INVERTED SYPHONS AND ROMAN HYDRAULIC TECHNOLOGY

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1. ROMAN AQUEDUCTS

In Roman times water was conveyed by means of aqueducts, mortared open channels, often roofed, having a regular (but often not uniform) downward slope from source to destination (fig.1). An aqueduct could have a considerable length, varying from a few to over 100 km. The longest aqueduct known is that of Constantinople, over 250 km. The Tempul aqueduct of Cadiz (*Gades*) counted 83 km (Table 1).

The route of an aqueduct usually ran for at least a part through mountainous areas and uneven terrains. To guarantee that the water would flow to its destination tunnels and bridges were constructed, and if needed the channel was cut right out of the vertical rock face (fig. 2). This required great expertise in surveying techniques, in planning and design[2]. The often anonymous Roman engineer, who had been given the task to bring good quality water to the town and to solve the problems that were encountered, stayed in the background, although this was not always the case. In the 1st c. CE a 17 km aqueduct was planned for ancient *Saldae* (Bejaïa, Algeria). In order to pass a hill a 428 m long tunnel was planned, to be dug from two sides to meet in the middle. At one instance the two stretches that were excavated had a joint length that exceeded the distance to be covered. Then an engineer from the Roman army, *Nonius Datus*, was called in for help, and he solved the problem This was commemorated in an inscription, still to be seen in Bejaïa, mentioning the three virtues that an able engineer should possess: *Spes*, *Virtus* and *Patientia* (*CIL* VIII 2128, Tazoult)[3].

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2. For Roman surveying, see Grewe 1998; also, Lewis 2001.

3. Copies of the inscription are in the Museo della Città in Rome, and in the Museum für antike Schiffahrt in Mainz, Germany (Waele 1996; Grewe 2002).

Fig. 1. Presently known aqueducts in the Roman Empire. (1367 aqueducts, see e.g. www.romaq.org, www.romanaqueducts.info).

Fig. 2. Channel of the aqueduct of Side, next to the Manavgat river, Turkey (Photo P. KESSENER).

LOCATION	COUNTRY	LENGTH (KM)
Constantinople	Turkey	>250
Carthage	Tunesia	95
Cologne	Germany	95
Rome (Aqua Marcia)	Italy	91
Rome (Anio Novus)	Italy	87
Cadiz (Tempul)	Spain	83
Lyon (Gier)	France	75
Rome (Aqua Claudia)	Italy	69
Lyon (Brevenne)	France	66
Rome (Annio Vetus)	Italy	64
Rome (Aqua Traiana)	Italy	58
Pergamon (Kaikos)	Turkey	50
Nîmes	France	50
Arles	France	48
Cherchel	Algeria	45
Alcanadre	Spain	30

Table 1. Length of some classical aqueducts. For Constantinopel see Çeçen, 1996; Carthago: Rakob, 1983; Cologne: Haberey, 1972; Grewe, 1986; Rome: van Deman, 1934; Ashby, 1935; Blackman, 1978; Cadiz: Casado, 1985, 319; Pérez, 2014; Lyon: Burdy, 2002; Pergamon: Garbrecht, 1987; Nîmes: Fabre et alii, 2000; Cherchel: Leveau & Paillet, 1976; Arles: Leveau, 1996.

The mortared channels were made from bricks and natural stones. Supported by a solid foundation and with thick walls the channel was often covered by an arched vaulting, less often by flat slabs. The dimensions of the channel ranged widely. The great aqueduct channels could be inspected from the inside: inside dimensions of the channel of the *Aqua Marcia* (Rome): 90x240 cm (width x height); channel of the Degirmendere Aqueduct of Ephesus 80x240 cm; Brevenne aqueduct (Lyon) 80x180 cm; Carthago 85x190 cm; Nîmes 120x166 cm; Cologne 70x142 cm; Cadiz (Tempul) 56x148 cm; Aspendos (Turkije): 50x90 cm; Mont d'Or (Lyon) 44x71 cm; Patara (Turkije): 40x35 cm. Access into the channel was possible through an opening in the channel's roofing; when running underground, a shaft from ground surface to the channels roof was constructed (inspection shaft, *regard* as the French say, *Einstieg-Schacht* for the Germans).

In case low lying terrain had to be crossed the channel was built on arches, if needed over long distances, so that the required slope could be maintained and the water arrived where planned. The 90 km Carthago aqueduct ran for 17 km on 30 m high arches to cross the Miliane plain (Rakob 1983). The aqueducts of Rome are famous for the endless rows of arches in the Campania plains of which sections still stand. A times channels were positioned on top of existing ones saving considerable costs and efforts.

Fig. 3. Channel of Tempul aqueduct of Cadiz, with *sinter* deposits (arrows) (PÉREZ 2014).

For water tightness the inner walls of the channels were covered with a special type mortar, *opus signinum*, that is relatively resistive to temperature changes (Malinowski 1979; 1996). Because the Romans preferred ‘hard’ water karstic springs were tapped. Over time calcareous incrustations (*sinter*) accumulated on walls and floor of the channels, which could lead to a substantial reduction of channel dimensions (fig. 3). The 120 cm wide channel of the Nîmes aqueduct has deposits 50 cm wide on both inner walls, indicating continuous operation for many centuries. In later times large sinter blocks from the channel were reused for construction works. The aqueducts of Lyon show no sinter at all: they were supplied from non-karstic (granite) areas. The sinter in the Cologne channel is of a high quality, having grown in thickness about 1 mm a year. In medieval times the up to 30 cm wide the sinter was broken out of the channel to be reworked serving as altar slabs, ornaments, and pillars in churches (fig. 4). The polished material showed a travertine like structure from the yearly and seasonal deposits. It was regarded as a valuable material (Grewe 2014, 298-382; 2017, 28). Unworked sinter slabs from the Aspendos aqueduct served as graves stones for Selçuk cemeteries (Kessener 2016, 352).

Fig. 4. Choir aisle of the Lebuinus church, Deventer, the Netherlands. Balustrade with sinter slabs (Photo P. KESSENER).

Fig. 5. Aqueduct of Carthago, water provision for local population (Photo P. KESSENER).

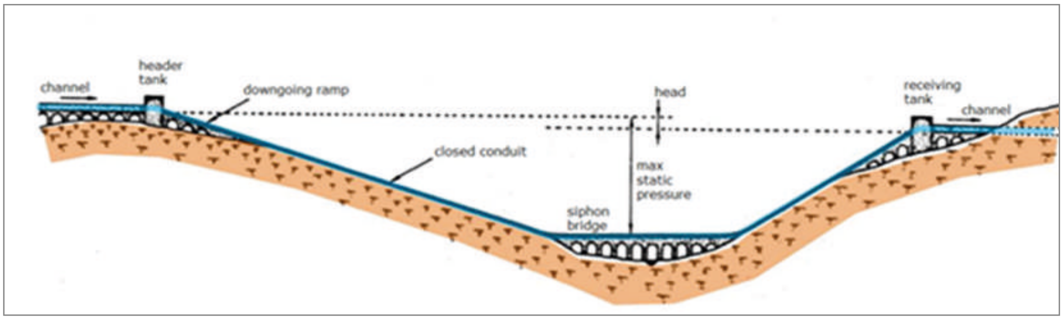

Fig. 6. Inverted siphon.

The slope (gradient) of the channel varied for each aqueduct and along its trajectory. Often the initial section was steep while on approaching its destination the slope became less. The 50 km aqueduct of Nîmes with its famous Pont du Gard has an average gradient of 35 cm per kilometer, yet downstream of the great bridge in extremely hilly terrain it was only 7 cm/km for 10 km, a great achievement of precision even today. The Carthage aqueduct had a slope of 95 m/km for the first 6 km from the spring at Zaghouan. Not far from one of its two springs the slope of the Aspendos aqueduct is estimated 140-150 m/km (Kessener 2000). The Carthage aqueduct still runs today for a stretch of 70 km, providing Tunis with water and serving local populace on its way, with a discharge in 1995: 150 l/sec, almost 13,000 m3 per day (fig. 5).

The amount of water that was transported could be considerable. The eleven aqueducts of Rome had an estimated joint discharge of over one million cubic meters per day —one could fill about 16 Olympic swimming pools each hour— a figure similar to the water provision of Paris in the 1970s. The 95 km aqueduct of Cologne conveyed 21.000 m^3 per 24 hours from the Eifel. The four aqueducts of Lyon delivered 75.000 m^3 /24hr (see e.g. Hodge 1992).

2. PRESSURE CONDUITS: SIPHONS

The Roman engineer had only one force available to transport water over long distances: gravity. He had to make sure that the water could flow downstream from start to finish. Whenever a valley was too wide to be circumvented or too deep to be crossed by a bridge an 'inverted siphon' was constructed, simply called 'siphon' (fig. 6).

With a siphon the water was made to flow to the other side of the valley by means of a closed conduit according to the principle of communicating vessels[4]. Water from the aqueduct entered a 'header tank'

4. For a discussion, see Smith 1979; 2007a; 2007b; Hodge 1985; 1992; Kessener 2004; 2016.

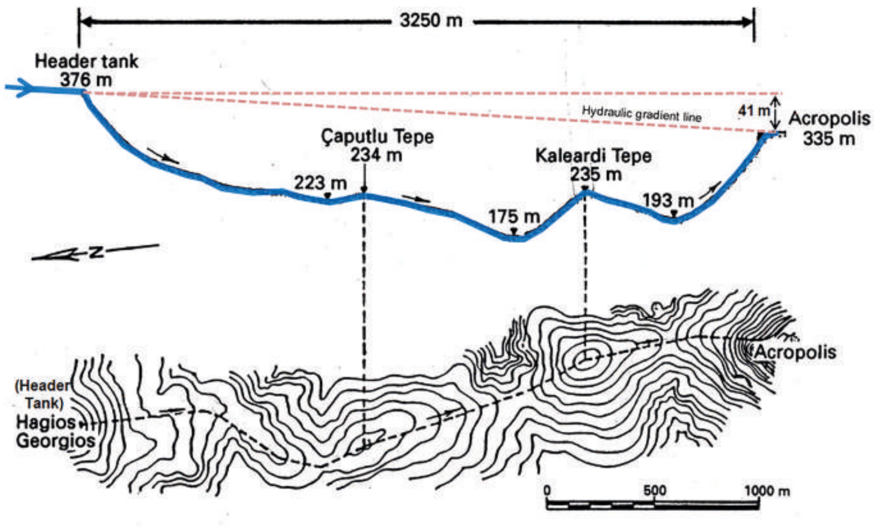

Fig. 7. The Madradag siphon of Pergamon (after FAHLBUSCH 1982, Abb. 42).

