ASPENDOS SU GETİRME VE TAŞ SİFON YAPISI
PAUL KESSENER 2000

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The aqueduct at Aspendos and its inverted siphon

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1. Introduction

The ruins of Aspendos are among the most impressive that are preserved in Pamphylia, and none stand more elevated than the hydraulic towers of the aqueduct. Situated some 50 km east of Antalya about 12 km from the south coast, the Aspendos acropolis lies about 60 m above sea level, near the light green waters of the ancient Eurymedon river. It occupies an oval, flat-topped hill with steep slopes on all sides at some 30 m above the surrounding plains.[1] The mountains begin at c.1.5 km to the north. An extensive description and plan was published in 1890 by K. Lanckoronski.[2] Today the skyline of Aspendos is dominated by the remains of the façade of the nymphaeum (2nd-3rd c. A.D.) (fig. 1) and of the monumental entrance hall of the basilica, both towering some 15 m high. The Roman theatre (capacity 7500), built against the slopes of the E side of the acropolis, claims to be the best preserved theatre of antiquity,[3] probably due to its use as palace by the Selçuks who carried out necessary repairs.[4]

The city, founded as a colony of the Argides who called it Estvedys, was already known as Aspendos by Thucydides and Xenophon.[5] In 133 B.C. it came under Roman rule, and its heyday occurred during the 2nd and 3rd c. A.D., when extensive building projects were realized, including the aqueduct. By its location, Aspendos commanded the land-traffic that frequented the coastal road from Antalya to Side. On the *Tabula Peutingeriana* the road from Perge and Sillyon to the east crosses the Eurymedon near Aspendos, probably by means of a bridge from early times.[6] The river was navigable up to Aspendos, making it an important inland port, as Strabo reports,[7] from where salt, wheat, wool and oil were exported.[8] Ships must have been able to pass the bridge to reach Aspendos. Across the river a road branched off on the E side of the Eurymedon, towards Selge and the Pisidian regions; for it the Romans constructed an impressive

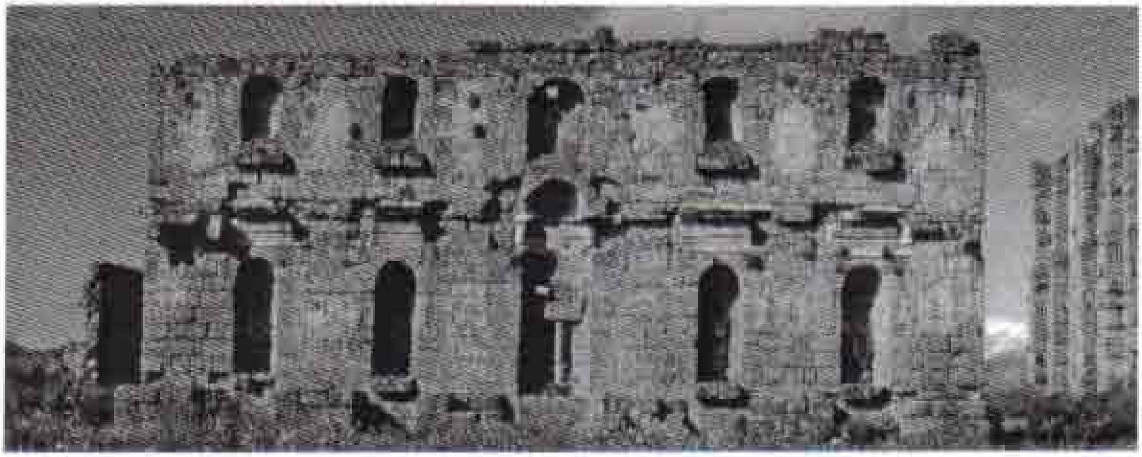

Fig. 1. Nymphaeum.

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[1] Ward-Perkins 1955, 115-23.

[2] Lanckoronski 1890, 85-124.

[3] Akurgal 1970, 334-35.

[4] Wagner 1986, 178.

[5] Lanckoronski 1890, 85.

[6] A Seljuk bridge crosses the river 2 km south of the acropolis. It was built on the ruins of an earlier Roman bridge; see Grewe, Kessener and Piras 1999.

[7] Strabo 15.4.2.

[8] Pliny, *NH* 31.73.

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Fig. 2. Inscription (location unknown).

bridge near Beskonak 25 km to the north.[9] Aspendos thus also controlled the N-S trade route.

As the acropolis is located on top of a hill surrounded by plains, the supply of water by means of an aqueduct could not be realized without substantial technical effort. An inscription described by G. Radet mentions a certain Tiberius Claudius Italicus spending 2 million *denarii* to bring water to the city (fig. 2).[10] Water was led to the city by means of a conventional Roman aqueduct channel, typical for that period and incorporating tunnels and bridges; the aqueduct's course was not known, however. The wide, shallow depression between the acropolis and the hills to the north was crossed by means of an inverted siphon.

Siphons in Roman aqueducts have been the subject of many discussions.[11] Water was carried through a valley under pressure in a closed pipeline, according to the principle of "water finding its own level". The Romans were well aware of this concept. The principle was already stated by Pliny: *(aqua) subit altitudinem exortus sui*.[12] The material of the pipes of these siphons varied: lead, stone, concrete and ceramics/terracotta are known. Though no expression exists in Latin for the concept of (inverted) siphon, several technical terms are mentioned by Vitruvius 8.6, such as *geniculus*, a vertical bend in the pipeline, and *venter*, the horizontal part of the pipeline in the lower part of a valley, often resembling a bridge (fig. 3).

The siphon of the Aspendos aqueduct is characterized by two 'hydraulic towers', giving the siphon a remarkable appearance (fig. 4). Both the 'north tower' and 'south tower' are located at horizontal bends in the siphon's course. Lanckoronski limited his description of the Aspendos aqueduct to both towers and the *venter* bridge in between (fig. 5). The start of the siphon (header tank) and its ending (receiving tank) were not yet located. The pipeline itself was made out of perforated limestone blocks (fig. 6), and ran over the top of each tower before arriving at the city. It is assumed, as Lanckoronski suggested, that the top of both towers was equipped with an open tank into which the water poured from the pipeline and from which water entered the next section again, thereby dividing the pipeline into three consecutive siphons. The reason why the Romans to chose to build these huge towers breaking the siphon into three remained unexplained.

To understand this feature a reconstruction of the entire siphon system was seen a precondition. In 1995 the Aspendos Aqueduct Research Project (AARP) was initiated by the author in co-operation with the Catholic University of Nijmegen (J. A. K. E. de Waele). The first field campaign took place in April 1996, when the siphon was surveyed. During the second campaign (April 1998) mapping of the aqueduct including its two supply sources was completed. The project is supported by the Netherlands Organization for Scientific Research (NWO) at the Hague, by Pol Geotechniek at Heteren, Virtus Architects at Nijmegen, and Delft Hydraulics at Delft.

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[9] The bridge, presently called Olukköprü, spans a canyon in a single arch 40 m above the waters of the Eurymedon. As sound today as when it was built, it was used until recent years by heavy truck traffic, to benefit which the large stone blocks that flanked the passage were thrown over the side. The stones can be seen *in situ* in a photo of 1968 (Bean 1979, fig. 65). In 1997 the bridge was closed to all traffic. During the 1998 restoration it gained a completely new parapet, losing some of its charm.

[10] Bean 1979, 53; *IGRP* 804. The name of the aqueduct's benefactor may be read from the inscription: see G. Radet and P. Paris, *BCH* 10 (1886) 160. The inscription was found on a stone slab in the wall of a "hangar près de l'aqueduc". The present location of the inscription is not known.

[11] E.g., Smith 1976, 45-71; Fahlbusch 1982, 63-93; Hodge 1983, 174-221; Hodge 1992, 147-60.

[12] Pliny, *NH* 31.57; Hodge 1992, 147 n.39.

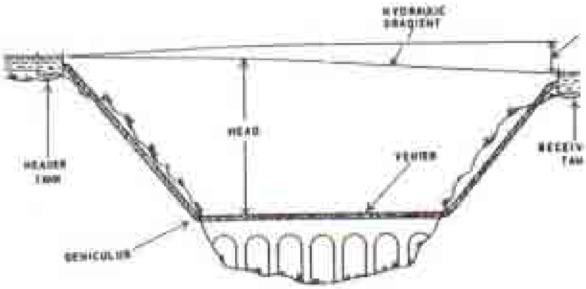

Fig. 3. Inverted siphon, general principles (Hodge 1992, 148).

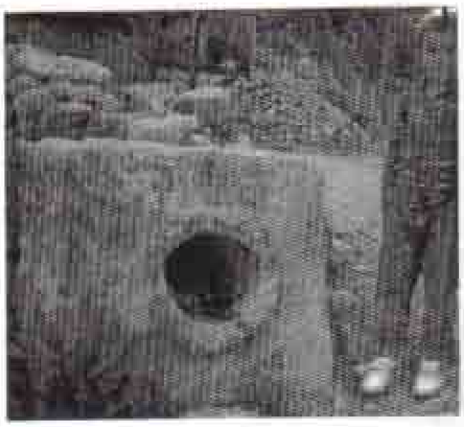

Fig. 6. Aspendos siphon, stone pipe element (near header tank).

Fig. 4. Aspendos siphon, N tower seen from the west.

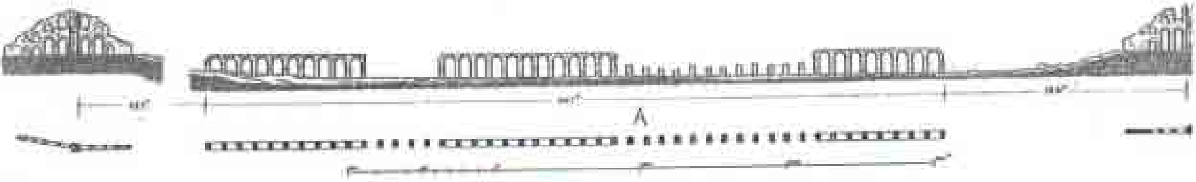

Fig. 5. Hydraulic towers and venter bridge in between (Lanckoronski 1890).

2. The course of the aqueduct

The mapping of the Aspendos aqueduct, begun in 1996, was completed in 1998 (fig. 7).[13] The 19-km-long aqueduct starts at the spring complex of Gökçepinar village ("heavenly spring") situated in a valley 550 m asl surrounded by rugged mountains ranging over 900 m high, 17 km northeast of Aspendos as the crow flies (fig. 8). In April 1998 the springs delivered 30 to 40 lit-

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[13] Kessener 2000.

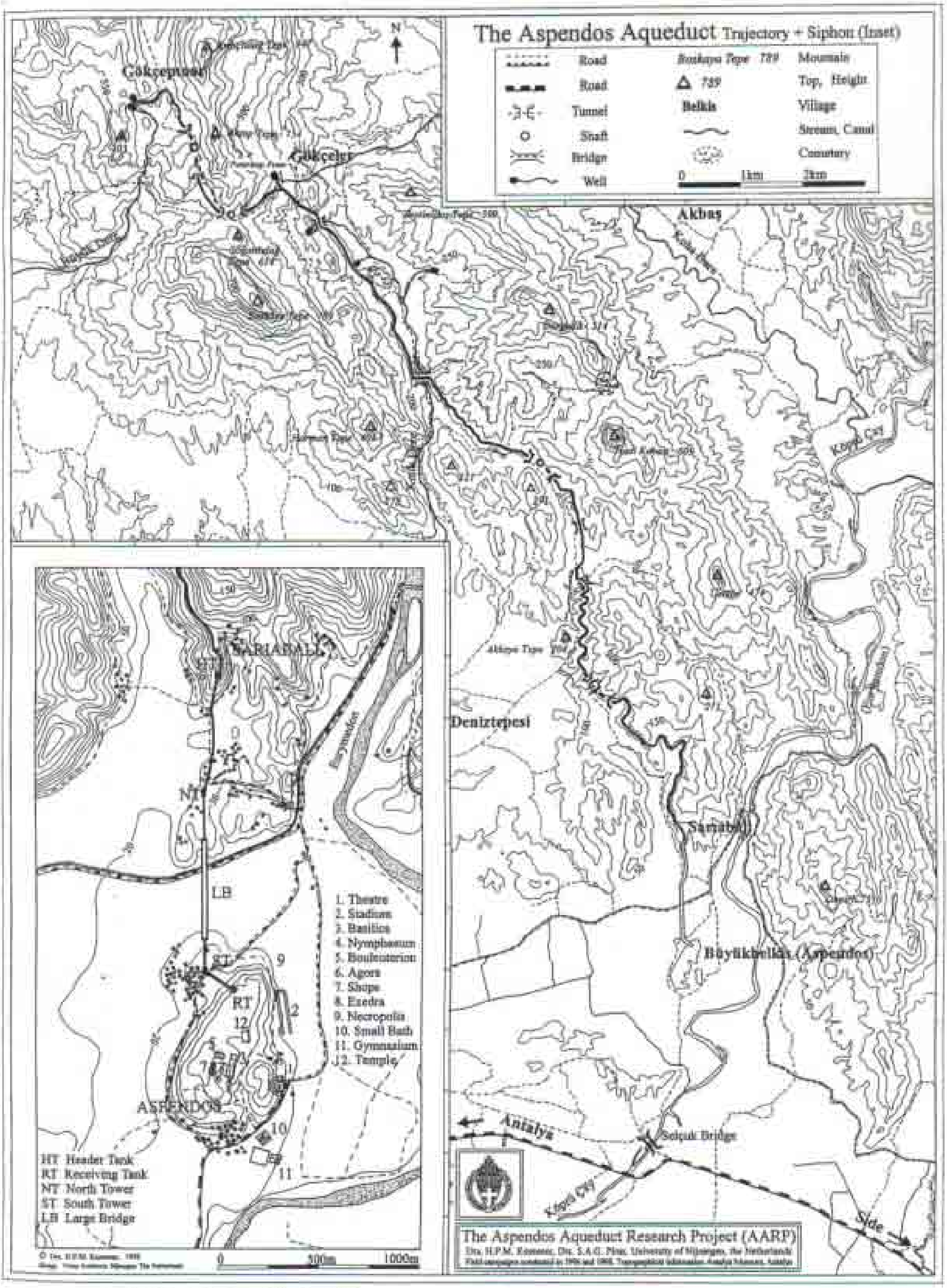

Fig. 7. Map of the Aspendos aqueduct.

