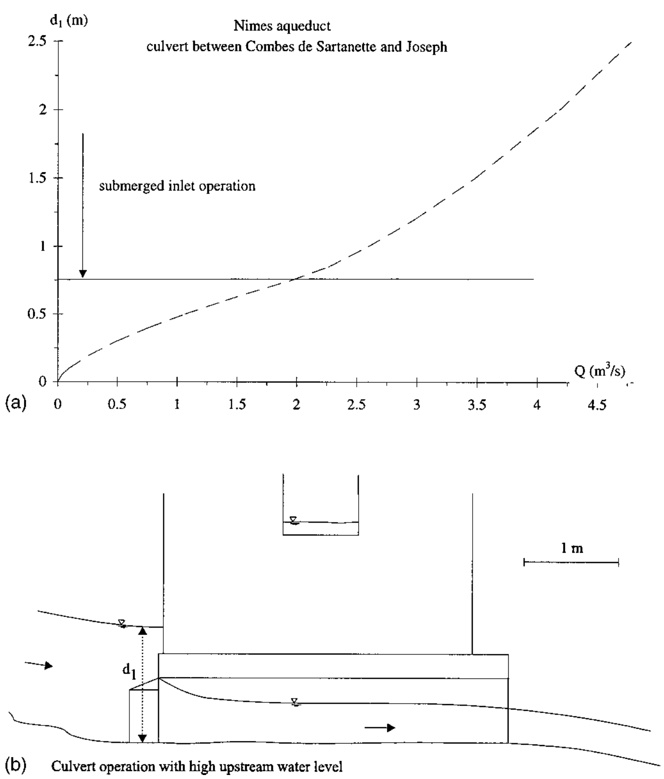


Fig. 3. Vallon No. 6 multicell culvert beneath the Nîmes aqueduct: hydraulic operation. (A) Relationship between flow rate Q and upstream water depth d_1 for inlet control operation; (B) schematic of culvert operation with high upstream flow depths.

Summary

This study describes a large multicell culvert built by the Romans around the 1st century A.D. beneath the Nîmes aqueduct. The structure is unique; no comparable large-size multicell box culvert has been documented. Hydraulic calculations demonstrate sound design with a large discharge capacity (~4 m^3/s). The writer hypothesizes that the Roman engineers had some hydraulic experience, if not knowledge, in dealing with large storm water runoff and its conveyance in a culvert.

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Notation

The following symbols are used in this paper:

d_1 = upstream water depth (m);
Q = water discharge (m^3/s) in the culvert; and
S_o = bed slope.

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