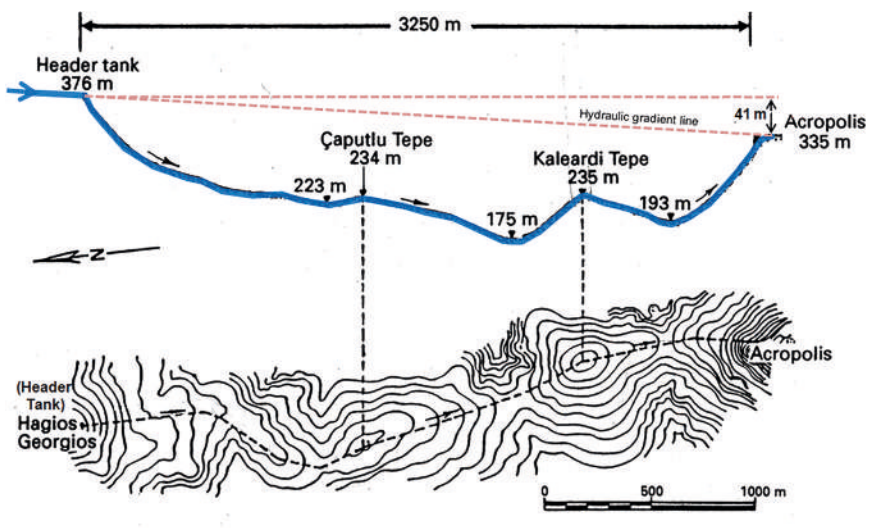

Fig. 8. Conduit stone of the Aspendos siphon (Photo P. KESSENER).

(*reservoir de fuite, Einlaufbecken, tanque de cabesera*) where it went into a pipe that ran down the sloping of the valley, to go up again on the other side. There it ended in a 'receiving tank' (*reservoir de chasse, Auslaufbecken, tanque de salida*) at a level somewhat below the header tank. From the receiving tank the water continued on its course to destination in an open channel again. In the lowest part of the valley the conduit was often installed on a 'siphon bridge' to have the river or stream there pass without damaging the line. The pressure in the conduit down in the valley could be considerable (table 2).

CITY	AQUEDUCT	SIPHON	MATERIAL OF CONDUIT	LENGTH (M)	MAX DEPTH (M)	HYDRAULIC GRADIENT (M/KM)
Cadiz (Spain)	Tempul	de la Playa	stone	19500	20	1 ?
Smyrna (Turkey)	Kara-Bunar	Kara-Bunar	ceramic/ stone	4400	158	1.1 (?)
Lyon (France)	Yzeron	Craponne-Lyon	lead	3600	91	9.2
Cadiz	Tempul	de los Arquillos	stone	3500	50	3,3
Lyon	Mont d’Or	d’Ecully	lead	3500	70	3.1
Lyon	Brevenne	Grange-Blanche	lead	3500	90	4-5.6 (?)
Pergamon (Turkey)	Madradag	Madradag	lead	3250	190	12.6
Alatri (Italy)	Alatri	Alatri	lead	3000	100	9 (?)
Lyon	Gier	Beaunant	lead	2660	122	3.0
Lyon	Yzeron	Grezieux-Craponne	lead	2200	33	3.2
Aspendos (Turkey)	Aspendos	Aspendos	stone	1670	45	8.3
Termini Imerese (Sicily)	Cornelio	Barratine	lead	1300	40	3.8
Lyon	Gier	Soucieu (le Garon)	lead	1210	93.5	?
Laodikeia ad Lykum (Turkey)	Laodikeia	Laodikeia	stone	800	50	26
Lyon	Gier	St. Genis	lead	700	79	8.3
Lyon	Gier	St. Irenée	lead	575	38	4
Oinoanda (Turkey)	Oinoanda	Oinoanda	stone	500-700	22	6-16 (?)
Lyon	Mont d’Or	Cotte-Chally	lead	420	30	19
Patara (Turkey)	Patara	Delik Kemer	stone	500	20	18.5

Table 2. Length, maximum depth, hydraulic gradient of some classical siphons. For gradients with (?) the exact location of header tank and/or receiving tank is not known. Cadiz: Pérez, 2012, 2014; Smyrna: Weber, 1899; Lyon: Burdy, 1991; 1996; 2002; Pergamon: Fahlbusch, 1982; Garbrecht, 1978; 1987; Manvroudis, 2015; Alatri: Laurenti,1987; Lewis, 1999; Aspendos: Kessener & Piras, 1997; Kessener, 2000; 2011; Termini Imerese: Belvedere, 1986; Oinoanda: Stenton & Coulton, 1986; Laodikeia a/L: Weber, 1898; Kessener, 2017: 150-9; Patara: Stenton & Coulton, 1986.

Highest pressure was reached in the Madradag-siphon at Pergamon, 19 bar (fig. 7). Of the conduit of the 2nd c. BCE Karabunar siphon of Smyrna virtual nothing has remained due to the enormous population increase of. In contrast the course of the Hellenistic Madradag siphon of Pergamon has not been disturbed and can be walked, in rather uneven and difficult terrain where one also passes bridges of later Roman aqueducts.

The longest pressure line is that of Cadiz (Sifón de la Playa): 19,5 km (Pérez Marrero 2012). The four aqueducts of Lyon had nine siphons. The Gier aqueduct, with 75 km the longest of Lyon’s aqueducts, had four siphons, up to 120 m deep and 3.5 km in length (figs. 7-8). For the required capacity nine to eleven 20 cm

Fig. 10. Lead conduits, 3 m long, retrieved from the Rhône river near Arles, of siphon that crossed the Rhône River (Arles Museum).

Fig. 9. Conduit stones of siphon at Cadiz (PËREZ 2008, 10).

diameter conduits made of lead were laid parallel. The amount of lead for these siphons, which all together had a length of 16,6 km, is estimated to have been 10 to 15,000 tons (Hodge 1992, 156). The lead has disappeared to be reused for roofs of churches, dwellings and other matters. A number of header and receiving tanks have survived, some partly restored, as well as siphon bridges and parts of sloping ramps (figs. 19-20).

The material of the siphon-conduits was diverse: lead, stone, terracotta, or combinations of these. They were assembled from prefab pipe elements having varying lengths, 40-70 cm for terracotta pipe elements, 50-100 cm for perforated stone blocks, up to 3 m for lead pipes. The lead pipes were either cast or —more often— made of leaden sheets that were bent around a wooden pole and soldered at the seam[5]. The pipe elements were joined by bringing the end of one pipe element into the somewhat larger end of the next (for terracotta conduits) or by means of socket and flange (for stone and terracotta pipes). The up to 1 m wide conduit stones of the siphons of Aspendos, Cadiz, Patara, and Laodikeia and Lycum are of the latter type, as are the smaller 50 cm cubic conduit stones at Oinoanda (figs. 8-9). The pipes were, depending on the quality of the water, subjected to calcareous incrustations –just as the open channels. Over the years the cross section open to flow would be reduced. For the piped conduits the incrustations could take a peculiar oval shape. At the upper side of the pipes incrustation would be less due to entrainment or air, while sand and pebbles would do so at the lower side. The estimated 3000 conduit stones of the Aspendos siphon that was ruined by an earthquake were reused by the Seljuks for the construction of a bridge to cross the nearby Eurymedon river. A number of conduit stones, with incrustation, can be seen in the fabric of the remains of the Roman bridge and of the Seljuk counterpart that was built on its ruins (Grewe *et al*. 1999). The Smyrna siphon is said to have been made of stone elements alternated with terracotta pipes. The joints were sealed with a mixture of live chalk, oil, and herbs, which expands when moisturized (Malinowski 1979; 1996). Conduit elements made of lead could be joined with socket and flange, either with a stone element in between or by means of a lead sleeve on both ends and sealed with the expanding mix, although the majority of the lead conduit elements were soldered to each other.

Sections of lead conduits of siphons have been preserved. A 90 cm long fragment of a lead conduit, diameter 31-34 cm and with inscription, is all that remained from a find of about 10 tons of lead conduit that was retrieved in 1980 from the Rhone River near Vienne at extremely low water level. Regretfully the pipes have been melted down without prior investigation. The find shows that at Vienne the Rhône River was crossed by a siphon (Burdy – Cochet 1992). A number of 33 lead pipe elements recovered from the Rhône River over the years 1570-1825 and now in the Arles Museum were investigated by Mr. Hansen of Denmark (fig. 10) (Hansen 1992). The pipes, with a length of 3 m and an inner diameter of 10-12 cm, and a lead seam along their length, were parts of a siphon that also crossed the Rhône, between Arles and Trinquetaille. The pipe elements were fixed to each other by inserting one end into the next and driving a large nail through both ends (fig. 11). Subsequently the joint was sealed with a thick layer of soldered lead that also covered the nail –still to be seen in some pipe elements and that must have hampered the flow to some extent.

Hansen noted that the joints were not weak points in the line (*waren nicht das schwache Glied der Kette*), and indication for the superior soldering techniques of the Romans. Such lead conduits may be regarded as made of homogenous material. This is not the case for conduits with joints sealed with the expanding mix. The tensile strength of this material is much lower than that of stone, lead, or terracotta, the material of the pipe elements is made of. These conduits are susceptible to bursting at the joints.

