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Vitruvius mysterious COLLIVIARIA decrypted?

I. The Problem

The Roman architect VITRUVIUS published around 22 BC, his famous work: 10 Books on Architecture. In Book 8, Chapter 6, where he writes about the water pipes, he mentions the *colliviaria*.
So far one has been unable to clearly see what VITRUVIUS understood by it. The word has been taken over untranslated in the revisions of the work for centuries.

There is no lack of explanations in an extensive secondary literature on the concept *colliviarium*. On one hand, no connection of the word is occupied by archaeological evidence, on the other hand, the word in its various spellings *colliviarium* is not to classify in the well-known latin vocabulary. From the texts only emerges: the *colliviarium* is a special device. Form and function are not specified. The purpose VITRUVIUS described quite clearly: c*olliviaria* shall protect pipes against the force of the water.
An attempt is made to analyse the question: How did the *colliviaria* look like? The Problem should be illuminated with a new methodological approach from the perspective of various disciplines and bring a closer clarification. Traditional translations of VITRUVIUS *vis spiritus* with "air pressure" are in need of critical scrutiny: Already after 1918 Stehlin had pointed to the incorrect translation of the term.
Special attention is given the engineers view for interpretation of the phenomena described by VITRUVIUS. In addition, recent archaeological findings are included.

II. Critical View about Text on *COLLIVIARIA*

The text Reflections on VITRUVIUS are initially based on the translation of *Fensterbusch* in German, which book also contains the Latin text. Moreover, the relevant passages in several Latin, German, French, Italian and English text issues were reviewed.

About "*vis spiritus"*

After a review of the relevant bodies in VITRUVIUS is striking the „*vis spiritus"* was translated from *Fensterbusch* as well as by many predecessors without scruple with „air pressure". The analysis of passages which show that this translation is not only misleading but wrong as *Ohlig* has demonstrated in a comprehensive study.
Under linguistic and technical point of view today in the sentence of ViITRUVIUS (8/6/6): *etiam in ventre colliviaria sunt facienda, per quae vis spiritus relaxetur.* (Even in the belly [the horizontal piece of pipe that crosses a valley floor colliviaria are provided through which the *vis spiritus* will be weakened) we translate the word *spiritus* with "impulse" and *vis spiritus* with "impulse force". In 8/6/9 VITRUV writes: *ita librata planitia tubulorum a vi decursus et expressionis non extolletur. namque vehemens spiritusl in aqae ductione solet nasci, ita ut etiam saxa perrumpet, nisi primum lentiter et parce a capite aqua immittatur ...*
"Thus, the horizontally extending tubes [while filling the line] are not brought from their position by power of down flowing and up-driven water. It emerges namely through the flow of water so fierce *spiritus*, that even stone blocks are scattered if not first from above water slowly and sparingly is inserted "
At this point arises clearly from the context, the observed consequences, (..that even stone blocks are scattered) an engineer will here translate the word *spiritus* in general with impulse, in the present case even with water hammer.
In the description of the same facts PLINY used the term *impetus*, which is in this context also to translate with impulse.
If *Fensterbusch* translates the word *spiritus* as air or air pressure, he moves in the centuries-old tradition of earlier authors who translated terms that had them unclear just as their predecessors.
For further consideration we translate VITRUVIUS *vis spiritus* here with "Impulse force" or "Transient".

III. Explanations of the word Colliviaria

Collis quinaria by PINY could mind: "Push-5-inch hole" into which by transients flows water.
Colluviarium can come from *colluvio* = confluence or mishmash. This vividly describes how a pressure wave lets water and air swirled into an air chamber.
Colliviarium is probably the translation of a Greek term. But no technical term came down to us from Greek. We have the same problem with holes in piping, for which no name is known in Latin and Greece, although the holes in Roman as in the Greek water mains were applied. In Greece they were known for centuries. Where the terms are missing, explanations remain conjecture.

IV. Closer examination of shape of Colliviaria

The following facilities can avoid water hammer damage:

•standpipes in towers with free surface of water above
• Double standpipes, open at the top

• Valve
• burst cover
• air receiver, surge chambers

One of these facilities will have been our *colliviarium*.

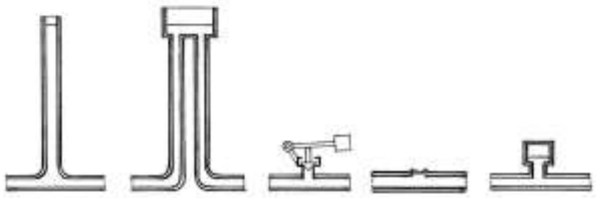


FIG. 1.

V. Morphological study

All these facilities were considered in terms of all its features. These were listed and evaluated in historical, archaeological and especially in the technical context, of which only a few points can be reproduced here.

Strikingly each of these facilities can have several functions. The function to reduce transient impulse forces was not the main function in all those facilities.