Fig. 8. Gökçepinar spring complex.

ers per second with a temperature of 15.6°C and a pH of 7.42.[14] They constitute the head of the Büyük Dere, a small stream descending to the southwest towards the Aksu river. The springs are exploited today by the local populace for their water supply, for which several concrete enclosures were built. The aqueduct channel, of which no trace remains near the springs, departed initially in an easterly direction, then turned more to the south after c.400 m.[15] About 500 m further on a stretch (7 m long) of the channel itself was found, intact but partly buried, on the N slope of a rather steep valley, 15 m above a small stream. Walls and vault destroyed, the channel floor could be traced for several dozen meters both upstream and downstream from here. The channel was 60 cm wide, with walls 40 cm thick, and the inside 95 cm high from channel floor to underside of the vault. As the direction of the water flow in the channel, at an estimated gradient of 20 m per km here, was opposite that of the stream below, the channel had to come level with it. Continuation by means of a tunnel was the only possibility, but no signs of a tunnel entrance could be discovered, which apparently had collapsed and been covered by dêbris. Near a mountain pass 300 m to the south and c.40 m higher, a vertical round shaft 2.75 m wide indicates the existence of such tunnel. From topographical considerations we estimate the tunnel to have been over 550 m in length. Another shaft (2.7 m square), 1200 m further to the south and made of mortared rubble, with a central circular opening 1.2 m in diameter, indicated the existence of a second tunnel related to a minor mountain pass.[16] Traces of the tunnel entrances or of the channel between the two tunnels were not found, possibly due to extensive work on the mountain road nearby.

The channel then turned east along the S slope of the Aktop Tepe, a mountain 754 m high, and descended towards the second spring that fed the aqueduct. This spring, called Pınarbası, Turkish for "natural fountainhead" or "springhead", is located near Gökçeler village. In April 1998 it delivered water of 16.7°C and pH 7.37, contributing to the Koba Dere which discharges into the Eurymedon about 12 km to the east. The spring lies at 440 m asl at the foot of a large limestone outcrop; it discharged about 40 l per second at the time of the survey.[17] The waters of this spring were collected in a modest springhouse of traingular shape (base 2 m, sides 5 m long), the waters emerging from the south angle in a channel 50 cm wide. The springhouse was originally roofed, a single stone slab still remaining. The discharge of the spring, delivering water all year round, varies with the season; it was said not to be at its minimum at the time of year we measured it.

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[14] Data for temperature and pH from G. Kaiser (Wuppertal).

[15] Several channel-like cuttings in the rocky terrain near the springs suggest ancient spring caption. The waters from the springs are still used for irrigation. The ditch running from the springs to the east continues with a steady gradient along the border of cultivated fields at the foot of the hill. It may well represent the aqueduct's original course, but traces of the old channel could not be found.

[16] For a general discussion of vertical shafts in relation to tunnel construction see, e.g., Grewe 1998.

[17] The spring, identified by Falhbusch as Gökçepinar spring, delivered 30-40 l per second in late summer 1979 (Fahlbusch 1987, 173).

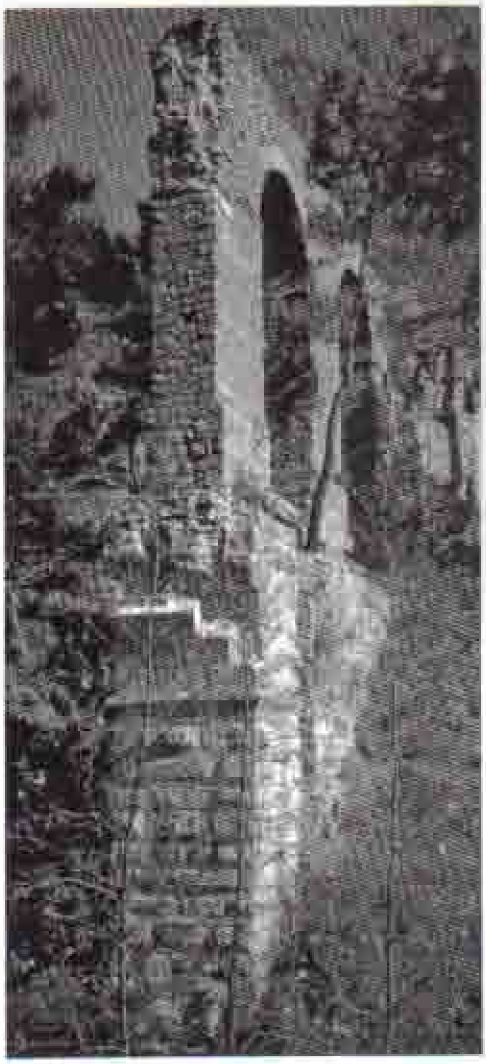

Fig. 9: Channel floor, walls and vaulting destroyed.
Fig. 10 (right). Two tier aqueduct bridge.

From this spring the aqueduct took a precipitously downward course to the southeast for some 500 m, having an estimated gradient of 160-170 m per km.[18] Extensive erosion in relation with logging activities has changed the topography of the steep terrain, destroying the channel and covering the remnants. Some 120 m lower than the Pınarbası spring a seasonal torrent crossing the course of the aqueduct happens to have cleared away the débris, causing the channel floor (walls and vaulting were destroyed) to come to light. A mass of calcareous incrustation (*sinter*), over 30 cm thick and consisting of layers over 5 mm wide, covers the channel floor (fig. 9).[19] The channel is 55 cm wide at this point, its gradient 85 m per km. From here it took a less steep course, crossing the Kisik Dere near its most elevated source by means of

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[18] Gradients of aqueducts are known to vary enormously, from as low as 7 cm per km for sections of the Nîmes aqueduct, to over 95 m per km for the Carthage aqueduct in its first 6 km from Zaghouan. The estimated gradient of this part of the Aspendos aqueduct is exceptionally large. See, e.g., Hodge 1992, 186, 216-19.

[19] Calcareous incrustation (*sinter*) in aqueducts is known to build up in layers of about 1-2 mm per year; see, e.g., Grewe 1992 and Hodge 1992, 227-32. A value of 5 mm per year is quite large. It may be related to the gradient of the channel at the site: the steeper the gradient, the faster, and the more turbulently, the water flows, whereby exchange of carbon dioxide out of the water into ambient atmosphere is facilitated, thus enhancing precipitation of carbonates. This is in contrast with the view mentioned by Hodge (1992, 228) that the greatest build-up of *sinter* must be expected on the sections where the gradient is least. The boulders in the steep torrents near this part of the Aspendos aqueduct on their downstream side are covered with thick masses of *sinter* in layers of similar dimensions, confirming the

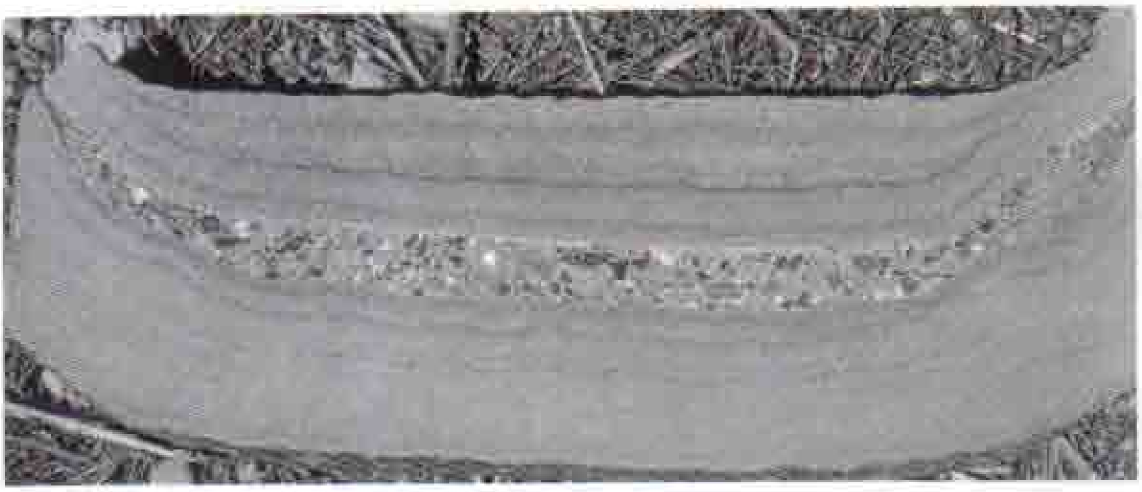

Fig. 11. Sinter slab from channel, with repair works (*opus signinum*).

a bridge (one pier of 2 x 2 m and *c*.8 m high stands today, the other piers were destroyed by the seasonal stream). The aqueduct then ran south on the right-hand side of the Kisik Dere. In an adjacent Seljuk cemetery tombstones made from slabs of calcareous incrustations broken out from the channel mark the graves.[20]

After continuing on the W side of the Kisik Dere for about 3 km, the aqueduct crossed the stream once more by means of an impressive two-tier bridge over 125 m long and 20 m high, of which two upper arches on the E bank are all that remain (fig. 10). The two lower arches spanning the Kisik Dere and the piers above, were intact in 1986 but had collapsed in 1991. An inscription, the bronze letters missing, was observed before the collapse but it was not possible to locate this stone now buried under the pile of enormous stone blocks from the pier.[21] The bridge runs E–W; it makes an acute turn of 45° on the W bank, carrying the channel at a height of 10 m, before it ends after *c*.30 m.

Further to the south the hills on the W side of the Kisik Dere have been extensively logged, and remains of the channel were found only where an occasional pine tree left standing had kept the channel from tumbling down the steep slopes. The aqueduct then left the valley of the Kisik Dere on a more southeasterly course towards higher ground, where after 2 km it continued through a tunnel for several hundred meters; a vertical shaft near a mountain pass at 190 m asl indicates its underground course.[22] After passing through the tunnel, it enters an area less eroded by logging and several remnants of the channel could be located, partly *in situ* on the sloping

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relationship between turbulence and build-up of *sinter*. For a general discussion of the relation between rate of *sinter* build-up and channel gradient, see Fahlbusch 1982, 125-29.

[20] At another Seljuk cemetery, *c*.4 km to the southeast in wooded mountain terrain, we discovered similar slabs, some measuring over 1.5 m long, 60 cm wide and 10 cm thick, shaped as negative imprints of the channel's floor, with traces of *opus signinum* adhering. Both cemeteries are indicated on the map of the aqueduct (fig. 7). Extensive re-use of calcareous incrustations is know from Europe, where the aqueduct of Cologne served as an important quarry for this material in mediaeval times (Grewe 1992; Hodge 1992, 231-33). Because of its excellent quality, Cologne *sinter* served as a substitute for marble which had become increasingly difficult to obtain in N Europe after Charlemagne. It was used for ornamental columns and altar pieces in numerous Romanesque churches and other buildings. The material was exported as far as Denmark and England. It was used for headstones in German cemeteries as late as 1964. Sinter from the Nîmes aqueduct, of lesser quality, is also known to have been used, mainly for construction (Fabre *et al.* 1992).

[21] The bridge is depicted in Fahlbusch 1987, 219 fig. 5, where it is erroneously attributed to the Side aqueduct. From one of Fahlbusch's photographs we became aware of the inscription, *in situ* before the collapse (pers. comm.). The fixing holes of the letterings may give information about the original inscription, possibly even about the aqueduct's date.

[22] Its construction characteristics and dimensions are similar to the shaft of the second tunnel described above.

Fig. 12. Tunnel entrance.

terrain and partly fallen down the hillside. A block of calcareous incrustation, in the form of the negative offprint of the channel's floor and walls (60 x 70 cm, and over 30 cm thick, with traces of *opus signinum* adhering) had clearly been removed from the channel intact. To our surprise a layer of *opus signinum* appeared in the middle of the thick mass of *sinter*. After it was cut in a local mason's yard, a layer of *opus signinum* *c*.5 cm thick was revealed, extending the entire width of the channel (fig. 11). It had been applied on top of a layer of calcareous incrustation *c*.8 cm thick which does not appear to have been worked or damaged. The material was applied in two phases, first in a horizontal reddish layer on top of the *sinter* and then, in the corners, grayish-black with a sloping edge as a "quarter round", meant to prevent cracking of the waterproof cement.[23] On top of the *opus signinum* a second layer of calcareous incrustation *c*.7 cm thick was deposited before water flow stopped altogether. The thickness of the individual *sinter* layers being about 1 mm and the channel having a moderate gradient of 7 m per km, the water must have run for some 70-80 years before the *opus signinum* was applied, obviously as a repair, after which the channel was kept in use for another 60-70 years. Hence the Aspendos aqueduct transported water to the acropolis for at least some 130-150 years.

Downstream from this point the aqueduct channel appears to be relatively undamaged, as the top of the vaulting is visible for several stretches in the wooded area. Remnants of two major bridges were found, one with a single arch of *c*.5 m diameter, 23 m length, and partly intact, and a two-tier bridge, completely collapsed, which was originally over 50 m in length and 15 m high. After passing Akkaya Tepe (204 m high) on the right, the aqueduct's course happened to be crossed by a modern waterway, exposing and destroying the ancient channel.[24] A short distance on the aqueduct entered a tunnel of *c*.50 m in length, its entrance and exit both identified, followed after a few meters by second tunnel (fig. 12).[25] In both tunnels traces of *sinter* and *opus signinum* were found. The exit of the second tunnel could not be located and a search for vertical shafts was also unsuccessful. The tunnels are accessible for a short distance only. After passing through the final tunnel, the channel descended the 3-km distance towards Sariabali village with a moderate gradient of 5m per km, to end at the header tank of the siphon.

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[23] See, e.g., Hodge 1992, 95-98. For a general discussion of *opus signinum* see also Malinowski 1979 and 1996.

[24] This large-scale project initiated by the Turkish public water company DSI aims to divert waters from the Eurymedon towards the town of Gebiz 20 km to the west by means of a canal over 10 m wide. Regrettably, the Roman channel was not preserved; a stretch of a few meters of the channel's *sinter*-covered rock-cut floor and left side wall is all that remains.

[25] Entrance opening 1.6 m wide and 1.9 m high.