5. About Roman soldering techniques, see Hodge 1992, 307-309.

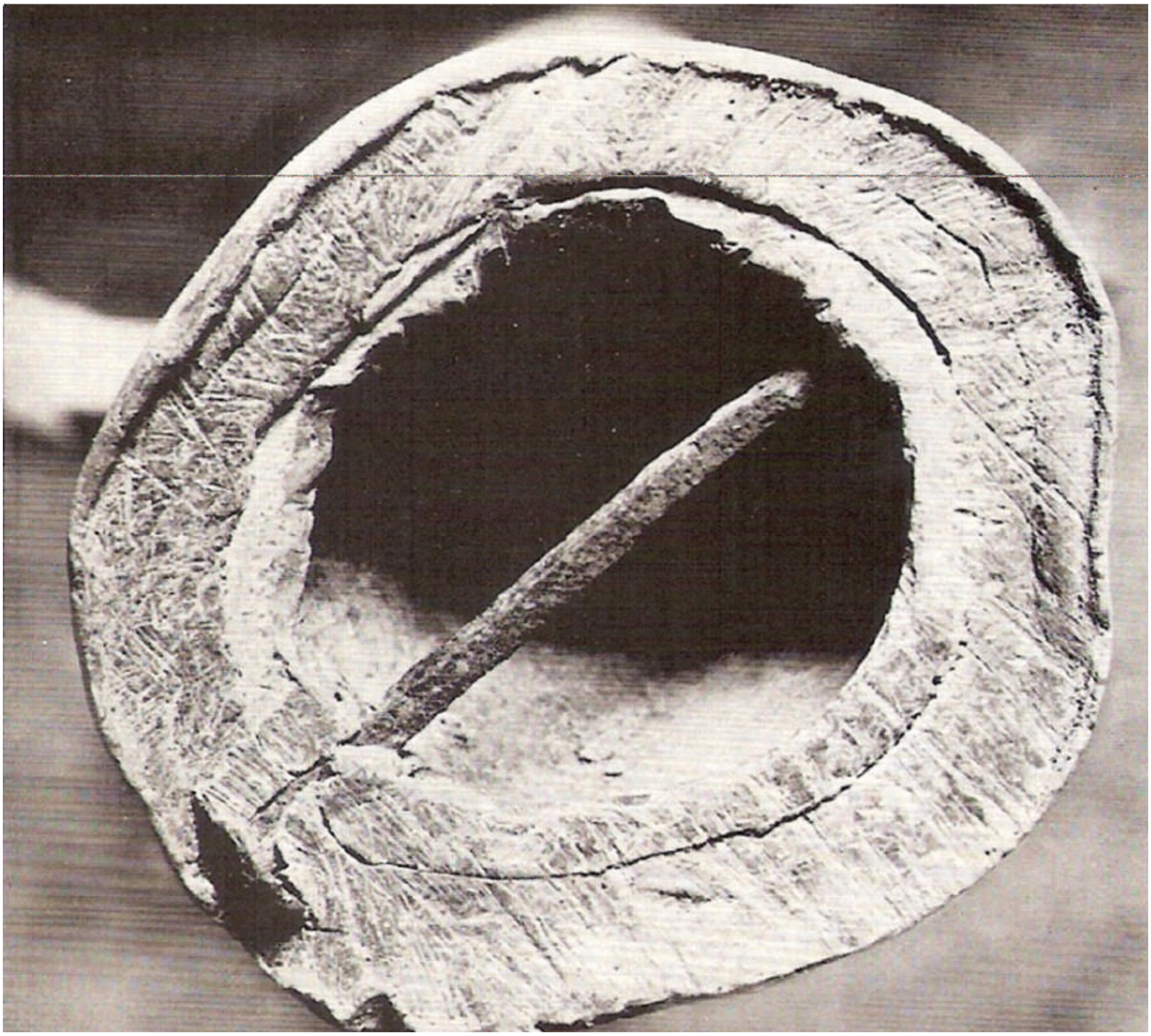

Fig. 11. Large nail driven through pipe ends slid into each other (Arles Museum).

The ancient pressure conduits can thus be split into two categories. Cat.1 conduits are made of lead, with soldered joints. These conduits can be regarded as 'homogenous', with uniform material all along the conduit, of which the tensile strength parallel to the conduit axis is equal to the tensile strength perpendicular to the conduit axis. Cat. II conduits have joints sealed with the weak expanding mix (resistive to pressure but with a low tensile strength). Here the tensile strength parallel to the conduit axis is lower than the tensile strength perpendicular to the conduit axis. These conduits must be considered as 'non-homogenous'.

Theoretically a pipe can burst in two ways; along its length, or perpendicular to its length. The minimum pressure P(l) to burst along its length equals.

$$P(l) = t(p) \cdot d/R,$$

with t(p) = tensile strength of the material of the pipe wall perpendicular to pipe axis
d = pipe wall thickness
R = diameter of the pipe.
To have the pipe burst perpendicular to its axis the pressure must at least be

$$P(p) = 2 \cdot t(l) \cdot (d/R) \cdot (1 + d/R)$$

with t(l) = tensile strength along pipe axis.

For pipes made of homogenous material (Cat.1 conduits) $t(p) = t(l)$, from which follows.

$P(p) > 2 \cdot P(l)$. Homogenous conduits will always burst along their length when the inside pressure gets too high, like a sausage in a frying pan, while for Cat.2 conduits, with $t(p) > t(l)$, this may not be the case. Because of the low tensile strength along the conduit axis the Cat.2 pipes are prone to burst at the joints. Thus, the choice of the material for the pressure pipes requires that certain precautions must be taken to guarantee proper functioning of the siphon and prevention of damage. So, one needs to have an idea what could happen in siphons, that is, the effects of water flow in pressurized conduits must be evaluated. Factors are static pressure, forces generated by the flowing of water, effects from presence of air in the conduit, and how pressure surges may evolve.

3. STATIC PRESSURE

If a siphon is just filled with water - not flowing - only static pressure has to be reckoned with. The static pressure p (in N(ewton)/m^2) at any point in the conduit is related to the vertical distance h between that point and the free surface of the water:

$$p = \rho \cdot g \cdot h \qquad (1)$$

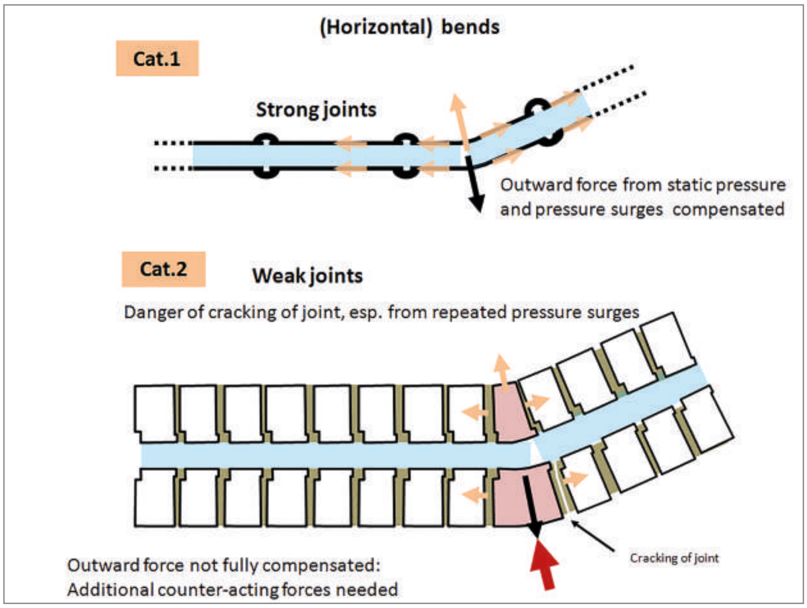

Fig. 12. Forces from static pressure at a bend for Cat.1 conduits (made of lead) and Cat.2 conduits (ceramic/stone) (Illustration P. KESSENER).

with
ρ = specific mass of water = 1000 kg/m^3
g = gravitational acceleration = 9.81 m/sec^2
h = vertical distance below free surface of the water in m

For a conduit full of water the water pressure p exerts forces perpendicular to the pipe wall along its circumference, which forces are evened out as long as the tensile strength of the pipe wall is sufficiently high. This is true for both categories of conduits provided that for Cat.2 conduits displacement of a pipe element along the conduit-axis is prevented by the next pipe element and so on. Things change, however, when there is a bend in the line. On the pipe element at the bend the static pressure exerts a net outward force along the bisector of the bend angle, with magnitude F (fig. 12):

$$F = 2 \cdot p \cdot A \cdot sin(\frac{\alpha}{2}) \qquad (2)$$

with
p = static pressure (Newton/m^2)
A = cross-section of conduit (m^2)
α = angle of bend.

Fig. 13. Madradag siphon of Pergamon. Top of Kaleardi Tepe. Perforated stone slabs to secure the lead pipes. The larger stone is located on the very top of the hill, where the conduit makes a vertical bend. In the back the acropolis of Pergamon (Photo P. KESSENER).

For an angle of 180 degrees, a 'U-turn', this force is at its maximum ($\sin(\alpha/2)=1$), while for a straight conduit, with $\alpha=0$, this force is of course zero. For a bend of 30 degrees in a 28 cm diameter conduit at a pressure of 40 m water column, which is the case for the Aspendos siphon where the conduit turns from going down the hill-side to horizontal, this force F (in N(ewton) or kgf) becomes considerable:

$$F = 2 \cdot 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 40m \cdot \frac{\pi}{4} \cdot (0.28m)^2 \cdot sin(15°) = 12{,}507\ N$$

or about 1275 kgf.

For vertical bends with the conduit changing direction from going down to horizontal or from horizontal to going up such force may be readily countered by an adequate foundation of the conduit. For the 3250 m long and 190 m deep Madradag-siphon at Pergamon the forces m were significant. The Madradag siphon consisted of pipe elements of cast lead, 3 m long and joined by means of lead sleeves slid over neighboring pipe ends. The 17,5 cm inner diameter conduit was kept in place by having every individual pipe element fitted into a perforated stone slab and burying the entire conduit underground. At the two vertical 20 degree bends on top of two intervening hills, the Caputlu Tepe and the Kaleardi Tepe, 136 and 146 m below the header tank, the force from static pressure is directed upward because the conduit here changes from rising up to going down. Here the fixation stones are larger (respectively 1,5 m^3 and 2,3 m^3) to compensate for the upward force from static pressure of about 11,000 and 12,000 Newton at these points (fig. 13) (Fahlbusch 1982, 73).

For pressure lines of the Cat.2 the force from static pressure exerted on a pipe element that makes up a bend will be diverted to the neighboring pipe elements, but only as far as the sealing material can keep the pipe elements together, so that additional means were needed to prevent the pipe element being pushed

Fig. 14. The 500 m Delik Kemer siphon of the Patara aqueduct (Turkey). Remains of stone conduit built on 10 m high 'Cyclopean wall' (Photo P. KESSENER).

Fig. 15. Cyclopean wall of Delik Kemer siphon, south view. On top conduit stones visible with holes for metal clamps to secure the integrity of the line. The flat stone above the passage bears the inscription (Photo P. KESSENER).

out of position. For vertical bends this could be achieved by having the conduit laid on a solid foundation or by adding mass to enlarge the weight, as was done at Pergamon on the top of the intervening hills. However, for horizontal bends additional measures must be taken, such as increasing friction forces with the underground by sand ballast, by building a wall pushing back, or by fastening the conduit elements to each other with bands, or metal clamps, as was done for the Delik Kemer siphon of Patara (figs. 14-15). An inscription above both passages underneath the Cyclopean wall recounts of the destruction of the siphon by an earthquake in 68 CE, after which Patara city was devoid of water for three years before the siphons was restored. A second siphon of three parallel ceramic pipelines was also installed as a safety measure for future earthquakes (Şahin 2007). For siphons made of lead pipes soldered together, Cat.I conduits, such precautions were not needed as at bends the forces from static pressure are being transferred away from the bend via the pipe wall. The conduit as a whole may need to be fixed to prevent sliding out of place, but the conduit would only burst along its length where pressure is highest: in the lowest part of the siphon.