There can be found remains of standpipes and towers or columns (*columnaria* of *columna* = column), which in case of two pipes had a gravity pool above.

These facilities have been associated with the concept of *colliviaria*. They should rather be called under the Roman term *castella.*

Valves (*asses*) were known from the pump construction. Because of their maintenance requirements they will have been hardly used in pipes. We can not interprete *colliviaria* as valves, because there are no adequate indications for this, neither in text nor in archaeological findings. Also unclear is still the function of small holes, discovered in stone tube elements, that may serve to prevent water hammer.

Surge chambers may have been known since heron. Similarly acting air chambers that were found on top of horizontal pressure lines could have been named *colliviaria* by VITRUVIUS and PLINY.

-Result of the study is: The main function of air chambers above a pipeline is degradation of transients. Thus, the search for *colliviaria* focused on air chambers.

VI. Archaeological findings

Various structures have been associated with colliviaria

Some examples are mentioned:

Fig.2 One of two giant water towers in the aqueduct of Aspendos (Turkey)..

There, from the original more than 2,000 tube stones are even individual specimens with vertical holes that indicate *colliviaria. Fig. 3*

FIG. 3. Aspendos

• The TOURILLONS de CRAPONNE the Roman aqueduct to Lyon (France). The high towers shortened the relevant length of pipe sections for transients. -*Colliviaria* in the pressure lines were not required, since pipes were made of lead which could withstand transients.

• Elbows upward in the clay tube-pressure line to CAESAREA (Israel), as they exist in the same form in Budapest (Hungary).

Fig. 4. Caesarea

These installations, which also served to shorten the pipe sections can, in VITRUVIUS sense, probably be regarded as *castella*.

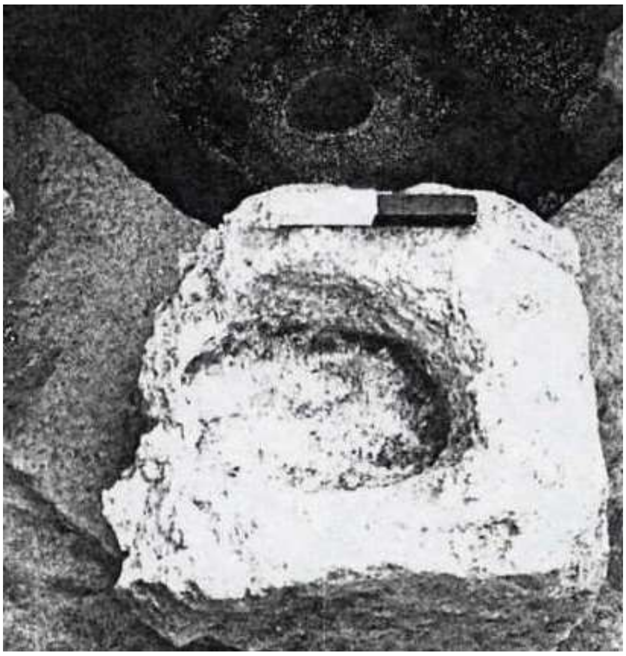
At horizontal pressure pipes, whether they be concreted clay pipes or of hewn stone lines cemented together, are often found in different distances holes with diameters of approximately 15 cm (~ 5 inches) vertically upwards, round, oval, cylindrical, conical, double conical, with small or more wide passage smooth or roughly trimmed, now mostly open. While

In operation, the holes were closed by branching tubes, by covers or by bungs.

• PATARA (Turkey), pressurized water line, about 3 km north-east of the city; many of the tube pieces have on the top downwards tapered holes.
FIG. 5.

• Two-strand Stone pressure water pipe at LAODICEA (Turkey) with numerous primary and secondary vertical holes in the block center and in joints. In the valley, another line piece in situ is present. There, the line has not yet been studied to closed holes on top in detail. (Fig. 11) A carved stone in the shape of a *colliviaria* cover stone similar to that in Susita (Figure 6) was still in 2002 near the road leading west outside the city of Laodicea.
• SMYRNA (Turkey). There are still 60 stones present of a pressurized water line, which would have to be examined with view on *colliviaria.*
• DOUGGA (Tunisia) pressurized water line
• In OINOANDA (Turkey), an insitu line should be checked for perforated stone elements and for cavities.
• SUSITA, ANTIOCHIA (Israel / Syria). Part of the underground pressure line. -Approximately from the 2nd century AD.- are still present *in situ.* Vertical holes 10 to 18 cm in diameter can be found in irregular intervals in the stone blocks. At one point, a special capstone was excavated with a cast in chamber.

Figure 6. Cover-stone lifted and turned above *colliviarium*



Many stone pipes with perforated elements found in the eastern Mediterranean indicate *colliviaria*.

VII. Engineers considerations to transients in pressure water pipes

At all times it was an important task for pipe fitters to avoid burst of pipes. That is precondition for reliable water supply. At that time there were no steel pipes, not plastic pipes and not our calculation tools.