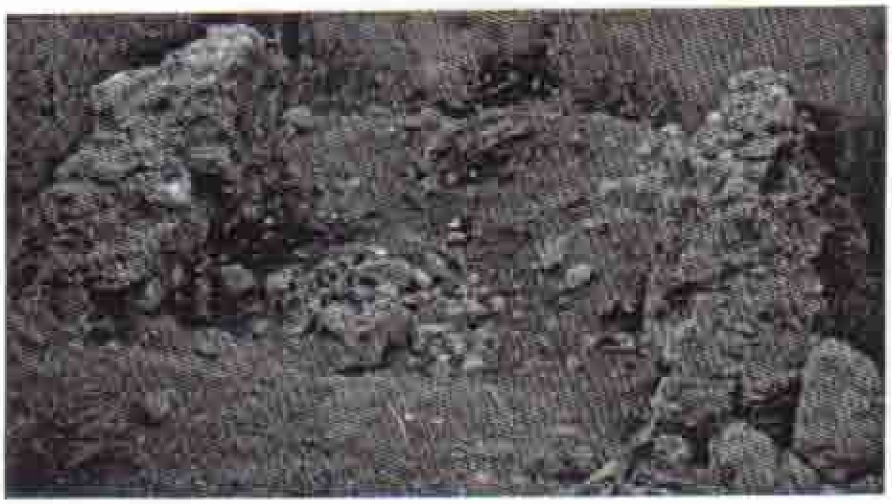

Fig. 13. Remains of header tank.

A steep hill at Sariabali, north of Aspendos, marks the beginning of the mountains west of the Eurymedon.[26] If one looks south from this hill, the towers of the siphon and the acropolis rise in the distance. The hill has a flat, triangular-shaped top at 80 m a.s.l.; it slopes down to the depression in the south at a steady angle of *c*.14°. On its top near the S edge are two parallel N–S walls, 1 m wide, 2.5 m long, *c*.1 m high, and 2.7 m apart (fig. 13). They are constructed from mortared rubble mixed with local stones (up to 20-30 cm diameter), with small fragments of brick inserted at the facing to fill the gaps. The area between the walls had been disturbed, and fragments of *opus signinum* up to 10 cm thick with traces of calcareous incrustations were found at modern ground level and in rubble thrown to the side. To the north, the walls were joined by a perpendicular wall 70 cm wide (now largely destroyed). To the south, large stones with *opus caementicium* adhering and a granite block nearby over 1.5 m long and 50 cm wide suggest a similar connection. The construction had thus served as a water tank or container (2.67 x 2.17 m). At the modern ground level the W wall is equipped with an opening, 30 cm square, all sides of it covered by *sinter* up to 5 cm thick. A gully-like depression in the hill on the W side of the tank would lead water emerging from this orifice downhill to the southwest, suggesting that the opening had served as an overflow. On the cultivated field north of the tank numerous fragments of *opus signinum* and *sinter* were found. Local farmers confirmed that an aqueduct channel had run over the flat top of the hill; its remains had been removed because they interfered with the field's cultivation but the tank, located on rocky ground at the very edge of the field, was left to stand. It may now be identified as the header tank to the Aspendos siphon.

The wide depression between the mountains at Sariabali village and Aspendos acropolis prevented the transport of water in an open channel unless an enormous bridge (over 60 m high and 1.5 km long) had been built. The engineers opted instead for a pressurized stone conduit, a solution not uncommon in Asia Minor, as seen, for example, at Laodikeia ad Lycum, Oinoanda, Kybira, and Patara.[27] At Aspendos two huge towers were included in the design. The towers dominate the plain north of the acropolis. Since Lanckoronski's description of the towers and the bridge in between, not much had been added to our knowledge.[28] Thus the primary goal of

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[26] Across the Eurymedon to the east, the Zincirli mountain range extends about 5 km further to the south. The mountain range is called after the Turkish word for chain (*zincir*). According to legend, a long iron chain had been used in antiquity for hauling up water from the inside of the mountain. From the top of this mountain range (310 m), which has a vertical face to the east over 100 m high, one gains an excellent view over the acropolis and the surrounding plains, including the Eurymedon. On the very top remains of a fortification wall standing 5 m high, of several buildings and of three cisterns suggest that it served as a permanent look-out post to the city. At the foot of the vertical face a spring wells up.

[27] Laodikeia: Weber 1898; Oinonada, Kybira, Patara: Stenton and Coulton 1986.

[28] Ward-Perkins visited the Aspendos siphon in the 1950s (id. 1955).

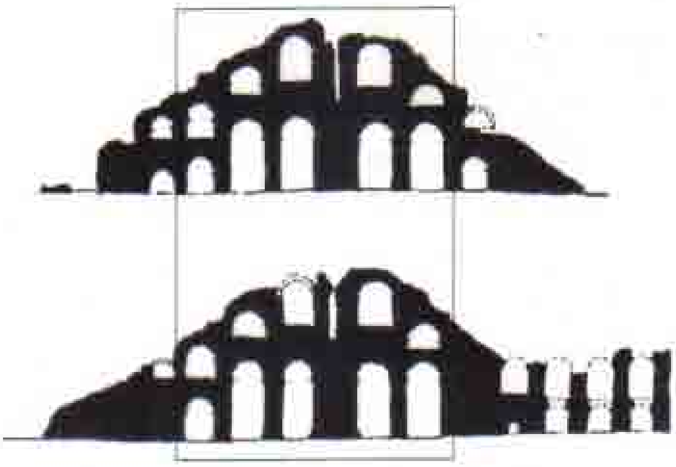

Fig. 14. North tower (top), and south tower (bottom), bends straightened out. Direction of water flow: from left to right. Identical designs (box).

the 1996 campaign was to inspect the several elements of the siphon, to identify both the header and the receiving tank, and then to survey by theodolite the entire siphon system.

3. Elements of the Aspendos siphon

The towers

The towers of the Aspendos siphon consist of a central section *c.*5.5 m square and two long ramps 2.4 m wide leading to the top, on opposite sides and pierced by arches. The towers are at present *c.*30 m high. They are almost identical in design except for the change of direction of the ramps (fig. 14). The lower part of the central towers is constructed with dressed conglomerate stone blocks, the upper part is made out of brick.[29] Lanckoronski interpreted the variety of materials as the result of restoration,[30] but J. B. Ward-Perkins has shown, by comparing the overall design and construction characteristics of the towers, that the surviving remains are all part of the original buildings.[31]

The central towers are equipped with a spiral staircase 90 cm wide, accessible by means of a door opening 1 m wide and 1.9 m high. At the S tower this opening is located over 3 m above modern ground level; at the N tower it is almost at ground level and access is more convenient. The staircase inside the squared stone part of both towers is intact, rising to *c.*14.4 m above door level. The walls of the central towers are 1.25 m wide, the staircase spiraling around a central pillar (1.2 m square). The interior of the towers measures 3. 0 m square. The steps, three for each 90° turn, are made out of large stone cuttings bridging the 90-cm gap between the central pillar and the interior wall. The height gained in one complete turn of 360° is 3.6 m, an average of 30 cm per step — not very convenient for climbing stairs. The walls not adjoining the ramps are equipped with longitudinal openings (*c.*1.0 x 0.3 m), allowing air and some light into the interior of the towers.

From a height of 14.4 m above door level the building material of the central towers changes from squared stones to bricks.[32] Here a sequence of brick vaults had spiralled up around the central square pillar, also made from brick, on which the staircase continued to the top (fig. 15). No remains of a water tank or of *opus signinum* was observed. A layer of calcareous incrus-

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[29] Bricks only, not mortared rubble faced with bricks as mentioned by Vann 1976, 85.

[30] Lanckoronski 1890, 124.

[31] Ward-Perkins 1955, 121.

[32] The bricks, dimension 60 x 30 x 5 cm and of excellent quality, are cemented together by layers of mortar 1-4 cm wide. Except for finger lines drawn in the surface for better attachment, imprints were not discovered.

Fig. 15. Brick part of south tower, remains of vaults on which stairs led to the top.

tation 0.5 cm thick on the inner W wall of the S tower, at a height of 19-20 m above ground level, attested to spillage of water from above.

The 2.4 m-wide ramps on either side of the central towers are built in a hard mortared rubble resembling concrete, laced with courses of brick brought to a vertical face by means of small, irregular blocks of stone, hand-laid and liberally mortared so as to produce a smooth, compact surface. The arches piercing the ramps are made out of a double layer of bricks, except for the two pairs of tall arches flanking the central parts which have stone voussoirs.[33] The ramps on either side of the central part stand at an angle to each other, 55° for the S tower, and 16° for the N tower. The design of the central part of the S tower and adjoining ramps is symmetrical, in contrast to the N tower where the south ramp is at right-angles with the central part but the north ramp makes an angle of 16°.

The main bridge

The towers stand 924 m apart. Between them a bridge 510 m long carried the pipeline across the lowest part of the valley. The bridge is made of local conglomerate blocks (dimensions up to 1.5 x 0.6 x 0.6 m) with a mortared rubble core. It is 15 m high for its greater part and 5.5-5.7 m wide, the top layer of conglomerate slabs protruding over the piers and arches for 20-30 cm on either side. The bridge counted 47 piers (3.6 x 5.4 m) and 46 arches (7.1 m wide). Today 32 piers and 29 arches are standing, in three stretches of 8, 11 and 10 arches counting from south to north, as was the case in Lanckoronski's day.

Two-tier bridge and receiving tank

The S tower is located at *c.*130 m from the steep NW slope of the acropolis, and is linked to it by a two-tier bridge (fig. 16). The top of this bridge ran at an intermediate level between that of the main bridge and the top of the towers. Ward-Perkins suggested that the receiving tank of the siphon "must have lain beyond the summit of the acropolis, at some point suitable for distribution to the city's public bath-buildings on the low ground to the south-east", and conjectured that "some part of the huge system of cisterns underneath the agora and the basilica may have been planned in connection with the building of the aqueduct".[34] Fahlbusch

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[33] Krautheimer (1986, 106) includes Aspendos as a 2nd-3rd c. prototype of building techniques employed at Constantinople in the late 4th c. and characterized by "mortared rubble masonry leveled off by broad brick bands; mortared rubble faced with small stone blocks and brick bands; solid masonry of alternating stone and brick bands; finally, vaulting of pure brick rather than cast concrete".

[34] Ward-Perkins 1955, 118, n.8.

Fig. 16. South tower and two-tier venter bridge. To the right: edge of acropolis.

mentions that the aqueduct should somehow have ended at the nymphaeum on top of the acropolis.[35] Lanckoronski's map shows the course of the siphon arriving from the S tower at the edge of the acropolis; it continues, after making a turn of about 80°, in a SE direction for c.130 m, ending a considerable distance away from the nymphaeum and without arriving at a clear distribution point.

The piers (2.4 m wide) of the two-tier bridge are standing today, all arches except one being destroyed; the surviving arch spans the gap between piers 7 and 8 counting from the S tower. Of the total of 14, the first 10 piers were connected by second-order arches; the remaining piers were built on higher ground on the slope leading to the vertical edge of the acropolis.

In line with the double arcaded bridge, and located on the acropolis at c.15 m from its steep edge, the remains of a square tower may be observed. Its position corresponds with the change in direction in the aqueduct's course marked on Lanckoronski's map. Now 4.5 m high, the tower, constructed of mortared rubble dressed with square stones, is essentially rectangular (1.8 x 2.35 m) and equipped with two extensions. Its base, almost level with the present top of the S tower, shows an extension (1 x 1.75 m) towards the S tower, with remains of a brick arch 4.8 m in diameter (fig. 17). The second extension, on the aqueduct's course on the edge of acropolis according to Lanckoronski's map, is 1.2 m wide but not as long. Above this extension, at the very top of the extant remains, the indications are that an arch was constructed, with diameter 3 m, and its extrapolated top ranging 5.4 m above the base of the tower. The distance spanned by this arch corresponds with the position of a rectangular pier 3 m to the west. Similar piers are found along the course of the aqueduct on Lanckoronski's map. If we restore an open aqueduct channel

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[35] Fahlbusch 1987, 174: "Die Wasserleitung endete auf der Akropolis anscheinend in einen Nymphaeum. Als solches wurde es durch Vergleich mit dem entsprechenden Bauwerk in Side identifiziert, da weder die ursprungliche Ausstattung noch die Verbindung mit der Wasserleitung erhalten sind."

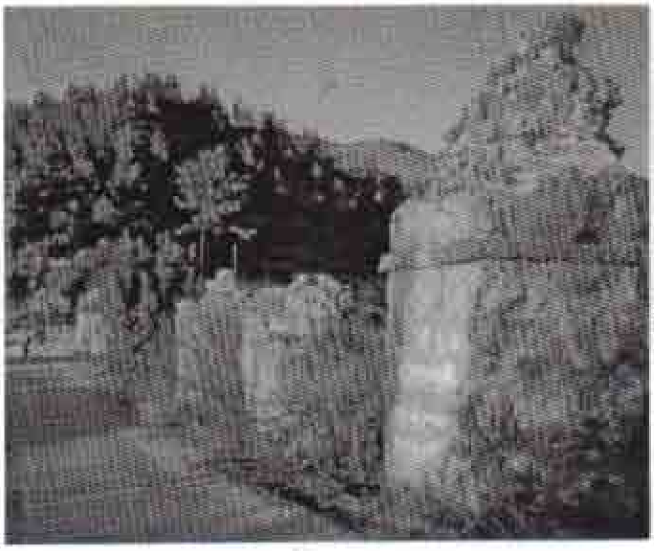

Fig. 17 (left). Remains of receiving tank.
Fig. 18 (above). First venter bridge to the siphon. In the back: wooded hill, header tank on the top.

supported by arches, and allowing for a thickness of 0.5 m for the material on top of the arches, the reconstructed level of the floor of an open channel would be at 5.9 m above the base of the tower. This level turns out to be 3 m above the highest ground of the acropolis, and to correspond with the top of the nymphaeum's central ground-floor niche. The open channel would thus have supplied the nymphaeum and the entire city, and there was no need for a pressurized pipeline to continue from this point. The tower on the edge of the acropolis was therefore the receiving tank to the siphon.