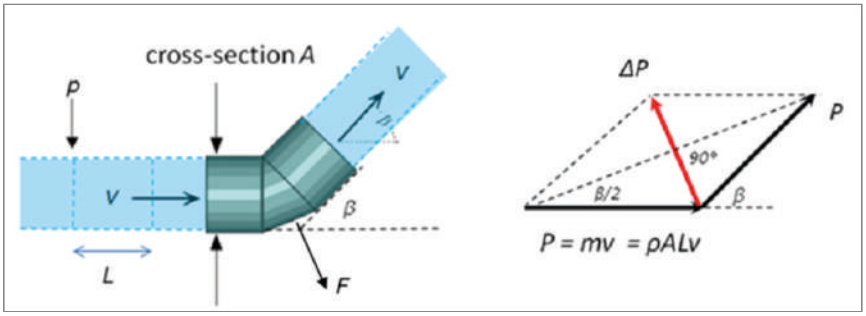

Fig. 16. Stationary water flow in closed conduit. Change of impulse of water stream going around a bend (inertial thrust) (Illustration P. KESSENER).

4. EFFECTS FROM THE FLOW OF WATER

Forces exerted onto the conduit from the flow of water are generated by the friction between the water and pipe wall ('drag'), and, at bends, by the force that is needed to change the flow direction ('inertial thrust'). Because the velocity of the water directly at the pipe wall is zero, the drag is mainly determined by viscosity and turbulence. Assuming that wall roughness and conduit diameter are the same all along the conduit, each pipe element will undergo a force in the direction of the flow. This force has a certain value per unit of conduit length. In an operating siphon the water will have a certain, constant value. This means that there is no net force operating on the flowing water, which in its turn means that the force by drag is equal but opposite to the overall component of the gravity force between header tank and receiving tank. For the stone siphon of Aspendos, with a length of 1670 m and a head of 14,5 m this means about 5,24 N per meter of conduit (diameter 28 cm). For the average length of a pipe element of 50 cm this represents a force of 2.62 N which is the equivalent of a weight of 270 grams. This force can be neglected compared to the friction forces between the conduit stones and the underground.

At bends in the conduit the direction of flow changes whereby a force is exerted onto the conduit element that makes up the bend (*inertial thrust*) (fig. 16). This force is related to the change of direction of the impulse of the water (impulse = mass times velocity) and tends to push the conduit element out of position.

To be precise, this is the force that has to exerted by the conduit element onto the flowing water to the effect that the direction of flow changes. It may be represented by a vector along the bisector of the angle of the bend, taking that the magnitude of the velocity of the water does not change. The change of impulse dP of a volume of water $A \cdot dx$ (A is cross-section of the conduit and dx the thickness of a corresponding slice of water) that goes around the bend equals.

$$dP = 2 \cdot \rho \cdot A \cdot dx \cdot v \cdot \sin[\frac{\beta}{2}] \qquad (3)$$

with
ρ = specific mass of water (kg/m^3)
v = mean flow velocity of the water (m/sec)
β = angle of the bend.

The mean flow velocity v can be estimated with the formula of Darcy-Weisbach (see http://www.pipeflow.co.uk/public/articles/Darcy_Weisbach_Formula):

$$v^2 = \frac{8 \cdot g \cdot \Delta H \cdot Rh}{\lambda \cdot L} = C \cdot \frac{\Delta H}{L} \qquad (4)$$

where
g = gravitational acceleration = 9.81 m/sec^2
ΔH = difference in level between start and end of the conduit (m)
Rh = hydraulic radius of the conduit = D/4 for full flow
D = diameter of the conduit (m)
λ = friction factor related to the roughness of the inner wall of the conduit (dimensionless, related to the irregularities of the inner surface of the pipe, to be determined from handbooks)
L = total length of the conduit (m)
C = $(\frac{8 \cdot g \cdot Rh}{\lambda})$ which has a fixed value for a specific conduit

The formula simply means that the longer a conduit is, the lower the velocity of the water will be, and the larger the difference in level between start and end of the conduit the faster the water will flow. The flow velocity in ancient siphons was not very high. For the 1.670 m long Aspendos siphon with its 28 cm diameter stone conduit, a wall roughness of at least some mm's (stone conduit, λ ≈ 0.043) and a ΔH of 14,5 m, as well as for the 3.250 m long Madradag pressure line at Pergamon, with wall roughness less than 1 mm (lead conduit, λ ≈ 0.026) and a ΔH of 45 m, the flow velocity for maximum discharge is about 1 m/sec, which is average walking speed.

This means that for a horizontal bend of 55 degrees, which is the case at Aspendos, the required force F equals about 6 kgf:

$F = dP/dt = (2 \cdot \rho \cdot A \cdot dx \cdot v \cdot \sin(\beta/2))/dt = 2 \cdot \rho \cdot A \cdot dx/dt \cdot v \cdot \sin(\beta/2) = 2 \cdot \rho \cdot A \cdot v^2 \cdot \sin(\beta/2)$.

With ρ = 1000 kg/m^3, diameter of conduit = 28 cm, water velocity = 1 m/sec, and β = 55 degrees it follows that $F = 2 \cdot 1000 \cdot \pi/4 \cdot (0.28)^2 \cdot 1^2 \cdot \sin(55°/2) = 57$ Newton, or a force equivalent to a weight of about 6 kilograms.

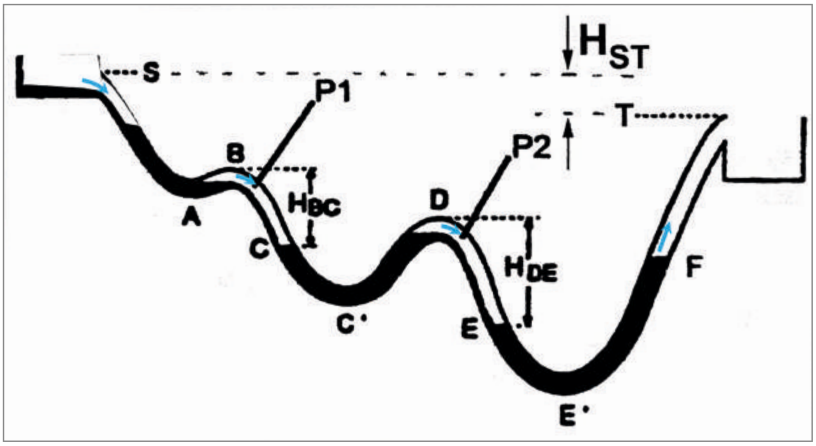

Fig. 17. Air pockets at the downstream side of high points. In case the total vertical height of the compressed air pockets HBC + HDE exceeds the available head to drive the siphon HST, the siphon will not start: water will not flow (Illustration P. KESSENER).

The magnitude of this force is small compared to the forces from static pressure. Compared to the friction forces between the heavy conduit stones and the foundation on which they are positioned this force is of no importance. Thus for ancient siphons the effects of flow can be neglected and no measures were needed to prevent the line to break apart at the bends from effects of flow. This may of course not be the case for high flow velocities that occur in modern systems.

Some authors discuss oscillations of the water column occurring at rapid start-up that may contribute to a minor extent to forces that are exerted on conduit elements. For the Aspendos siphon the authors think that by the towers the siphon was split up into three sections to reduce the length of water column (Ortloff – Kassinos 2003). This, however, does not make much sense, because starting a siphon must be done at slow pace, which was already prescribed by the /roman engineer Vitruvius in the first c. BCE.

5. AIR

There are several reasons why the presence of air in the conduit may interfere with the operation of a siphon. At the start-up of a siphon air may accumulate in air pockets at the downstream side of high points (fig. 17). These air pockets, depending on how far below the header tank they occur, reduce the pressure difference between start and end of the siphon. The siphon then delivers less water than envisaged, and it may even be so that the siphon does not start at all and the header tank just overflows. In deep siphons air pockets will be compressed, while some of the air may be driven into the water (as in a soda bottle), whereby this effect is reduced (see e.g. Corcos 1989).

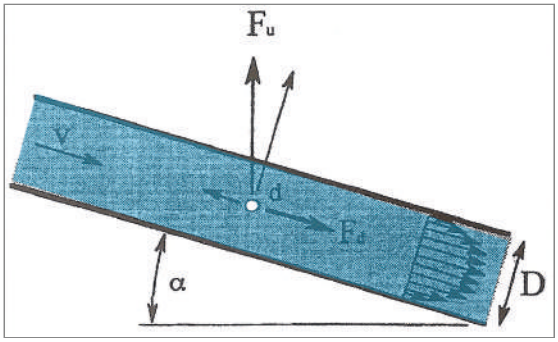

Fig. 18. Forces on air bubble in conduit sloping down. The air bubble will be stationary (but rise to the upper side of the conduit) if the drag force from the flowing water Fd equals the rising force Fu of the air bubble times sin(α) (After FALVEY 1980).

As indicated above the Madradag siphon of Pergamon two high points corresponding with the two intervening hills, the Çapultu Tepe end the Kaleardi Tepe (fig. 7). Because of the high static pressure at these points, some 140 m below the header tank and 100 m below the receiving tank, the air pockets were compressed to the extent that the discharge of the siphon was reduced to only 90 percent of its maximum value, which may not have been noticed by the designers. However, an additional problem had to be reckoned with. At the header tank air may be entrained into the conduit and transported to the air pockets, enlarging their volume. This results in a further reduction of the head driving the siphon, which in the end may even lead to a total stop of water flow. The intake at the two metres deep header tank of the Madradag siphon was positioned not far below the upper edge of the tank (see fig. 31). The entrainment of air could not be avoided at this point. Entrainment of air at intakes is a problem that is not easy to resolve (e.g. Knauss 1983).

Yet, at the downstream side of the air pockets there is a transition of a partly filled conduit (the water passes underneath the air pocket) to full conduit flow. At this point, of considerable turbulence, air may again be entrained with the water flow further down the conduit, reducing the volume of the air pockets. Whichever process is more important determines what will happen. And what happens is determined by the conduct of air and air bubbles in the conduit. One may ask why the course of the Madradag siphon runs over the tops of intermediate hills and not around them to avoid high points in the line. By choosing the hill tops the static pressure was reduced as much as possible, but more probably the trajectory was preferred to prevent damage by environmental events. Along the entire course the terrain slopes down on either side of the conduit, whereby damage from torrential rains and storms is prevented: the conduit runs on the local watershed.

The conduct of air bubbles in conduits is related to the size of the air bubbles, to the diameter of the conduit, the slope of the conduit, the velocity of the water in the conduit, the roughness of the inner wall of the conduit, and the viscosity of the water. For a conduit sloping down at an angle α an air bubble will be transported with the flow if the flow velocity is larger than a critical value Vcr (fig. 18; formula 5).

It can be deduced that (Falvey 1980, 48):

$$Vcr = \sqrt{4 \cdot g \cdot Db \cdot \frac{sin\alpha}{3 \cdot Cb}} \qquad (5)$$

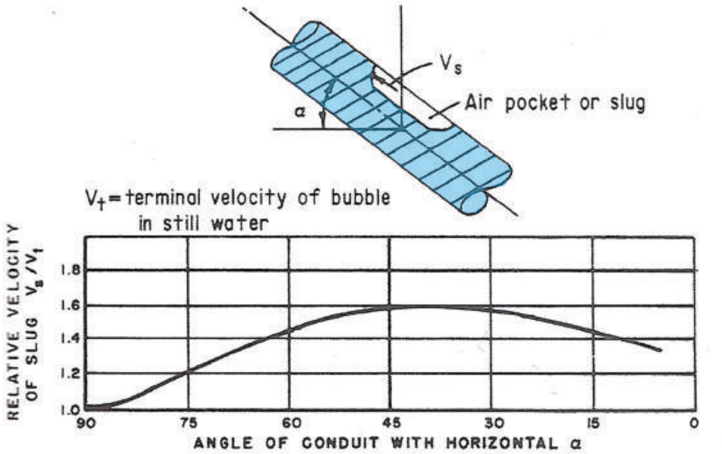

Fig. 19. Rising velocity of large air pockets (slugs) in sloping conduits relative to rising velocity in vertical conduits. Maximum at a slope of about 40 degrees (after FALVEY 1980, 52).

with
g = gravitational acceleration = 9.81 m/sec^2
Db = bubble diameter (m); α = slope angle
Cb = 'drag coefficient' of air bubble.
For convenience the value of Cb often is often set to 1. An alternative formula for Vcr is used by Kamma – Zijl (2002, 56), $Vcr = 1.23 \cdot (g \cdot Db \cdot \sin\alpha)^{1/2}$, with Cb = 0.88.

From formula 5 it can be seen that the larger the air bubble will be the faster the water must flow to entrain it. Also, the steeper the slope, the less readily air bubbles will go with the flow. As air bubbles tend to accumulate at the upper side of the conduit one must correct for the fact that the flow velocity near the conduit wall is less high, which for small bubbles has a greater effect than for large bubbles. The result is that the mean critical velocity Vm,cr above which small bubbles close to the conduit wall will go with the flow is higher than for larger air bubbles, and that Vm,cr is related to the diameter of the air bubbles, to the diameter of the conduit, and to the wall roughness (Aksoy 1997):

$$Vm,cr = ((\log(3.4 \cdot Dc/k)/(\log(15.1 \cdot Db/k)) \cdot (4 \cdot g \cdot Db \cdot \sin\alpha/3)^{1/2} \qquad (6)$$

with
Db = diameter of air bubble
Dc = diameter of conduit
k = wall roughness.

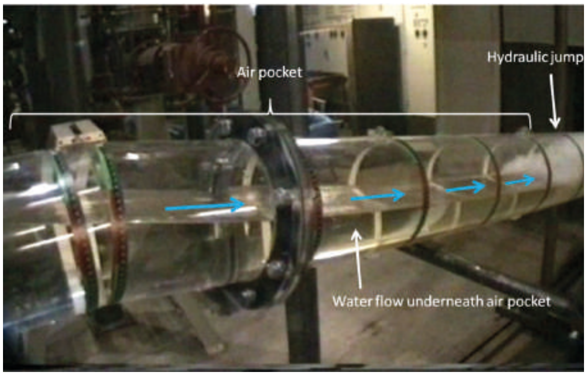

Fig. 20a. Water flow in 30 cm Perspex conduit sloping down from horizontal with air pocket and water flow beneath air pocket. Hydraulic jump (extremely turbulent) at point where full conduit flow is restored (Deltares experiment, Delft, the Netherlands. Photo P. KESSENER).

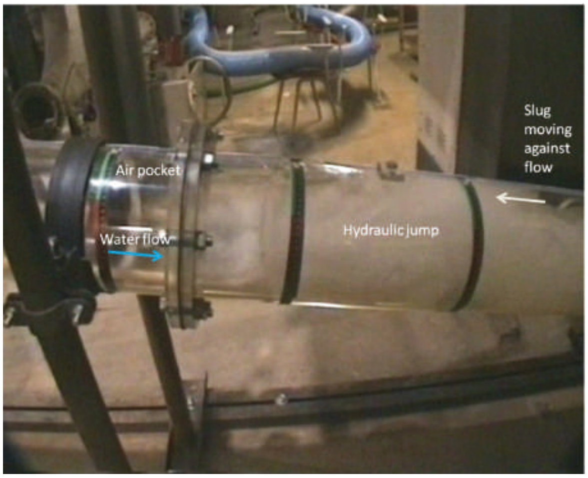

Fig. 20b. End of air pocket and highly turbulent hydraulic jump. Slug moving upstream against flow: 'blow-back' (Deltares experiment, Delft, the Netherlands. Photo P. KESSENER).

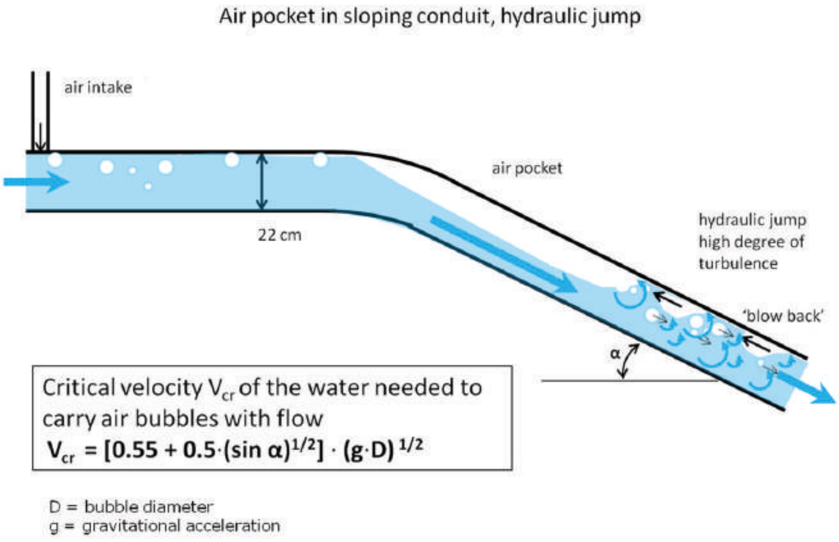

Fig. 21. Air pocket and air bubbles in sloping conduit, hydraulic jump at end of air pocket, with 'blow back' (Illustration P. KESSENER).

Things get increasingly complex when air bubbles coalesce to form large air pockets. Of large air pockets, also called 'slugs', it is known that the rising velocity in conduits sloping up is larger than in vertical conduits, with a maximum for a slope of about 40 degrees (fig. 19) (Falvey 1980, 50-52/61-65).

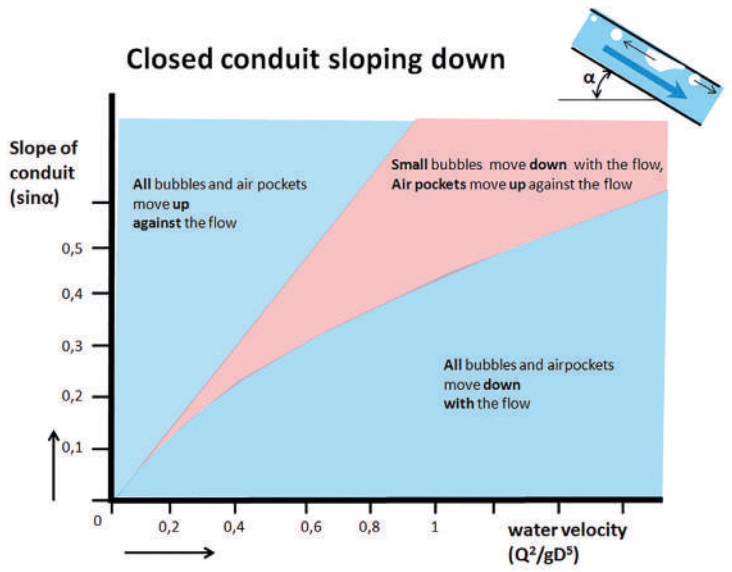

Fig. 22. Conduct of air bubbles and air pockets in closed conduits as function of slope angle (after FALVEY 1980, 29).

In conduits sloping down slugs may move upward against the flow, a process called 'blow back' (figs. 20a/b-21). Such slugs may at their front side collect small air bubbles that move with the flow increasing their size, while at the back side small air bubbles may be entrained again with the flow thereby reducing the slug (Baines – Wilkinson 1986). The behavior of air bubbles and slugs as function of the slope angle and flow velocity is given in fig. 22.

The conduit of the Madradag siphon at the header tank has a slope angle much larger than that downstream of the high points. Therefore, air was less readily entrained into the conduit at the header tank but rather easy at the downstream side of the air pockets. This means that after start-up the siphon developed to full capacity on its own. We may doubt whether the designers were aware of this phenomenon. The siphon operated as expected and brought water to the acropolis on top of the hill, no doubt to the amazement and wonder of her people.