The level up to which water must have been brought is *c.*6 m above the present top of the S tower. An open tank located on top of the S tower should have been positioned above the receiving tank if water was to flow to it. This applies to both the N and the S tower. If equipped with open tanks, the tank on top of the N tower should have been positioned higher again than its counterpart on the S tower. The header tank to the siphon should in its turn be positioned at a level somewhere above the tank on the N tower.

The two-tier *venter* bridge combines three types of masonry: conglomerate blocks, bricks, and mortared rubble; the receiving tank was made of dressed stones of smaller dimensions (e.g., 10 x 20 x 40 cm), conglomerate material and limestone alike, with a core of mortared rubble.

Header tank and low bridge

The pipeline started from the header tank (see fig. 13) and ran down the steep but regular slope of the hill which had been employed as downward ramp. At the very bottom of the hill (50 m below) a wall, 2.4 m wide, had been built as the start of an 11-pier bridge running south, the first *venter* to the siphon. The bridge was 5 m high and 2.4 m wide. Remains of 8 piers (2.4 x 2.5 m square, maximum height 3 m, and spaced at *c.*4.5 m) stand today; three piers were destroyed some 30 years ago in connection with the construction of the road (fig. 18). The arches of the bridge were made of a single layer of bricks; the piers consisted of mortared rubble with isolated trimmed blocks at the edges. On the mortared faces of the piers drawn imitations

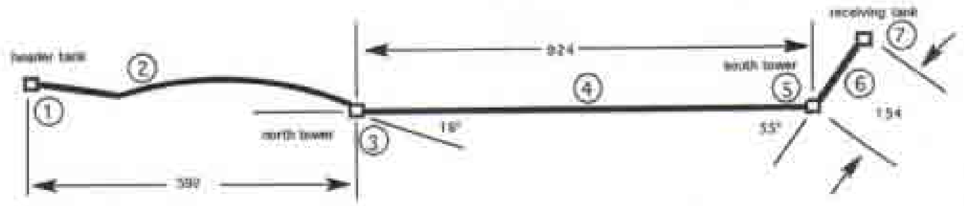

Fig. 19. Plan of Aspendos siphon. 1 - Header tank; 2 - Low *venter* bridge; 3 N tower; 4 - Large *venter* bridge; 5 - S tower; 6 - 2-tier *venter* bridge; 7 - Receiving tank. Distances in meters.

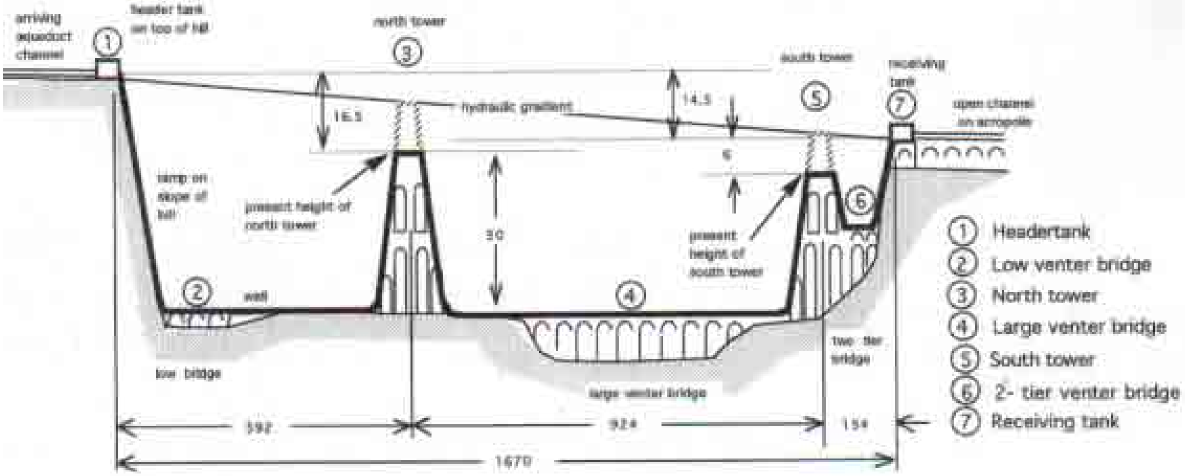

Fig. 20. Profile of Aspendos siphon (vertical dimensions enlarged).

of squared blocks (*Fugenstrich*) are visible. After *c.*80 m the bridge continued as a mortared rubble wall, over 70 m long, destroyed but for the initial 3-m high section on top of which the pipeline was carried. Running towards the N tower on the left side of the local road, the wall decreases in height as the ground rises. It subsequently crosses the line of the road where it was used in the road's foundation. The course of this *venter* is slightly curved, apparently because of higher ground east of the direct line between its start at the bottom of the hill and the N tower, since the curved course required a shorter and lower bridge and wall.

The siphon overall

After the elements of the siphon had been identified, the entire system was surveyed with a Nikon NTD-4 theodolite. The plan of the siphon is shown in fig. 19. The overall length of the siphon is 1670 m (154 m + 924 m + 592 m). A schematic profile of the siphon is shown in fig. 20. The hydraulic gradient line extends well above the present top of both towers. The position of the overflow orifice in the header tank determines the maximum water level at the starting point of the siphon, whence the pressure in the pipeline would not have exceeded 45 m of water column. We have no direct proof for open tanks on top of the towers; but if the towers were equipped with open tanks, then their tops should have been reaching up to the hydraulic gradient line if the siphon was to function at maximum capacity. The tanks must have fallen from the towers and the broken parts been carried away. We do not know what the tanks looked like, how large they were, and how the pipeline was connected to the tanks. If we assume, on the other hand, that a *closed* pipeline ran over the top of the towers, positioned below the hydraulic gradient line, no tanks would have been necessary. But then air cushions would accumulate on the downstream side of the top of the towers during the filling procedure. It can be shown on hydraulic grounds that these air cushions, which will be compressed because of static water pressure, are the cause of a loss of head available to run the siphon. In the case of Aspendos, with a closed pipeline running over the top of the towers even at present height, these air cushions would prevent the siphon from getting started at all. Clearly the same would be true in the case of even more elevated towers. Thus there must have been open tanks on top, and these tanks must have been positioned according to the hydraulic gradient line.[36] This means that we may reconstruct the S tower as having reached up to 37 m, about 8 m above the present top, while the N tower would have been 40 m high. Figure 21 (colour foldout) shows a reconstruction (with "wire frame" by CAD terminology) of the siphon (the pipeline itself is not shown), together with an overview of the present remains.

The overall hydraulic gradient between header tank and receiving tank is 14.5 m, that is 8.7 m per km. The hydraulic gradient of the siphon, the diameter and the inner roughness of the stone pipeline determine the maximum amount of water transported to the acropolis. From the Darcy-Weissbach formula, the mean velocity V of the water inside the pipeline and the discharge Q of the siphon may be calculated. Disregarding minor effects caused by the bends (*geniculi*), by the additional length due to the sloping of the ramps, and by the inlet and outlet orifices at the tanks, the mean velocity of the water in the pipe at full capacity would be 1.05 m per second.[37] The corresponding discharge is 65 l. per second or 5.6 million liters per 24 hours. Assuming a daily consumption of 300-500 liters per head per day — a generous but not unusual figure — the population in Aspendos' heyday might be estimated as *c.*11,000-18,000 persons.[38]

The course of the Aspendos siphon in relation to topography

The towers are located at sharp horizontal bends in the pipeline, 55° at the S tower, and 16° at the N tower. There is another horizontal bend of about 15° at the bottom of the hill below the header tank, at the first *geniculus*, where the *geniculus* element may have been firmly secured in the hillside.[39] Assuming that the Romans believed that pressure towers were needed at sharp bends in the pressure line where a natural anchoring could not be realized, it raises the question why the Roman engineers decided on a course with two sharp bends, and whether they were forced to do so because of topological considerations.

In 1998 the terrain around the course of the siphon was surveyed for an area of *c.*500 x 1800 m. The results are depicted in fig. 22. The slope of Sariabali hill on which the header tank was located served as the downward ramp; to the south is the steep edge of the acropolis with the receiving tank. The S tower is located on a 15-m high rise which extends from the edge of the acropolis north for *c.*250 m. Most of the village of Belkis is built on this rise. It extends further to the north than the most northerly edge of the acropolis, which makes it a preferred starting point for a bridge crossing the deepest part of the valley. From the mountains on the opposite (N) side of the valley three low ridges extend to the south. The main *venter* bridge starts at the middle one. All three ridges were quarried for the conglomerate stone blocks found in the bridge, the west ridge most extensively.

In fig. 23 some alternatives to the siphon's course, from the header tank as the starting point, are proposed. In fig. 23A a bridge would cross the lowest part of the valley between the westernmost ridge and the rise at the acropolis. The bridge would have been a bit shorter than

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[36] Assuming that all 3 sections of conduit had the same cross-section and the tanks did not overflow.

[37] The extra length due to the sloping of the ramps amounts to some 50 m, less than 3%. The effect of the bends and the orifices on the mean velocity is less than 1%.

[38] Stenton and Coulton 1986, 55 cite figures varying from 160 to 190 l. per person per day for Pergamon, 520-900 l. per person per day for Rome, to as high as 1000 for Trier. In 1998 water consumption in the Netherlands was 135. See also Hodge 1992, 305. The reliability of the ratio between water consumption and population numbers, however, is questionable.

[39] Traces of such provision were not observed. If one assumes that a tower had been built at this point as well, the tank on top, reaching up to the hydraulic gradient line, would be located close to the header tank, and almost level with it. The section between the header tank and the top of this tower would represent a very short and shallow siphon having a *venter* at high elevation, which might just as well be constructed as an open channel on top of a bridge.

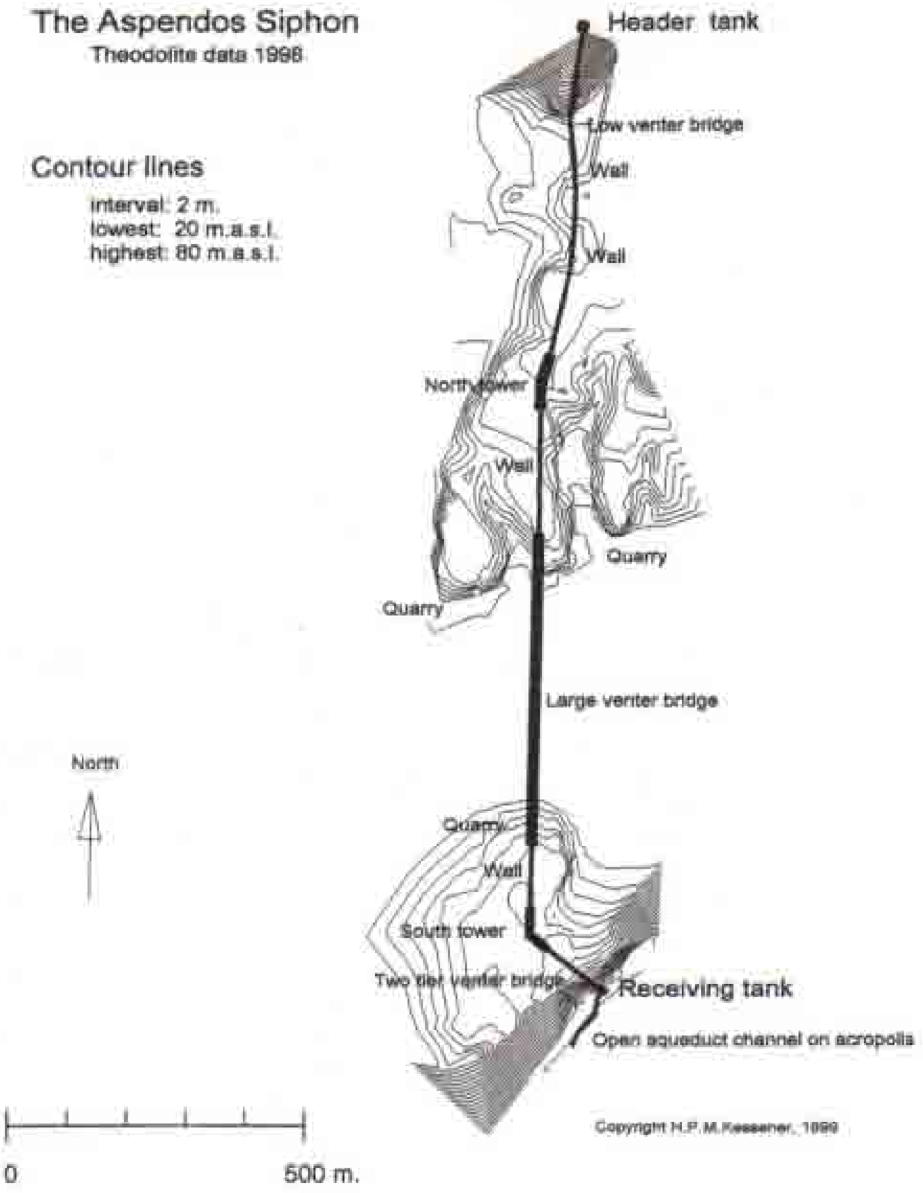

Fig. 22. Survey data of siphon terrain.

the present one, but the course of the siphon has two sharp bends for which two towers would have to be built just the same, while two further bridges, one over 400 m long and 15 m high, would have been needed to cross the depressions between the first *geniculus* and the N tower. In fig. 23B the siphon would run in a straight line from the bottom of the hill at the north towards the receiving tank. There would be no bends, so no hydraulic towers, but the result is a *venter* bridge twice as long as the existing one. In fig. 23C the present curved section in the north would be made straight. Here one would need a much longer first *venter* bridge, about twice as high as the existing one. One might leave out the N tower, replacing it by a slightly curved section — apparently acceptable to the Romans. The S tower could be left out by continuing in a straight line from the large *venter* bridge, but then the ramp up the acropolis would have to have been built much longer, at an angle of about 45° to the contour lines of the edge of the acropolis, which might have necessitated special precautions, while to have constructed a receiving tank at a new location may also have met with objections. It appears then that the Romans did choose the better alternative for the siphon's course, with bends in the pipeline and accepting the fact that they had to built the huge pressure towers. This solution must still have cost the