For the Grezieux-Craponne-Lyon siphon of the Yzeron aqueduct of Lyon (not to be confused with the Yzeron-*siphon* of the Lyon's Gier aqueduct) a different situation existed. Here also there was a high point in the line that in this case could not be avoided because of the topography (fig. 24). The sloping of the terrain just downstream of the high point is much steeper than at the header tank. Air would thus be readily entrained at the header tank but only sparingly from the air pocket that formed at the high point during start-up. It may be calculated that, in case a closed conduit would run along the entire trajectory inclusive this high point, the siphon would start up for only 60% of its maximum discharge. And that, because of air increasingly accumulating at the high point, the siphon

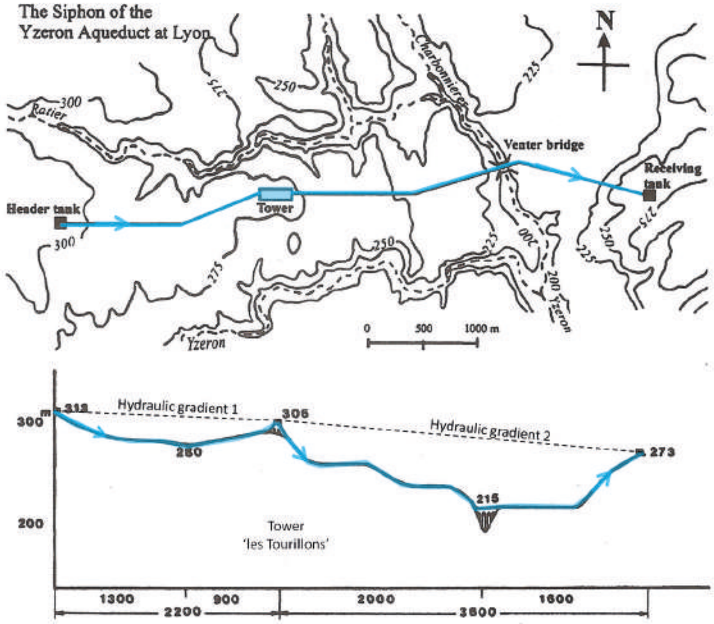

Fig. 23. The Grezieux-Craponne-Lyon siphon of the Yzeron aqueduct, with intermediate tower 'les Tourillons'. Distances and elevation in m (adapted from BURDY 2000).

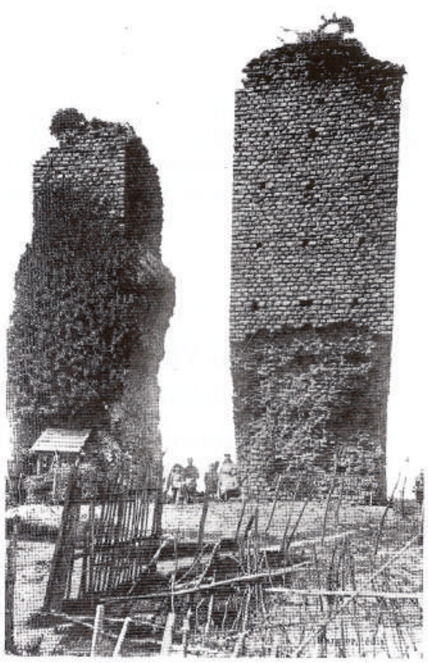

Fig. 24. Remains of hydraulic tower, known as 'les Tourillons'. Early 1900, south view (BURDY 2000).

Fig. 25. 'Les Tourillons'. Early 2000, north view (photo P. KESSENER).

Fig. 26. Aspendos siphon, with remains of two hydraulic towers with sloping ramps, one to the left, one near header tank to the right. View from the Aspendos acropolis (photo P. KESSENER).

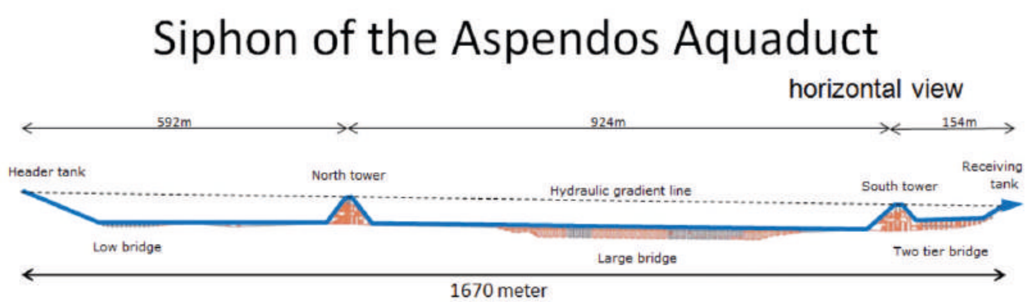

Fig. 27. Aspendos siphon, profile (Illustration P. KESSENER).

would after some time come to a complete and definite stand-still. The Romans solved this problem by having the conduit run over a nearby hill, on which they built a tower with sloping ramps, 16 m high and with an open tank on top. The conduits (the siphon consisted of a number of parallel lead pipes) discharged into the open tank where the air entrained at the header tank was released and formation of air pocket at the high point was prevented. From the tank on top of the tower the lead conduits went down again to rise up again at the other side of the valley. By means of this 'hydraulic tower' the siphon was divided into two subsequent siphons with a length of respectively 2.200 m (Grezieux-Craponne) and 3,600 m (Craponne-Lyon). Regarded as one siphon it is with 5,800 m one of longest from Roman time.

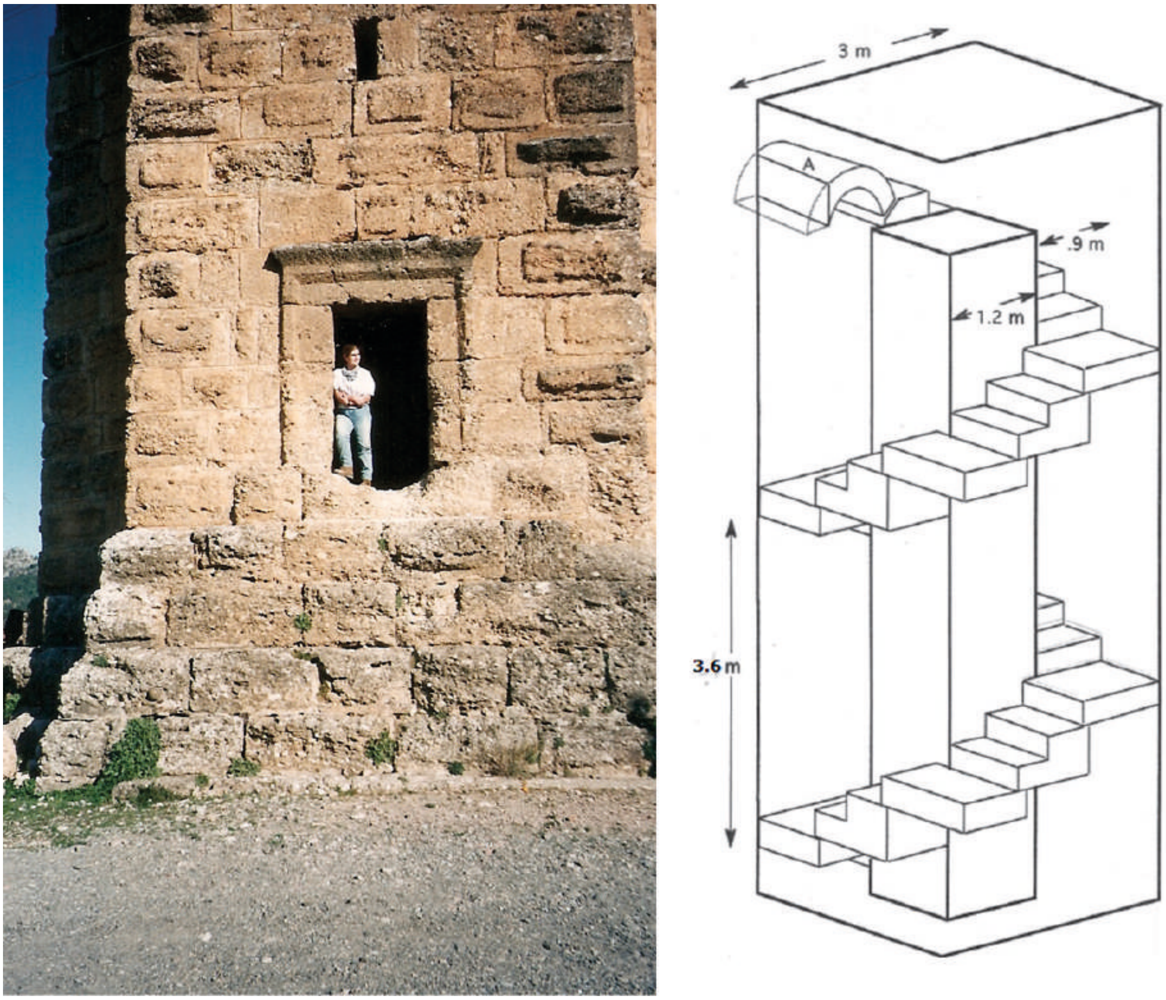

Fig. 28. Aspendos, south hydraulic tower, central part. Entrance to 90 cm wide stone stair way made of stone slabs around central pillar, reaching 15 m high (photo and reconstruction P. KESSENER).

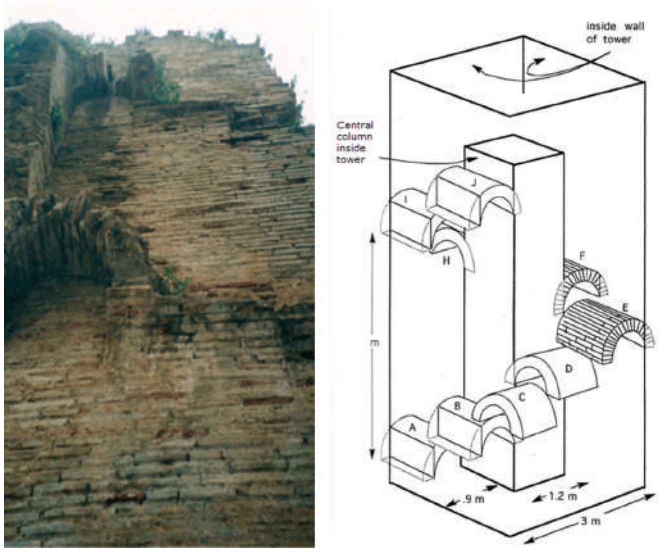

Fig. 29. Aspendos hydraulic tower, central part. Remains of brick vaulting, that supported the 90 cm wide staircase that continued to the tank on top of the tower (photo and reconstruction P. KESSENER).