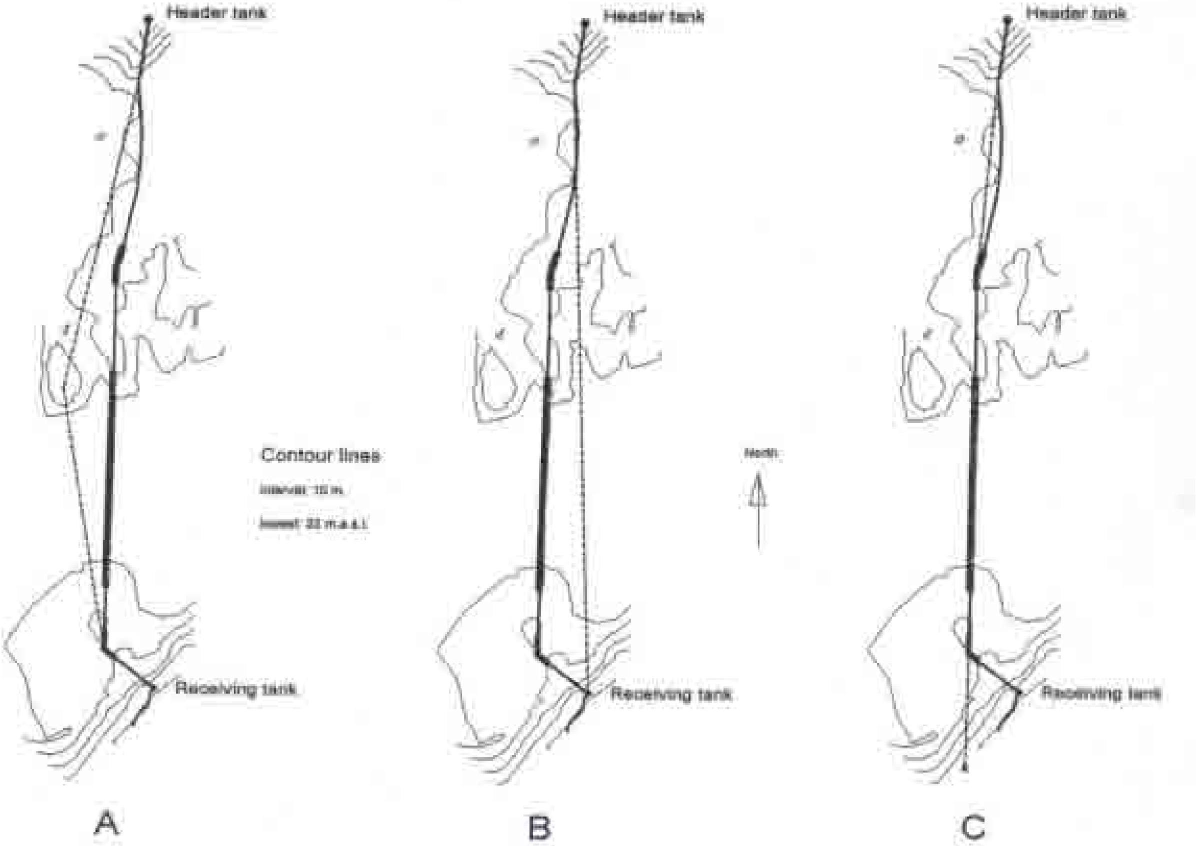

Fig. 23. Some alternatives to the siphon's course.

least effort and expense.[40]

4. 'Retrospective analysis'

General considerations

The question why the engineers decided to construct towers at the horizontal bends remains. Could they have done without the towers and simply gone around the bend at ground level? In attempting to solve this problem, the principal means available are those described by N. Smith:

> The history of technology is an interesting historical discipline not being restricted to documents, pictures and objects for its sources of information. It can resort also to what we might call retrospective analysis. Retrospective analysis can utilise any of four techniques, or combinations of them. They are: mathematical analysis, scale models, full sized replicas, and, perhaps, the original artefact itself (Smith 1991, 115).

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[40] The course depicted in fig. 23A does not seem a realistic alternative, for reasons mentioned. For the course shown in fig. 23B the construction effort in comparison with that of the extant course may be estimated as follows. The volume of material for the main bridge (510 m long, 15 m high, 5.5 m wide, with 47 arches of 7.2 m) is about 18,000 m^3. For both towers together the volume amounts to about 5,500 m^3. The material was lifted up to the present position, and the higher the material had to be lifted, the more energy, thus manpower, this would require. For the main bridge the work done (or gravitational energy gained) amounts roughly to the work that has to be done to lift all the material to half the maximum height of the bridge (15 divided by 2 = 7.5 m). For the towers, which are essentially triangular in shape, this corresponds to one-third of the maximum height (one-third of 40 m). Thus the work needed for the main bridge compares to the work for the towers as 18.000 x 1/2 x 15 to 5.500 x 1/3 x 40, or as 135 to 73, i.e., *c.* 2 to 1. Building a main bridge twice as long as the present one in order to be able to leave out the towers would require 33% more work. The course of fig. 23C seems a realistic alternative, although a new location for the receiving tank on the edge of the acropolis is required, which might not have been possible. Also, the extra bridges in the north and the more extended ramp towards the receiving tank reduce or even eliminate the advantage of leaving out the towers.

Smith shows himself pessimistic about the potential of retrospective analysis "because of the nature and number of assumptions which have to be made". As far as the subject of siphons goes, he is right: of the original artefacts only scant remains survive, hampering mathematical analysis. Scale models face problems of scaling the properties of the material used in the original construction. A full-size replica, for example of the Beaunant siphon at Lyon or of the Aspendos siphon, is out of the question for reasons of cost. In the field of the history of hydraulic technology we have no choice but to resort to mathematical analysis using archaeological findings. For siphons we may extend mathematical analysis with 'experiment of thought'. This comprises three steps:

1) imagine that one had to construct the artefact (a siphon) oneself with the means available at that time;
2) make an inventory of the physical problems that one would encounter in the building process and with respect to proper functioning of the artefact; and
3) propose solutions for those problems in view of the means available at that time.

For the inventory of the physical problems we may resort to present-day knowledge of physics and chemistry, whereas the original builders had to learn by trial and error. When trying to solve in this way the problems encountered, we may develop a set of rules in relation to the design of the artefact and compare them with "what is generally agreed to be the basis of technological and engineering design in not only the ancient world but much later and reaching right down to modern times, that is to say the evolution of experience and expertise into know-how and rules-of-thumb".[41]

In the case of siphons, such 'rules-of-thumb' from 'experiment of thought' may be compared with the classical literature, Vitruvius 8.6. Vitruvius has been criticized as not being wholly reliable, especially on the subject of siphons.

> But Book VIII, devoted to water supply and aqueducts, is not Vitruvius at his best. His explanations are often confused and confusing, the account of siphons being particularly obscure and contentious ... Scholars have speculated on whether some of his sources were in Greek, and how good his Greek was. Others, daringly hazarding their reputation, have wondered whether he had the remotest idea of what he was talking about. (Hodge 1992, 124).

Smith considers the possibility "that the extant versions of Vitruvius' manuscript are not, in fact, a faithful rendition of the original ...", but he adds

> On the other hand, even *if* they are faithful renderings, it is possible that Vitruvius did not fully understand his material himself. And *if* Vitruvius did not know what he was talking about, then it is hardly surprising that we cannot find out ... Conceivably he is rather inferior and presents a less than full or typical picture of contemporary practise. (Smith 1976, 56 and 68).

Whether Vitruvius really *understood* what he was writing about does *not* seem very relevant. The level of scientific knowledge at his time prevented proper insight and comprehension of the physical principles and effects that apply to artefacts as siphons. It seems appropriate rather to regard his manuscript as a set of 'rules-of-thumb' that the builders of aqueducts and siphons had developed by experience over a long period of time. Of course, Vitruvius may have mixed up some of these rules, for example by not mentioning them in the proper sequence. But in this way we have a working method: develop a set of rules by 'experiment of thought', applying the modern state of knowledge, and compare them with Vitruvius' set of rules. One may then attempt to compare the set of rules with the Aspendos siphon and its towers.

Materials

When one set out to design an inverted siphon in Roman times, its location already determined and intended course surveyed, on had to choose the material from which the pipeline will be constructed.[42] The material for pressurized pipelines in classical times was diverse: stone, ceramic (terracotta), lead, and combinations of these are known to have been used.[43] The pipelines were built from prefabricated pipe elements. The lengths of these elements varied, 40-70 cm for terracotta pipes, 50-100 cm for perforated stone blocks, and up to 3 m for soldered lead pipes. The elements were generally fitted together by sliding one pipe end into its larger

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[41] Smith 1991, 118.

[42] For surveying techniques in Roman times see, e.g., Grewe 1998, Hodge 1992, 172 ff. The surveying techniques were highly accurate. The gradient of the Nimes aqueduct, having a very simuous course in mountainous terrain, was as low as 7 cm per km for about 10 km downstream from the Pont du Gard.

[43] Disregarding wood and masonry. See, e.g., Fahlbusch 1982, 65; Hodge 1992, 106-15. In Asia Minor pressure lines were mainly made of stone or terracotta pipes (the lead piping of the Madradag siphon at Pergamon being a notable exception); see also Weber 1904/5.

neighbour, one end of the pipe being slightly narrower than the other (for terracotta pipes), or by means of a male/female socket and flange system (for stone pipes, terracotta pipes). These joints were sealed by means of an expanding oil/quicklime mixture.[44] For lead conduits, cast pipes as well as lead sheets bent into a pipe soldered at the seam were used.[45] The joining up of lead pipes was either done by means of male/female joints, sometimes applying a stone intermediary and sealed in the usual way with the expanding mixture, as was done at Ephesus, or by soldering the pipes together at the joints.[46] Fragments of lead piping from siphons have survived. In 1992 J. Hansen investigated the 33 lead pipes recovered from the Rhône over many years (1570-1825) and now in the museum of Arles. The pipes, 3 m long and 10-12 cm in diameter, were part of a siphon that crossed the Rhône on the river bed, between Arles and Trinquetaille. The pipe elements were soldered together at the joints. Hansen noted that the soldered joints are not to be considered weak spots in the pipeline ("waren nicht das schwache Glied der Kette").[47]

We may thus divide the pipe elements at our disposal into two categories: (1) lead pipe elements that are soldered together at the joints, and (2) pipe elements with joints that are sealed with the classic oil/quicklime mixture. The first category, the lead pipes with soldered joints, make up pipelines in the modern sense: the joints are as strong and resistant to pulling forces as the pipe elements themselves. The second category make up pipes that are not very resistant against pulling forces, the tensile strength of the sealing material in between the pipe elements being the only restriction. This tensile strength has not yet been thoroughly studied: it is estimated to be less than 1/10th of the value of its compressibility, and much less than that of stone, lead or terracotta, the materials of which the pipe elements are made.[48]

Static pressure

The resistance of a pipe against pressure from the inside is determined by the tensile strength of the material(s) the pipe is made from. Theoretically a pipe can burst in two ways: lengthwise or perpendicular to its longitudinal axis. For a homogeneous material the tensile strength is equal in all directions. From this it follows that, if the inside pressure gets too high, first category pipes will burst along their length, like a sausage in a frying pan.[49] Not so for second category pipes, where the tensile strength in lengthwise direction, because of the sealing material between the pipe elements, is much smaller than its counterpart perpendicular to the pipe axis. These pipes will burst at the joints long before the pipe wall gives way to pressure.

When constructing a siphon from pipe elements of the second category, one has to take into account this inherent weakness of the pipeline. A minor displacement at one of the joints will cause leaking and impairment of the siphon. Under what circumstances will this happen, and what can be done to prevent it?

Let us imagine an inverted siphon made of pipe elements of the second category. Assuming that the siphon is filled with water, without flow, we have to consider only the effects of static pressure. The static water pressure at any point in the pipeline is determined by the vertical distance between that point and the free surface of the water. For a pipe element in a straight section of the conduit, the water exerts an outward force on the inner wall along the whole circumference of the bore, resulting in a zero net force, and nothing will happen provided that the tensile strength of the material is high enough. Except for gravitation (the weight of the element itself and the water it contains) the pipe element does not experience any net forces. At the joint

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[44] Malinowski 1996 discusses sealing materials for aqueducts and pipelines under pressure.

[45] Cast pipes: Pergamon, Ephesus, possibly Alatri. Soldered pipes: e.g., Lyon, Arles, Vienne. See Hodge 1992, 307-15; Fahlbusch 1982, 68-80.

[46] Hodge 1992, 110; Tölle Kastenbein 1992. Soldered joints: Hodge 1992, 156, 314; At the Madradag siphon at Pergamon the cast pipes were presumably joined by lead sleeves slid over the ends (Fahlbusch 1982, 70-71).

[47] Hansen 1992, 478. A finding of a segment of lead pipe, 90 cm long, diameter 31-34 cm, which is all that remains from an amount of 10 tonnes of lead recovered from the Rhône at Vienne as late as 1980 and subsequently 'recycled' by melting it down, indicates that a lead siphon crossed the Rhône at that point as well (Burdy and Cochet 1992).

[48] Malinowski, pers. comm.

[49] Both for cast pipes as well as for pipes made from lead sheets with a continuous soldered seam as strong as the pipe wall itself (which depends on the quality of the soldering; see below). Resistance of lead pipes to static pressure has been discussed by Fahlbusch 1982, 78-80, see also Hodge 1983, 211-12 and 1992, 429 n.49. It must be noted that if the soldering of the seam and of the jointing between the pipes is inferior compared to the material of the pipe wall, the conduit will burst lengthwise unless the soldering of the jointing is more than twice as weak as that of the seam — which does not seem probable in view of Roman soldering techniques and of Hansen's observations.

between two neighbouring pipe elements of equal bore there will be no force in longitudinal direction along the pipeline, as there is no inside surface area exposed to the water pressure in that direction.[50] This is all quite obvious, and repeats itself at every joint as long as it continues in a straight line, until we reach a bend.

The element that makes up the bend, the *geniculus* element, will experience a net force directed outward along the bisector of the angle of the bend: $F = 2^*p^*A^*\sin(\alpha/2)$, where p is the inside pressure in N/m^2, A is the cross section of pipe in m^2, and α is the angle of the bend. It is easily understood that for a U-turn, with α equal to 180°, this force is at its maximum, while for a straight section, with α equal to 0°, the force is zero. For an intact pipeline, the force exerted on the *geniculus* element will be transmitted to neighbouring elements to the extent that the sealing in between keeps the elements bonded together. If one wants to keep the pipeline intact, the *geniculus* element must be kept from being pushed out of position — that is, a counteracting force must be provided for. For a pipeline made of elements of the first category, lead pipe elements soldered together, this does not apply: no net force except gravity will be exerted on the *geniculus* since the section that makes up the bend is bonded to the neighbouring sections by the soldering that transmits forces away from the bend to neighbouring elements. The pipeline as a whole must be fixed somewhere but it is not important at what point. Before any displacement of the *geniculus* section occurs, the conduit will burst lengthwise at some point. For pipelines of the second category however, special precautions have to be taken, and these precautions differ for horizontal and vertical bends.

Vertical bends

Vertical bends occur where the downward course of the pipeline changes to horizontal at the start of the *venter*, and from horizontal to sloping upward at the end. The Aspendos siphon counted 6 vertical *geniculi*.[51] At the *geniculus* of the north ramp of the N tower the pipeline slopes upward at about 30° from horizontal. The force exerted by static water pressure amounts to over 12,500 N, the equivalent of a weight of about 1275 kg.[52] The component directed vertically downward onto the terrain on which the element is positioned corresponds to a weight of 1105 kg, to which must be added the weight of the *geniculus* itself as well as some part of the collective weight of the pipe elements on the sloping ramp. The downward force exerted by the first pipe element on the *venter* next to it is caused just by the weight of the element itself and the amount of water it contains only. For the large perforated stone blocks as were used at Aspendos this amounts to a few hundred kilograms, and much less if ceramic pipes were used. This means that the downward force or pressure exerted on the terrain by the *geniculus* element is much larger than the force exerted by the horizontal pipe element next to it. If the terrain is not firm and tends to settle, which may happen if it does not consist of solid rock or if no special precautions have been taken, it is more likely to settle underneath the *geniculus* element, which may result in dislocation with respect to its neighbouring element. The joint in between may become stressed, and the pipeline may start leaking. Thus the very first joint between the *geniculus* element and the horizontal part of the siphon is at most risk. This applies to both *geniculi*, at the start of the *venter* as well as at the end.

What can be done to prevent this? Obviously one can build a solid foundation stable enough to prevent any dislocation downward. This may not always be possible, depending on the conditions of the terrain. Alternatively, one may reduce the force per surface area by constructing a *geniculus* element of large dimensions compared to the horizontal pipe elements. In this way the difference in pressure exerted on the terrain by *geniculus* element and by the horizontal elements will be diminished. This is all the more the case for ceramic pipes as they are of smaller size than the stone blocks. One may of course apply some means of attachment between the *geniculus* element and its horizontal neighbour, metal cramps for example, but then the next joint, between the first and the second horizontal element, will be at risk, and this element will have to be attached to its neighbour, and so on.

Horizontal bends

In the case of horizontal bends one encounters a similar but slightly different situation. Again the static pressure exerts a force on the *geniculus* element which tends to move the element outward from the bend. For a siphon 40 m deep at a bend of 55°, as is found at Aspendos at the S tower, this force would be the equivalent

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[50] Or, alternatively, as the force exerted by the water pressure perpendicular to the plane between two elements is balanced by its counterpart in the neighbouring element.

[51] In general, vertical bends may occur also at intermediate high points in the *venter* as well, as for example in the Madradag siphon at Pergamon, which has two such *geniculi*.

[52] The pressure p corresponding to a water column h meter high: $p = \rho^*g^*h$, where ρ is the specific weight of water = 1000 kg/m^3 and g is the acceleration of gravity = 9.81 m/sec^2. Assuming a pressure of 40 m of water column, $F = 2^*1000\ kg/m^{2*}9.81 m/sec^{2*}40m^*(\pi/4)^*(0.28\ m)\ 2^*\sin(15°) = 12{,}507$ N.

of a weight of 2275 kg. Apart from the bonding strength of the sealing material, the *geniculus* element will be prevented from sliding away only by the counteracting friction between the element and the terrain, a force which is related to the weight of the element. The *geniculus* has to be backed up by some additional factors, such as by adding weight to increase friction, or by some structure with a stable foundation which 'pushes back'. One might again consider connecting the elements to each other, but then one has to connect all in this fashion.

Thus the conduit of the second category is in danger of cracking, especially at the joint between the *geniculus* element and the first element on the *venter*, and in the case of horizontal bends at both joints adjoining the *geniculus* element. At all points where the pipeline is not perfectly straight, at any bend, whether horizontal or vertical, small or large, the static pressure exerts a force that endangers the joints. What measures can be taken? First, one could secure every single pipe element onto the terrain. This may be accomplished by burying the pipeline, a method that Greeks often practised. Settling of the terrain, however, would allow displacement of the pipe elements, causing the joints to crack, which occurs more readily in the case of high static pressure conditions. An improved method, as was practised in the high-pressure pipeline at Pergamon, is to secure every pipe element in a large perforated stone and then bury the entire pipeline.[53] We could also connect each element to its neighbour, an early example of which may be seen in the pressure pipeline at Knossos,[54] where the heavy terracotta pipes excavated by Evans over 60 years ago are equipped with 4 'handles' suitable not only for carrying but also for tying them together. At Patara the pipe blocks of the Delik Kemer siphon were prevented by metal clamps from moving either horizontally or upward.[55]

Another method to cope with problems caused by static pressure is to build the pipeline in straight sections, avoiding horizontal bends as much as possible. When the course between the header tank and receiving tank cannot be drawn in a straight line, sharp bends are needed. This reduces the danger points to specific locations where special precautions (weights, sand ballast) must be taken. One might also reduce the pressure inside the pipeline at the horizontal *geniculus* by locating it at elevated position, or one might even dispense with the *geniculus* altogether by bringing the pipeline up to the level of the hydraulic gradient. Here one might incorporate a receiving tank which also serves as a header tank for the subsequent section. This is clearly what was done at Aspendos,[56] but we must ask why this elaborate solution was chosen if the same effect could have been achieved in an easier and cheaper manner by placing extra weights and back-ups at the horizontal bends.

To summarize: static water pressure constitutes a hazard to siphons made out of pipelines of the second category, which is not the case for lead pipelines of which the joints are soldered together (the first category). Problems arise especially at bends, either vertical or horizontal; of these the horizontal bends are the more difficult to deal with. The danger caused by static pressure consists of the cracking of the joints at the *geniculus* element. Steps to deal with these problems consist mainly of preventing dislocation of the *geniculus* elements with respect to the neighbouring elements. For horizontal *geniculi*, the elimination of the bends altogether by bringing the pipeline up to the hydraulic gradient must be regarded as an option.

Dynamic forces

So far effects of static water pressure have been discussed, without considering possible effects of water flow. We now have to consider the forces exerted on the pipe by the flow. For straight sections of a running siphon, the force to be considered is the force between the inner wall of the pipeline and the water (the 'drag'). The overall effect of this drag is the loss of head between the header tank and the receiving tank. At Aspendos the loss of head is 14.5 m over a length of 1670 m for the siphon. This is about 0.008 N/cm^2 per meter of conduit. If each pipe block were 50 cm in length, the net force exerted on each pipe element by the drag of the flow would be the equivalent of a weight of 267 grams, an amount we may safely disregard.

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[53] The Madradag siphon at Pergamon, deepest of all classical siphons, has two intermediate high points on top of consecutive hills. At the vertical bends at these intermediate high points, the force from static pressure, directed upward, was counteracted by the weight of the perforated stones, which were of enlarged dimension at these points (Fahlbusch 1982, 73).

[54] Fahlbusch 1987, 135.

[55] Stenton and Coulton 1986, 56.

[56] It is remarkable that in the course of the Aspendos siphon there is a straight section of pipeline between the two towers and between the S tower and the receiving tank on the acropolis, but that the section between the bottom of the hill of the header tank and the ramp of N tower has a slightly curved trajectory. It is not clear in what way horizontal forces in this section at Aspendos were dealt with.

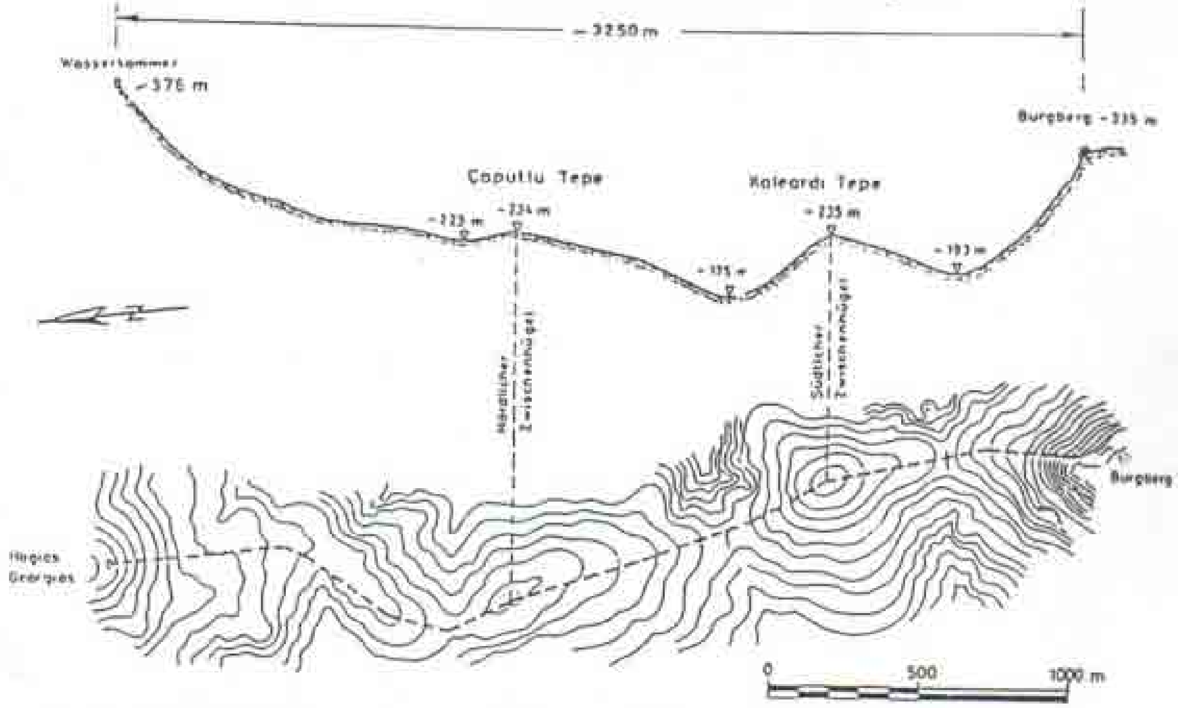

Fig. 24. The Madradag siphon at Pergamon (Fahlbusch 1982, fig. 42).

At bends, the direction of flow is changed, whereby a force is exerted on the *geniculus* element. Hodge refers to this force as 'inertial thrust'. This force is necessary to induce the change of impulse in order to go round the bend. In the case of Aspendos, where there is a bend of 55° at the S tower, the force would amount to almost 60 N. This force is small compared to the forces exerted by static water pressure, and the effect of this force may also be disregarded.[57] Of the three effects discussed above, static pressure, drag of flow, and inertial thrust, static pressure is the main and only factor that seriously threatens the conduit at the bends. Yet one more factor must be considered: air.

Air bubbles and air pockets

As we have seen, the Aspendos siphon, with a closed conduit running over the top of the towers at present height, would not start up due to the air pockets which occur in the conduit on the down ramps. In general, air pockets will accumulate during the filling procedure on the downstream side of high points, resulting in a loss of head which equals the sum of the vertical heights of the compressed air pockets (difference in height between the top and bottom of the air pocket).[58] If this loss of head is greater than the head available, the siphon will not start up. To solve this problem, one may either bleed air out of the conduit by means of a valve near the high point (which valve should be able to withstand the available pressure when it is closed), or one may raise the high point to the hydraulic gradient line and provide for an open tank, as at Aspendos.

The situation at Aspendos may be compared with two other classical siphons which incorporate high points: the Madradag siphon at Pergamon,[59] with two intermediate high points but no hydraulic towers (fig. 24), and the siphon of the Yzeron aqueduct at Lyon,[60] equipped with one hydraulic tower at Craponne (figs. 25-26). For the Madradag siphon it can be shown that, because of the elevated pressure, air pockets at the two high points (125 and 105 m below the hydraulic gradient line) would be compressed to such an extent that the loss of head was only 8.5 m of the available 37 m, so that at start-up the siphon operated at about 90% of full capacity. Moreover, due to entrainment of air at the bottom of the air pockets into the water flowing towards the receiving tank, occurring at a faster rate than entrainment of air into the conduit at the header tank, the air pockets would be purged out and the siphon developed to full capacity on its own, without special precautions taken such as bleeding of air by means of valves at high points.[61] In the case of Yzeron, a

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[57] Considering the low velocity of the water in running classical siphons.

[58] See, e.g., Corcos 1989; Jordan 1984; also Falvey 1980.

[59] See Garbrecht 1978, 1987; also Fahlbusch 1982.

[60] Burdy 1991.