Of the tower two impressive piers have been preserved today, locally known as 'les Tourillons' (figs. 24-25). Remnants of more piers are still visible at ground surface. According to Jean Burdy, who investigated Lyon's aqueducts, the top of the tower would not correspond exactly to the hydraulic gradient line between header tank and receiving tank but some distance above it. Thereby the pressure difference between the container op top of the tower and the receiving tank at Lyon, the longer and more problematic section of the siphon, was increased (Burdy 1991).

There is a siphon that incorporates even two 'hydraulic towers': the siphon at Aspendos on the south coast of Turkey (fig. 26) (Kessener 2000). Along the course of this 1,670 m siphon there are no natural high points. But the stone conduit was just as well led over sloping ramps to an open tank on top of two subsequent towers, 40 m high. The towers are among the highest buildings of Roman times. They are located at the north of the acropolis of Aspendos (50 km east of Antalya). In the central part of the towers stairways led to the top. Today the stairs are accessible to a height 15 m giving an impressive view to the surroundings. The towers are located at horizontal bends in the line, 16 degrees for the 'north tower', and 55 degrees for the 'south tower'. The containers on top of the towers must have been positioned at the hydraulic gradient line between header tank and receiving tank (at 14,5 m below header tank, fig. 27). In case a closed conduit would have run over the towers at their present height of 28 m, one may calculate that the siphon would not start up because of air pockets at these high points. Originally the towers have been higher, therefore the towers must have been equipped with open tanks to release the air, and, consequently, the open tanks must have been positioned along the hydraulic gradient line between header tank and receiving tank (assuming that the pipe line between header tank and receiving tank had a fixed inner diameter).

The tanks on top had to be accessible on behalf of maintenance and repair, for which a staircase had been constructed in the central part of the towers (figs. 28-29). However, there is no basis to build such enormous towers with open tanks on top in order to release air to guarantee flow as was the case for the Yzeron siphon at Lyon, because there are no natural high points in the siphon´s course. The towers of Aspendos were built for another reason, which, however, also relates to air.

6. AIR AND PRESSURE SURGES

Besides that, air pockets at high point that may reduce the discharge of a siphon or even be the cause of a total stop, air in pressurized conduits may lead to 'water hammer' effects, pressure surges. Water hammer may be defined as a 'pressure surge due to a substantial and sudden change in the velocity of the water', for instance by rapid closure of a valve. The water hammer effect is the driving principle of the 18th c. invention of the 'hydraulic ram'. With the hydraulic ram, which applies a self-repeating automatic shutting of a valve, part of a water stream that comes down from a height h may be lifted to a height ten to forty times h (Stern 1983, 177-179). Ancient siphons were not fitted with valves or shutters. However, water hammer may also be the result just of the presence of air in the line, by interaction of water with the water flow (Schnapauff 1966), especially at uncontrolled start-up, and from air escaping through leaking spots. For the latter case: if in a pressurized conduit a (compressed) air bubble is transported with the flow and passes a leaking spot, air will be released out of the conduit. Because the compressed air escapes much faster than an equal volume of the much heavier water, the water column behind the air bubble will be accelerated as long as air escapes.

When the air bubble is depleted or has passed the leaking orifice, water will leak out again at lower pace and the water flow in the conduit will be decelerated (fig. 30). Applying automatically operating air release valves may thus result to water hammer effects, which effects may be reduced by proper dimensions of the orifice through which air escapes.

The magnitude of the pressure surge that is caused by this can be estimated with Joukowski's law (Falvey 1980, 57-77):

$$dH = 0.5 \cdot c \cdot dV \cdot g^{-1} = C_1 \cdot dV \qquad (7)$$

with
dH = pressure increase in meters of water column
c = sound velocity in water ≈ 1000 m/sec
dV = difference in flow velocity of the water upstream from the leaking spot just before and just after the escaping of air out of the conduit (m/sec)
g = gravitational acceleration = 9.81 m/sec^2
C_1 50 sec.

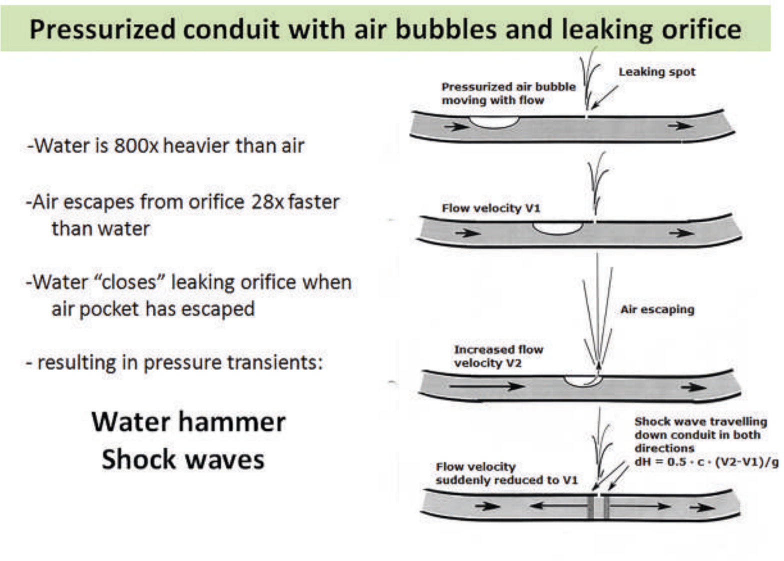

Fig. 30. Pressure surge from air bubble escaping through leaking spot (Illustration P. KESSENER).

So, the pressure surge is directly related to dV: the larger the difference in flow velocity, the more forceful the pressure increase. dV may be determined from continuity arguments, as the decrease of the volume of air in the conduit is related to the escaping of the compressed air through the leaking spot:

$$dV \cdot A_c = V_a \cdot A_b \qquad (8)$$

where
Ac = cross-section of the conduit in m^2
Va = velocity of the compressed air that escapes through the leaking spot in m/sec
Ah = cross=section of the leaking spot in m^2.

Va is set by characteristics of airflow through small orifices under high pressure (Falvey 1980, fig. 45). For instance, for a leaking orifice 12 mm wide and conduit pressure of 40 m of water column as for the Aspendos siphon (about 400 kPa) the air flow through the orifice is about 0,05 m^3 per second. This results in a velocity of escaping air of 440 m/sec, which is supersonic (noise). Thus

$dV = Va \cdot Ah \cdot Ac^{-1} \approx 0.8$ m/sec, and
$dH = 0.5 \cdot 1000 \cdot 0.8 / 9.81 = 39$ m of water column.

This means that for the Aspendos siphon, 40 m deep, and apart from factors that may have a reducing effect such as the presence of many more air bubbles, water hammer from escaping of air through a leaking spot 12 mm in diameter leads to a sudden pressure increase —a pressure surge— of almost 100%. In modern conduits automatically operating air release valves may thus result to water hammer effects, which effects may be reduced by proper dimensions of the orifice through which air escapes.

Leaking spots could not be avoided in stone pipe lines —in contrast to lead conduits— because when installing the pipe elements, the joints were covered with the expanding mixture after which the elements were pushed against each other. A rigorous check to see whether the joints were watertight was not possible; the only thing could be done was to remove excess material from the joint on the inside of the conduit and then install the next pipe element. Only after the entire siphon had been finished and put into operation the quality of the joints became clear. At Aspendos abundant calcareous deposits hanging down from one of the arches of the over 500 m long bridge between the two hydraulic towers indicate that the siphon must have leaked considerably. Moreover, entrainment of air at the header tank was common practice, because the start of siphon's conduit was positioned at or not far below the water level in the header tank (Kessener 2016). When entering the siphon at the header tank a vortex forms that may pull air bubbles into the conduit (compare the emptying of a bathtub). The deeper the intake is below the free water surface, the less readily vortices will form. There is a minimum submergence required to avoid vortex forming with entrainment of air (submergence law):

$$S = D + c \cdot D^{1/2} \cdot v \qquad (9)$$

with
S = minimum submergence to avoid vortexing (m)
D = diameter of inlet pipe (m)
v = velocity of water in conduit
c = a constant.
See e.g. https://paulbrimhall.com/newsletter-archives/submergence-law-why-it-matters/´; also http://www.pumpfundamentals.com/help11.html (July 2019)

For the Madradag siphon, the siphons of Lyon, and for the Aspendos siphon the submergence was much less than the required minimum submergence (figs. 31-32). Once the siphons were running, air thus entered the conduit together with the water and moved down the line with the flow. The air bubbles could then give rise to pressure surges from escaping through leaking spots. The release of compressed air out of a leaking conduit went with noise and water spluttering around, which must no doubt have made an impression on the passer-by who got an idea of the elevated pressure in the conduit.

Inside the conduit the resulting pressure surges traveled both upstream and downstream, causing a sudden increase of the forces that tend to push pipe elements that make up a bend out of position, on top of the forces from static pressure. Reflection of pressure waves on boundary surfaces between air and water (e.g. from air bubbles and slugs) cause pressure waves to be superimposed resulting to even more forceful pressure surges. Such pressure surges may occur repeatedly, in the end exceeding the forces that keep the conduit intact, especially at bends.

Fig. 31. Header tank of the Madradag siphon of Pergamon. A: incoming triple ceramic zero-pressure pipeline. B: 2 m deep settling tank. C: header tank receiving water through holes in separating wall. D: overflow. E: start of pressure line, about 10 cm below free water surface in tank C (adapted from GARBRECHT 2001, Tafel 21-1).

	submergence (cm)	
	needed	estimated
Pergamon	**75**	**10**
Lyon	**80**	**30**
Aspendos	**100**	**20**

Fig. 32. Submergence of intake - required to prevent air entrainment, and estimated from archaeological remains - in header tank for some classical siphons. Entrainment of air was not avoided.

A minor displacement of a conduit element at a bend could result to cracking of the sealing material and the occurrence of an additional leak, whereby the inflow into the conduit at the header tank was enhanced and with it the entrainment of air, so that pressure surges / water hammer effects would occur more frequently. In the end the leaks could get so large that water entered the conduit faster than the incoming aqueduct supplied, so that large slugs would periodically form and move with the water flow. Thus, the Aspendos towers, positioned at horizontal bends of the siphon where the water was led into open tanks (no static pressure), were built to avoid destruction of the siphon at these bends.

Interesting is the siphon de los Arquillos of the aqueduct of Cadiz (Pérez Marrero 2012). The aqueduct of *Gades* was equipped with two siphons, the 3,5 km and 50 m deep *los Arquilles* siphon, and the 19,5 km long low pressure sifon del la Playa that had its end point in Gades itself. The *los Arquilles* siphon, made of an estimated 11,500 conduit stones having a 30 cm perforation, had two intermediate towers positioned

Fig. 33. Remains of 'Torre A' (PÉREZ 2012, Fig. 1).