[61] Since the slope of the conduit at the header tank is much steeper than at the downstream side of the high points. For a general discussion of the entrainment of air in closed conduits see Falvey 1980, 48-51, as

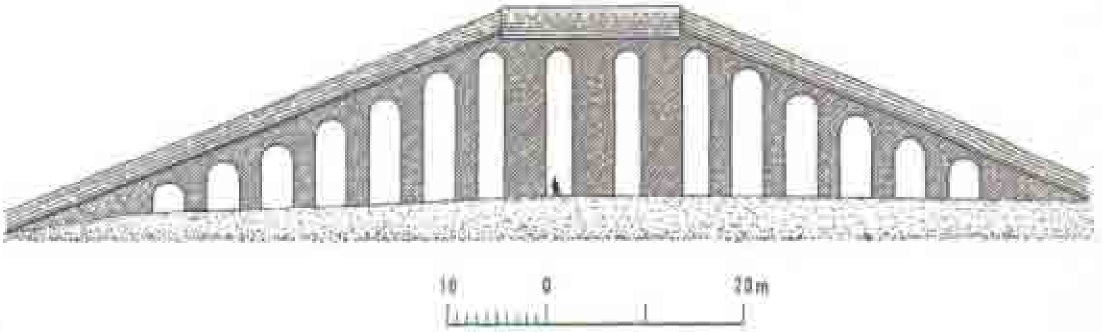

Fig. 25. Hydraulic tower at Craponne (reconstruction, Haberey 1972, 156).

high point in the siphon's course could not be avoided (see fig. 27, e.g. alternative course). The siphon, without a tower, would have stopped functioning altogether after a period of initial start-up, as air entrained at the header tank would now accumulate at the high point, decreasing the available head to zero. The tower at Craponne, by which the air pocket was released, must be regarded as an obligatory part of the system. At Aspendos the towers had to be equipped with open tanks reaching up to the hydraulic gradient, otherwise the siphon would not have started at all. But at Aspendos the towers constitute artificial high points not dictated by conditions of the terrain. The Aspendos towers were built at horizontal bends in the pipeline, but there are several horizontal bends in the Yzeron siphon and in the Madradag siphon, lacking towers at those spots.[62]

Water-hammer

Apart from problems caused by air pockets at high points, the presence of air in closed conduits may give rise to several more effects. One of these is water-hammer, defined as a pressure surge in the conduit caused by a sudden change in the velocity of the water flow.[63] Such a change may result in a shock wave running up and down the conduit at high speed. It may be caused by a sudden interruption in water flow, such as by closing a valve. In daily life today it is familiar from the banging caused by an improper household tap. If the water column moving upstream from the valve comes to a sudden halt, the counteracting force needed to stop the flow gives rise to a shock wave moving upstream inside the conduit. The magnitude of this surge depends on the time span in which the flow decreases from full flow to zero. For a given conduit and flow velocity, the shorter the time of closure, the larger the shock wave. Air pockets in the conduit may complicate matters, as the water still moving upstream from an air pocket will compress the air pocket, while the water downstream from the pocket has already come to a standstill, and that may give rise to superimposed shock waves.

It is not known, however, that classical siphons were equipped with valves or shutters.[64] It does not make sense to shut off an inverted siphon at the *venter*, nor at the receiving tank, since the siphon may be stopped very conveniently at the header tank by preventing water from entering the conduit. The opening in the right-hand wall of the Aspendos header tank may have served to divert water when the siphon had to be interrupted. One may also prevent water from entering the header tank by diverting it out of the open channel somewhere upstream from the header tank, or even at the start of the aqueduct. Emptying a siphon that has come to a standstill, for example for maintenance or repairs, should be regarded a separate topic.[65]

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well as fig. 29. For the entrainment of air at the header tank of the Madradag siphon, see also Garbrecht 2000, I, 211-15.

[62] Yzeron: 4 horizontal bends; Madradag: 5 horizontal bends.

[63] See, for instance, Falvey 1980, 61-65; Schnapauff 1966.

[64] For a general discussion of valves in relation with classical siphons, see Hodge 1983, 202-8. For valves in modern siphons, especially air valves and vents see, e.g., Falvey 1980, 57-77.

[65] In many stone pipelines, funnel-shaped holes connecting the inside of the conduit to the outer surface on the top of the pipe elements may be noted. Sometimes these holes were made on the joint, as described by Lanckoronski and observed for at least 3 pipe elements found at Aspendos (Lanckoronski 1890, 124, fig. 98; pers. obs.). Similar holes have been found, e.g., in the double siphon of Laodikeia ad Lycum, the stone pipeline at Susita (Israel), the Delik Kemer siphon at Patara, the stone siphon at Kybira (Laodikeia ad Lycum: Weber 1898, 6; Susita: Peleg 1991 and Meshel *et al.* 1998; Patara: Stenton and Coulton 1986, 50-51; Kybira: pers. observation 1999). The holes were closed off by stone plugs fitted with plaster, probably of the expanding mix type. I have observed a 90 x 90 cm stone pipe block with closing plug *in situ* at the Roman Hamam Museum in Ankara, and several stone plugs *in situ* on the twin pipeline of Laodikeia ad Lycum. Similar holes are known to exist in terracotta pipelines (Tölle-

Although the sudden operation of valves would give rise to pressure problems, this option will not be considered for classical siphons since indications for valves on siphons are lacking. There are, however, two more conditions that may give rise to water-hammer effects or shock waves in closed conduits, and both are related to the presence of air in the conduit. The first is caused by air pockets which may accumulate at local high points. These high points may not be recognized as such since they are caused by irregularities in the inner conduit's diameter or by minor variations in the levelling of a horizontal segment of the pipeline. Vertical holes in stone pipelines that are closed with stone plugs shorter than the length of the hole might constitute such local high points. Air may accumulate at such point to form a pocket beneath which water will flow through; the effective cross-section available for water flow may be reduced by the pocket, and the velocity of the water below it will increase. As long as the air pocket is stationary, nothing much will happen, but problems arise when, at the downstream end, parts of the air pocket are separated and transported away with the flow, reducing the volume of the air pocket, or when new air is transported from upstream, adding to the volume of the air pocket. The velocity of the water beneath the air pocket is suddenly changed, whereby the column of water upstream from the pocket accelerates and decelerates, giving rise to pressure surges. This problem becomes worse with an increasing air to water ratio in the conduit.[66] Conduits with static pressure conditions below 5 bar are most at risk. Conduits made of terracotta or stone elements with irregular or varying internal diameters are more susceptible to such problems than lead pipes.

A second, and worse, problem arises from leaks in the conduit. Leaks will occur more often in conduits made of stone or terracotta elements than in those made of lead, by the mere fact that the number of joints is greater. But the sealing of the joints of stone pipe blocks, and to a lesser extent of ceramic pipes, with Vitruvius' lime-oil mix must have been an awkward task, as the joints disappear from view as soon as the blocks are pushed into position and inspection to see if the sealing material is properly distributed along the joint is not possible. One can only skim the inside of the joint to remove excess sealing material and create a smooth surface. The joints can only be tested for their impermeability and resistance to pressure after the siphon is finished and put to the test. The Aspendos siphon counted over 3000 sealed joints, and leaks must have occurred; indeed, they did occur, as shown by massive calcareous incrustations hanging from the underside of one of the arches of the large *venter* bridge. The soldered joints of lead pipes were much less prone to leaking as the soldering mixture was applied from the outside, which greatly facilitated inspection and repair.

If an air bubble or air pocket, moving with the flow, passes by a leak, the air will be released into the atmosphere, which occurs at a much faster rate than the leaking of water. Hence the water column upstream from the leak will be accelerated until the air pocket is completely released, after which it is decelerated again.[67] This procedure gives rise to water-hammer effects, the magnitude of which increases with static pressure inside the conduit. The release of the compressed air into the atmosphere may be accompanied by hissing noises and water sputtering out, which no doubt made the onlooker fully aware of the elevated air pressure inside the conduit.[68] For the Aspendos siphon, at a static pressure of 40 m of water column, a 12-mm hole (about 1 cm^2) will cause water to leak from the conduit at about 2 l per second. Air from a compressed air

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Kastenbein 1991). The purpose these holes is not clear; it has been suggested that the holes served as drain cocks to empty the system when maintenance was required, or as rodding holes for clearing blockages (Hodge 1992, 37-39); also their possible use as safety valves, the plugs intended to blow off in case of a dangerous pressure surge, has been mentioned (Stenton and Coulton, ibid.). Fahlbusch in turn proposed (1989) that the holes were cut to permit removal of calcareous incrustations by means of hot vinegar. Some associate the holes with Vitruvius' *colliquiaria*. See for a general discussion see Hodge 1992, 37 ff. and 154 ff., Tölle-Kastenbein ibid. The holes appear to occur in the top of the pipeline at Patara and at Laodikeia, in most instances well above the bottom of the siphon, which does not square with draining purposes. The Laodikeia pipelines had been largely preserved intact except for a stretch of the right-hand conduit at the foot of the acropolis. In 1999, however, a stretch of several hundred meters of the left-hand conduit was destroyed in connection with the construction of a local drainage/irrigation system, the pipe elements and the massive stone foundation blocks left lying about in sad heaps along the original course.

[66] For a general discussion see, e.g., Schnapauff 1966.

[67] Depending on the location of the leaking spot, the downstream water column may decelerate and accelerate as well, resulting in similar effects.

[68] A similar occurrence on a lesser scale may be experienced when a partly-filled garden hose, with a closed valve at one end and connected to a pressurized water supply at the other, is opened, or when a household tap is turned on after repair works that required disconnection from the public supply and draining of the conduits.

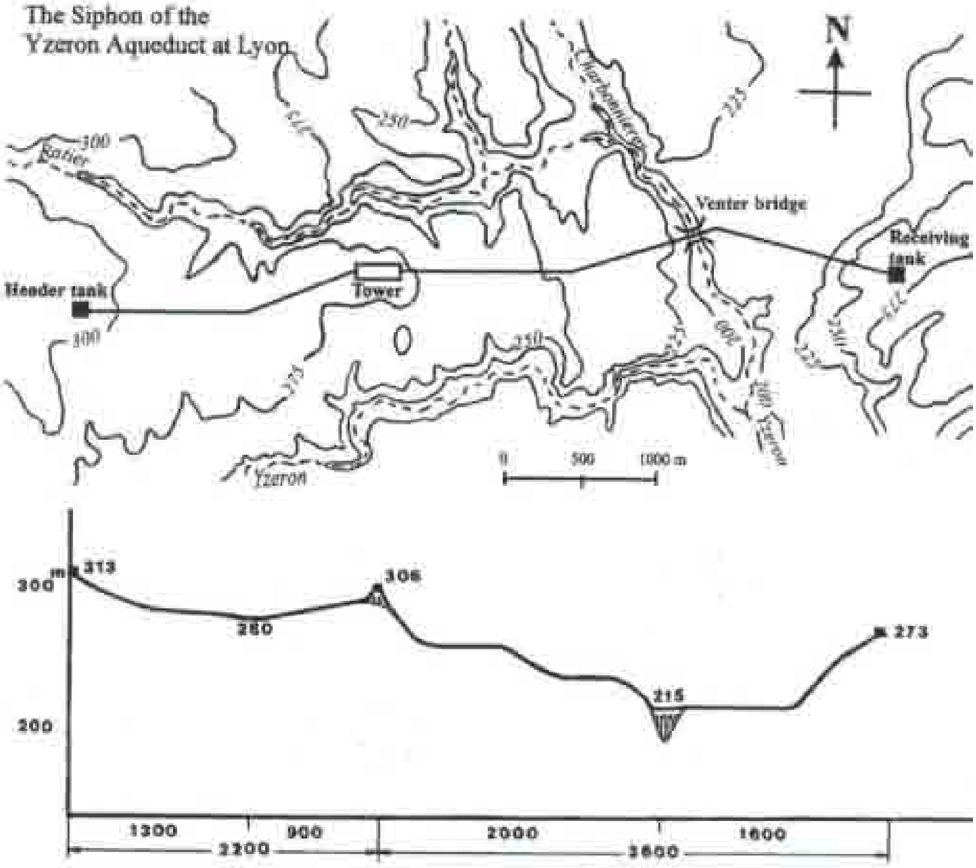

Fig. 26. Siphon of the Yzeron aqueduct (profile of siphon: Burdy 1991, 101).

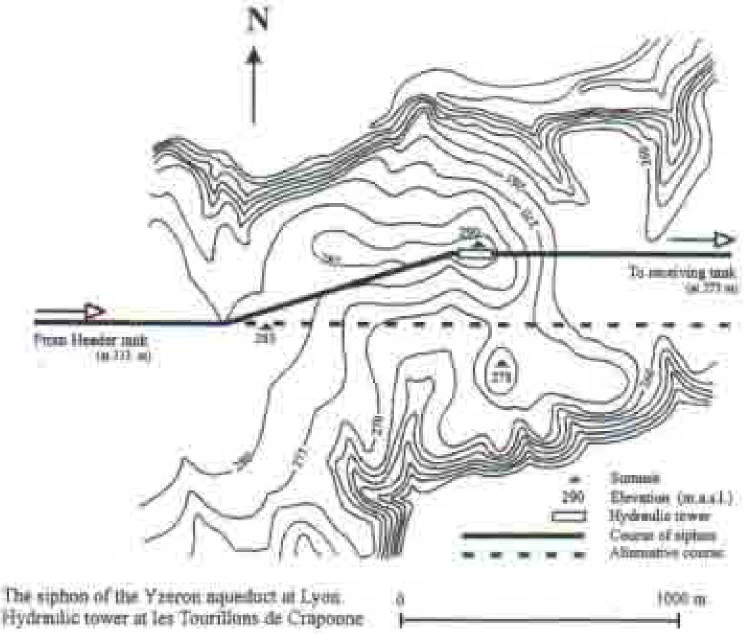

Fig. 27. Topography at les Tourillons de Craponne.

pocket will be released into atmosphere at a rate of about 50 l per second through the same orifice. As soon as the air pocket is released, a pressure shock of over 3 bar may arise, almost doubling the pressure inside the conduit.[69] The generated shock wave runs along the pipeline, and at bends of pipelines made of elements of the second category (stone and terracotta alike), these waves cause a short and sudden increase of the force which tends to dislocate the *geniculus* element, on top of the force from static pressure. Such increases may occur repeatedly in some sort of banging and vibrating, exceeding the counteracting forces applied to meet static pressure. Once one of the joints starts leaking, the water flow in the conduit will be increased because of the water escaping, and more air may be mixed with the water at the header tank to be transported through the conduit, adding to the occurrence of shock waves damaging the pipeline. In the end the leak may be increased to such an extent that the header tank is emptied more quickly than the aqueduct brings in water, whereby large air pockets periodically enter the conduit. The siphon now enters the last phase of its destruction, when all water that enters the conduit at the header tank comes out at the destroyed point alternating with pressurized air pockets noisily escaping into atmosphere. Also, the pressure shocks may have destroyed a weak pipe element somewhere along the line, and that would only speed up the process of destruction.

For lead conduits with soldered joints, the bends do not constitute danger points since the joints and the pipe walls are of equal strength. Such pipelines are less liable to damage by water hammer than their stone or earthenware counterparts, and the bends are no favoured spot for damage. But once they leak, these pipes offer the same intermittent hissing noises of escaping air and squirting out of jets of water. It must have been a common experience, and when Ovid tells of Pyramus killing himself by the sword thinking that his beloved Thisbe had fallen victim to a lioness, he writes describing the blood pounding with the heartbeat (*Met.* 4.122):

... cruor emicat alte	... blood squirted high,
non aliter quam cum vitiato fistula plumbo	no different than when a water conduit, with damaged lead,
scinditur et tenui stridente foramine longas	tears open and through the hissing crack long jets of water
eiaculatur aquas atque ictibus aera rumpit ...	are propelled and with beating blows burst into the air ...

Leaks in the conduit jeopardize siphons made of elements of the second category, the worse the deeper the siphon is. Intake of air at the header tank cannot be avoided entirely; already at start-up, problems will arise if the conduit is not completely watertight, and that is hardly feasible. In any event, water-hammer effects may arise and threaten the system. All bends, vertical but especially horizontal bends, constitute danger-points. The obvious remedy is to get rid of the danger points, that is, build in straight sections and avoid sharp bends. Vertical *geniculi* cannot be avoided, and the *geniculi* can and must be secured on the terrain, either by a solid foundation or by making the *geniculus* itself of such dimensions that it is immovable and can withstand the pressure blows. Sharp horizontal bends, much more difficult to protect against intermittent water-hammer banging, may be dispensed with all together by dividing the siphon up at the bends, and that can only be done by bringing the water to its "natural level". This is what was done at Aspendos.

Thus the hydraulic towers at Aspendos and the tower at Craponne were built for completely different reasons. At Aspendos the towers were meant to avoid damage to the conduit at horizontal bends, damage caused by water-hammer in relation to the characteristics of the pipeline, it being made of stone elements fitted together with plaster. The tower at Craponne was built to ensure that the siphon would function at all, since without it would have come to a standstill soon after start-up due to air pockets at the unavoidable intermediate high point. In both cases the problems were caused by air. In both cases the ancient engineers planned their design ahead, obviously from a knowledge of what had to be done.

We may therefore enumerate a set of 'rules-of-thumb' for building siphons.
For siphons built from elements of the second category (plastered joints):

- Build in straight sections as far as possible. Secure the elements to each other to prevent displacement sideways (by clamps, walling). Avoid high points in the conduit.
- For vertical *geniculi* build well-secured foundations to prevent downward dislocation of the *geniculus* element with respect to neighbouring elements. If this is not possible, make the *geniculus* element of enlarged dimensions to compensate for weakness of the terrain.
- Avoid horizontal bends as far as possible; if unavoidable, try to fix the *geniculus* element immovably on the terrain and/or to each other, or eliminate the horizontal *geniculus* entire-

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[69] Ignoring factors that may have a diminishing effect such as the presence of much air in the conduit, in the Aspendos siphon the water-hammer caused by a leaking orifice of 12 mm-diameter might result in sudden pressure increases of almost 100%. The calculations on which these estimates are based are available from the author.

ly by constructing a tower bringing water up to the hydraulic gradient.
— Fill the siphon slowly to prevent water-hammer effects at start-up.
— Try to seal leaks to reduce water-hammer effects.

For siphons built from elements of the first category, lead pipes soldered together, these precautions do not apply. Horizontal bends are not much of a problem (the Yzeron siphon counts no less than 4 horizontal bends, fig. 27). When positioned on a slope, the conduit may have to be prevented from sliding from its weight, or bending sideways because of lead's natural flexibility, by fixing the pipeline on the terrain at regular intervals or by encasing it into concrete. These conduits are suitable for crossing a river by being submerged.[70] One has to avoid high points, however, as they may interfere with the functioning of the siphon because of air pockets stopping the flow. If unavoidable, one should consider the option of building a tower and splitting up the siphon.

I shall reserve for another place a detailed discussion of Vitruvius 8.6 and the problem of the identification of that *hapax legomenon*, *colliquiaria* or *colliviaria*. Clearly it was known to Vitruvius that air was the agent that caused the problems (*spiritus*, 8.6.6 and 6.9), and that at the start-up of second category siphons, if it was not carried out with the utmost care (8.6.9), these problems most assuredly would arise due to air escaping from unavoidable leaks. The loss of water due to leaks was not the problem, but the water-hammer effects resulting from air escaping, threatening the integrity of the entire siphon. Vitruvius' treatise on siphons may be regarded as clear and coherent, distinguishing between pipes made from elements of the second category (8.6.8-9) and those of the first category (8.6.4-7). His set of 'rules of thumb' corresponds well with our own set of rules derived from today's insights and knowledge. Air is the problem to deal with, and Vitruvius mentions air in relation with both types of siphons. For the second-category siphons, air may destroy the siphon at the bends, at any bend, and especially at horizontal bends, because of the water-hammer effects due to leaks. And leaks can not be prevented in second-category siphons; one can only attempt to seal them by introducing ashes into the conduit before start-up (8.6.9). The deeper the siphon is, the worse this problem becomes. For shallow siphons, with lower pressure and lesser water-hammer blows, one could suffice with sand ballast and weights or bands in case horizontal bends could not be avoided. In Aspendos, because of the elevated pressure, the solution with hydraulic towers was chosen — a solution that perhaps was unique at the time and applied first at Aspendos. Vitruvius wrote his book VIII in 23 or 22 B.C.,[71] long before the Aspendos siphon was built, so he can not have known this specific situation. The Yzeron siphon is dated sometime in the last two decades B.C.. It is estimated to be the first of the four great Lyon aqueducts,[72] and the chances are that Vitruvius knew of its existence. When he refers to air for siphons of the first category, soldered lead conduits, he says that something must be added in the *venter* to ease air pressure. Vitruvius does not refer to damage or the like, which he expressly does in relation with the second-category siphons. He simply states that something must be added to relieve air pressure. And it is air, in a pocket, and under pressure, that would have prevented the Yzeron siphon from functioning had the "Tourillons" tower not been built. Thus Vitruvius' *colliquiaria* may be related to the Craponne tower of the Yzeron siphon.

5. Conclusion

The Aspendos aqueduct does not stand out for its length nor for the size of its bridges and tunnels. It transported water at a modest 65 l per second, surely not the highest flow, even in

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[70] See, e.g., Hodge 1992, 157. Note that submersion protects the lead water conduits against pressure problems because of counteracting hydrostatic pressure from the river water. If the conduit holds against inside pressure at the river's edge, it will also hold when laid on the river bed.

[71] Fensterbusch 1964, 5.

[72] Burdy 1991, 214-15.

this region. Its crossed the depression separating city from mountains by means of an inverted siphon made of stone pipe blocks, not uncommon at the time. But the siphon incorporated two huge towers, a provision not known elsewhere. The towers, with open tanks on top, took the bends out of the siphon's course, thereby countering the effects of water-hammer (and of static pressure as well), pressure shocks that doubled the inside pressure in the Aspendos siphon and were related to the presence of air escaping from the conduit through unavoidable leaks. When a conduit is made from stone or earthenware, these pressure shocks endanger siphons, especially at horizontal bends. At Aspendos the engineers chose to eliminate bends altogether, since the alternative of a siphon with no horizontal bends could only be realized at a cost surpassing that of building the towers. The Roman engineers knew very well what dangers threaten siphons and they knew what to do. The Aspendos towers may therefore be regarded as an outstanding example of Roman hydraulic technology.

Vitruvius, who lived long before the Aspendos siphon was built, adequately described in his book VIII, chapter 6 the problems encountered when building siphons. He distinguished between two categories of pipelines, lead pipes soldered together, and conduits made from pipe elements joined and sealed with a lime-oil mixture. Air may endanger the functioning of both categories of siphons, but it does so in different ways. For siphons of the first category, made from lead pipes with soldered joints and no leaks, the danger is that air at intermediate high points stops water flow altogether. For siphons of the second category, of stone or ceramic pipe elements, with unavoidable leaks, the conduit is prone to be destroyed, especially at horizontal bends, by water-hammer effects caused by air escaping from leaks. Vitruvius mentions both dangers, and clearly describes what has to be done. Vitruvius' *hapax legomenon* "*colliquiaria*" may be related to the hydraulic tower of the Yzeron siphon at Lyon, where it served as a provision that assured that the siphon, with an unavoidable intermediate high point, would function at all. The situation at Aspendos, where the engineers decided to build towers, instead of adding weights or bands, to cope with destructive water-hammer forces at horizontal bends, was not known to him, but, as in our time, technology evolved, and large-scale projects required new solutions for old problems, problems known to the Aspendos engineers as they had been to Vitruvius.

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Bibliography

Akurgal, E. 1970. *Ancient civilisations and ruins of Turkey* (7th edn., Istanbul).

Bean, G. E. 1979. *Turkey's southern shore* (2nd edn., London).

Burdy, J. 1991. *L'aqueduc romain de l'Yzeron* (Lyon).

Burdy, J. and Cochet, A. 1992. "Une date consulaire (213 après J.-C.) sur un tuyau de plomb viennois," *Gallia* 49, 89-97.

Corcos, G. 1989. *Air in water pipes* (Berkeley, CA).

Fahlbusch, H. 1982. “Vergleich antiker griechischer und römischer Wasserversorgungsanlagen,” *Mitt. des Leichtweiss-Institut für Wasserbau* Heft 73.

Fahlbusch, H. 1987. “Elemente griechischer und römischer Wasserversogungsanlagen; Aspendos; and Side,” in *Die Wasserversorgung antiker Städte* II, 133-64, 172-75, and 218-21 (repr. 1991, Mainz am Rhein).

Fahlbusch H. 1989. “Ueberlegungen zur Möglichkeit der chemische Entsinterungen von Druckrohren im Verlauf römischer Fernwasserleitungen,” *Mitt. des Leichtweiss-Institut für Wasserbau* Heft 103, 219-45

Falvey, H. T. 1980. *Air-water flow in hydraulic structures* (Engineering Monograph no. 41, Denver).

Fensterbusch, C. 1964. *Vitruvii de Architectura libri decem* (Darmstadt).

Garbrecht, G. 1978. “Die Wasserversorgung des antiken Pergamon, die Druckleitung,” in *Mitt. des Leichtweiss-Institut für Wasserbau*, Heft 60.

Garbrecht, G. 1987. “Die Wasserversorgung des antiken Pergamon,” in *Die Wasserversorgung antiker Städte* II, 13-47 (repr. 1991, Mainz am Rhein).

Garbrecht, G. 2000. “Die Wasserversorgung des antiken Pergamon,” in W. Radt (ed.), *Altertümer von Pergamon* (Berlin)

Grewe, K. 1992. *Aquädukt Marmor, Kalksinter der römischen Eifelwasserleitung als Baustoff des Mittelalters* (Stuttgart).

Grewe, K. 1998. *Licht am Ende des Tunnels* (Mainz).

Grewe, K., H. P. M. Kessener and S. A. G. Piras 1999. “Im Zickzack-Kurs über den Fluß, die römisch/seldschukische Eurymedon-Brücke von Aspendos (Türkei),” *Antike Welt* 30, 1-12.

Haberey, W. 1972. *Die römischen Wasserleitungen nach Köln* (Bonn).

Hansen, J. 1992. “Die antike Wasserleitung unter der Rhone bei Arles,” *Mitt. des Leichtweiss-Institut für Wasserbau*, Heft 117, 470-531.

Hodge, A. T. 1983. “Siphons in Roman aqueducts,” *PBSR* 51, 174-221.

Hodge, A. T. 1992. *Roman aqueducts and water supply* (London).

Jordan, T. D. 1984. *A handbook of gravity-flow water systems* (Intermediate Technology Publications, London).

Kessener, H. P. M. 2000. “The Aspendos Aqueduct Research Project (AARP), field campaigns 1996 and 1998,” in G. Jansen (ed.), *Proc. 10th Int. conference on the history of water management and hydraulic engineering*.

Kessener, H. P. M. and S. A. G. Piras 1997. “The pressure line of the Aspendos aqueduct,” *Adalya* II, 159-87.

Kessener, H. P. M. and S. A. G. Piras 1998. “The Aspendos aqueduct and the Roman-Seljuk bridge across the Eurymedon,” *Adalya* III, 149-68.

Krautheimer, R. 1986. *Early Christian and Byzantine architecture* (4th edn., New York).

Lanckoronski, K. 1890. *Städte Pamphyliens und Pisidiens*, Bd. 1 (Vienna).

Malinowski, R. 1979. “Concretes and mortars in ancient aqueducts,” *Concrete International* Jan. 1979, 66-75.

Malinowski, R. 1996. “Dichtungsmörtel und Betone in der Antike,” in N. de Haan and G. Jansen (edd.), *Proc. 9th Int. Conference on the history of water management and hydraulic engineering in the Mediterranean region* (Leiden).

Meshel, Z., T. Tsuk, H. Fahlbusch and Y. Peleg 1998. *The water-supply system of Susita* (Lübeck–Tel Aviv).

Peleg, Y. 1991. “Ancient pipelines in Israel,” in A. T. Hodge (ed.), *Future currents in aqueduct studies* (Leeds) 113-28.

Smith, N. A. F. 1976. “Attitudes to Roman engineering and the question of the inverted siphon,” in *History of technology I* (London) 45-71.

Smith, N. A. F. 1991. “Problems of design and analysis,” in A. T. Hodge (ed.), *Future currents in aqueduct studies* (Leeds) 113-28.

Schnapauff, J. 1966. “Luftblasen in Rohrleitungen — vereinfachend betrachtet,” *Neue Deliwa Zeitschrift* (August) 371-73.

Stenton, E. C. and J. J. Coulton 1986. “Oinoanda: the water supply and aqueduct,” *AnatSt* 36, 15-59.

Tölle-Kastenbein, R. 1991. “Entlüftung antiker Wasserleitungsrohre,” *AA* 25-30.

Vann, R. L. 1976. *A study of Roman construction in Asia Minor* (Diss. Cornell University).

Wagner, J. 1986. *Türkei, Die Südküste von Kaunos bis Issos* (Munich).

Ward-Perkins, J. B. 1955. “The aqueduct of Aspendos,” *PBSR* 23, 115-23.

Weber, G. 1898. “Die Hochdruck-Wasserleitung von Laodikeia ad Lycum,” *JdI* 13, 1-13.

Weber, G. 1904. “Wasserleitungen in Kleinasiatischen Städten I,” *JdI* 19, 86-101.

Weber, G. 1905. “Wasserleitungen in Kleinasiatischen Städten II,” *JdI* 20, 202-10.

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Aspendos su kuleleri (Foto M. Bildirici, 2007)