Fig. 34. Remains of 'Torre B', downstream of Torre A (PÉREZ 2012, Fig. 2).

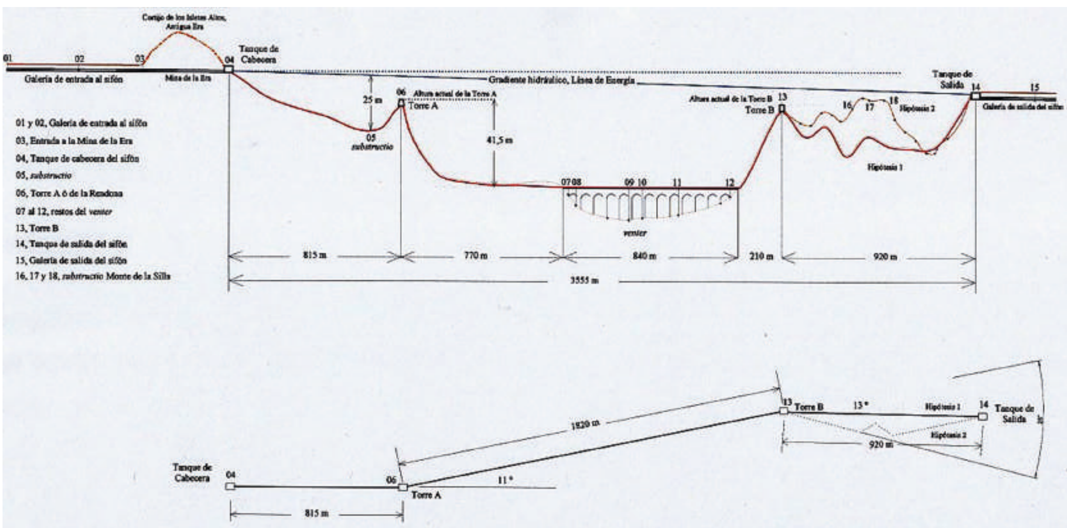

Fig. 35. Siphon *de los Arquillos* of the Gades aqueduct, profile and plan as proposed by PÉREZ (PÉREZ 2012, 112). *Torre A* and *Torre B* must have reached up to the hydraulic gradient line having open tanks on top. The section between *Torre B* and the receiving tank (*Tanque de Salida*) is problematic because of the high points in both hypothetical trajectories, where air pockets may have prevented water to arrive at the receiving tank.

at horizontal bends (of 13 and 11 degrees) in the line, just as was the case for the Aspendos siphon (figs. 33-35). There is some uncertainty about where the siphon started and where it ended, but according to the present state of knowledge the towers were probably 14 and 11 m high, and must have been equipped with open tanks on top. It is not clear whether the towers had sloping ramps as in Aspendos. Between the two towers the conduit was carried for 840 m on a 15 m high bridge across the deepest part of the valley.

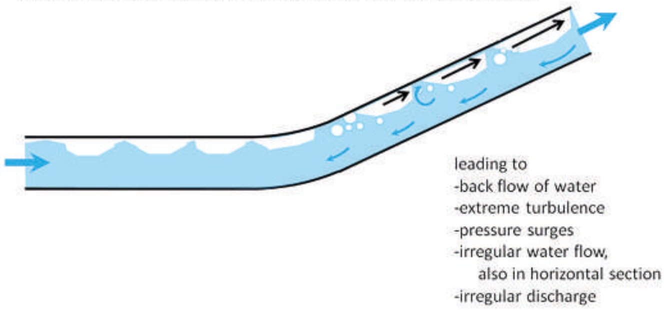

Fig. 36. Interaction of air and water in siphons at uncontrolled start/up (Illustration P. KESSENER).

7. THE START UP OF SIPHONS

There is another situation in which air may be detrimental to the siphon: the start-up, especially of Cat. II siphons. The filling of siphons had to be carried out with extreme care, as problems could easily occur if not first all air was slowly driven out of the conduit. At an uncontrolled, rapid start-up, when large amounts of water suddenly are introduced into the conduit, large air pockets will form and move with the water to be increasingly compressed on their way down towards the horizontal and deepest part of the siphon. Once arrived in the rising section these slugs tend to move up faster than the water and expand due to diminishing static pressure, forcing water to move backwards beneath the slugs, similar to the process called 'blow back' discussed above for conduits sloping down (fig. 35).

This causes pressure surges to develop in the horizontal part of the siphon as well, with rapidly moving spray plugs alternated with stagnant flow and forceful expulsions of air and water from the end of the conduit, endangering the integrity of the line. It has been shown by large scale experiments in the Netherlands that it is indeed the rising section of a siphon that is causing significant pressure surges when there is much air in the conduit (Kessener 2016).

At Aspendos the two hydraulic towers were built at horizontal bends. Hereby the siphon was split up into three consecutive siphons, effectively taking the bends out of this Cat.II siphon. This prevented damage at the bends from static pressure, and, more important, from water hammer effects and pressure surges during rapid start-up. The choice of the Roman engineer to design the siphon with horizontal bends led to the construction of the hydraulic towers. The towers had to be fitted with open tanks on top to reduce static pressure to zero and to release the air at these artificial high points that had to reach up to the hydraulic gradient line. From topographical arguments it can be deduced that the siphon, with two horizontal bends and with two enormous towers, was cheaper to build than a siphon that went in a straight line, without bends and without towers (Kessener 2000).

8. VITRUVIUS

The Roman architect Vitruvius (25 BC) treats in book VIII of his ten books on architecture the means for water conveyance of his days. Translations of Vitruvius' *De Architectura* are available in several languages, among others Fensterbusch 1976 (German), Peters 1997 (Dutch), Rowland 2001 (English). He also describes the technique of siphons and the problems that may occur, and mentions proposals of how to solve these problems. Vitruvius discerns between conduits made of lead (Cat.1) and those made of ceramic pipes and stone elements (Cat.2). He explicitly advises to fill siphons carefully and slowly, as otherwise a 'very strong air (pressure)' (*vehemens spiritus*) may arise that endangers the line (as we have seen above). Before starting Cat.2 siphons Vitruvius recommends to introduce ashes into the conduit to seal possible leaking spots. This sealing procedure, on the principle that dry organic material expands when moisturized, gets stuck into the leaking orifice and closes it off, has survived into our time as a recipe for mending leaking car radiators. For the ancient siphons it was not the loss of water that was quite the problem, but the water hammer effects and pressure surges from air escaping that could endanger the line. Furthermore, Vitruvius recommends to install *colliquiaria* in the line, means to release air from the conduit (*colliquiaria facienda sunt, per quae vis spiritus relaxetur*). The expression *colliquiaria* does not occur elsewhere in all of Latin literature, so that its meaning is not evident leading to many speculations (Fahlbusch – Peleg 1992; Lewis 1999; Kessener 2001; 2002; Ohlig 2006). From the hydraulic arguments above it will be clear that Vitruvius refers to provisions to release air from the conduit —example: les Tourillons— in order to guarantee a continuous water flow (Kessener 2003; 2016).

On the subject of siphons Vitruvius has been critized in the past for not understanding what he was writing about. Hodge 1992: 'his siphon account … does not show any real understanding on the part of the author'. Lewis 1999: Vitruvius' book VIII is '... bitty and discursive, and the sections … on aqueducts, hardly convey the impression of a writer who is master of his subject' (Hodge 1992, 124; Lewis 1999, 145/171). As shown above, Vitruvius' treatise on aqueducts and siphons very well meets the physics of gravity driven conduit systems. It reads like a general manual of how to build water conduits, including pressure lines with the construction materials available at the time.

9. DISCUSSION

The problems that occurred in the ancient pressurized conduits were caused by static water pressure, and, more important, by effects from the presence of air in the siphon, both at start-up as well as during operation. The kind of problems that occur is related to the properties of the conduit, consisting either of homogenous material (soldered lead conduits, Cat.1), or of non-homogenous materials (conduits put together from prefab pipe elements made of stone or ceramics, Cat.2). The archaeological findings show that the ancient engineers were well aware of the problems and knew how to cope with them. For the Cat.1 siphon of the Yzeron aqueduct at Lyon a hydraulic tower was built at a high point to release air so that a stand-still of the siphon was prevented. In the Cat.2 siphon at Aspendos and the *de los Arquillos* siphon at Gades two hydraulic towers were incorporated at horizontal bends, to prevent damage from static pressure and pressure surges from uncontrolled start-up and water hammer. For the ancient siphons only gravity was available as driving force, whereby the head, the difference in level between header tank and receiving tank, was not very large. Problems caused by air became quickly manifest. In the modern systems, with high-pressure pumps and superior conduits such problems may get unnoticed for long periods of time and confront the engineer with unexplained capacity reductions. But the principles that lie at the base of modern pressure lines do not differ from those of the old days: the laws of nature are invariable.

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Índice

El VI Congreso Internacional de Ingeniería Romana organizado por el Colegio de Ingenieros Civiles y celebrado en Santo Domingo de la Calzada en noviembre de 2019, supuso un nuevo hito en la investigación de la ingeniería antigua. En esta monografía se ponen de relieve nuevos aspectos sobre el abastecimiento de aguas y la ingeniería sanitaria en el mundo romano.

Roma fue una cultura donde el agua garantizaba la *salubritas* y *securitas* de las ciudades y convertía a sus territorios en paisajes irrigados. Las estructuras hidráulicas que desempeñaban esta función, sobre todo los acueductos, eran vistas como el símbolo de la grandeza de Roma, de su obra civilizadora. Estrabón los consideraba, junto con las calles y las cloacas, las obras públicas más extraordinarias de una ciudad (Str. 5.3.8); Frontino, por su parte, dice que son más útiles que las pirámides de Egipto o las famosas construcciones griegas (*Aq*. 16). Pero, como se puede leer en estas páginas, los acueductos no son solo las admiradas arquerías de que en ocasiones disponían, aunque realmente son casi las únicas estructuras que el imaginario colectivo ha asociado a este valiosísimo legado romano. El abastecimiento de agua quedó garantizado por tuberías de diversas naturalezas, galerías subterráneas que conducían el agua por el subsuelo, o canales de fábrica cubiertos que, aunque no son perceptibles a simple vista, sí que formaron parte entre todos, junto con las arquerías, de esas grandes obras de abastecimiento de agua potable que dotaron de salud, bienestar y seguridad a aquella civilización por todo el *Orbe* entonces conocido.

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