Transients

In a compressible medium, each change in velocity causes a pressure wave. In the pressure wave front (as in sonic boom) move areas with very high pressure. Pressure waves are the cause of water hammer in pipes. Water hammer can be heard occasionally in home water pipes when a valve was suddenly closed.

Such hydraulic shocks or transient states are called "**transient**". They were already described in 1898 as formula by Joukowski. Today pipe fitters have extensive computer programs to their predictions.

Pressure waves

Pressure waves occur in a flow through pipe when you open and close as well as at any speed change of fluid. When the outlet of a pipe is closed, the information about current stop moves as a pressure wave upstream with speed of sound. The pressure wave is reflected at the inlet as a suction wave and travels downstream. At discharge it is reflected again and so many times walking in a decaying oscillation back and forth. In this case a conversion of the kinetic energy of the flow into potential energy and vice versa takes place each time. The potential energy can be found in compressed water and in the elastic tube wall. Since the elasticities of water and wall are very small, there emerge high pressures in the water.

As dangerous as pressure waves are suction waves: By vacuum pipelines can implode. Fatal are suction waves, in which the vapor pressure of water (ca. 0.03 Bar), is undershot. The water column separates. The result is a cavity. This cavity closes immediately. The colliding water columns lead locally to a high pressure that destroys the line.

A suction wave can thus bring to imploding or bursting the pipe. In Southern California in 1991 burst a water pipe as a result of pressure waves. Fig. 7. This created a suction wave that folded up the line more than 500 m length. Fig. 8.

Fig. 7 Water pipeline to Los Angeles crashed by pressure wave

Fig. 8 Water pipeline to Los Angeles imploded by suction wave

Pressure waves occur in each line. The risk depends on many factors that must be examined in each individual case.

Simple calculation of pressure waves

After Joukowski the duration **t** of a pressure wave along a tube of length **l** is:

$$t = l / c_o$$

co is the speed of sound. For water is expected co = 1000 m/s, with elasticity of apipe wall is taken into account.

Example: Duration of a pressure wave back and forth in a 2-km pipe is 4 seconds.

Increase in pressure dp in a pressure wave is calculated by

$$dp = Rho \cdot c_o \cdot dv$$

with **Rho,** the density of water and **dv,** the change in velocity of water.

For example, when a line suddenly is closed while water flew with a velocity of 2 m/s in pressure wave a transient pressure arises at 20 bar.

Reduction of pressure waves

Pressure waves are reflected at the tube end, at branches and with cross-sectional changes. In short pipes the period of the pressure wave is shorter than the time for changing the speed. Onward and backward

waves are superimposed, pressure- and suction waves cause interferences which reduce the peak pressures.
- Meets a pressure wave an air chamber, then water flows into it. Thereby air is compressed: The pressure wave is partially reflected and travels weakened further.
- Flexible pipes and pipes with air bubbles reduce the resulting sound velocity of the liquid, the positive and negative pressure pikes of pressure waves are drastically reduced. Thanks to this mechanism, we can live: Transients excited by our hearts are degraded in the elastic arteries.

In summary: Short pipe sections and elasticities hold transients at bay.

Air chambers

The now mostly open holes on the top of the preserved remains of stone penstocks must have been closed as long as the lines were in operation. Under the capstone or the not quite down to the channel reaching Plugs there was in each case a cavity, an air chamber.
This air chamber fills up on itself: In each of a gravity fed water pipe air is entrained. In the horizontal flow through line, the bubbles rise up and unite for bigger size bubbles. These move with flow to the upper tube wall until they are stopped by an obstruction or they flow into an air chamber. Thus the function of the air chambers is maintained even when small air losses occur.
The chiselled top in perforated masonry holes formed air chambers, which were sealed with mortar cemented capstones or with conical bung stones. Capstones, as they were found in Susita, withstood only low pressures. In deeper localities of a line with pressures of 4 bar and more deck bricks and mortar alone were not sufficient. They used bung stones, cemented and possibly secured with iron cramps.

Fig. 9. *colliviarium* stone with cramp holes

It is also reported a special bayonet joint to a conical rock, which has been wedged after the insertion by rotation.
Conical bung stones were state of the art.

FIG. 10. Perge, conical bung stone on an ancient sewage line

Vertical holes in pipes only had to be tigtly sealed where inside pressure head was higher than atmospheric pressure. Small pressures were also at the beginning and sometimes at the end of a discharge pipe. There, the cover could be leaking. Holes in water pipes may also have had other functions. Not every hole can be regarded as air chamber to avoid water hammer damage.
To promote our knowledge about the purpose of the various holes and the connection with those required by VITRUVIUS *colliviaria* all pipe residues should be studied systematically, especially those of the composite from stone blocks.

FIG. 11. LAODICEA in situ venter line with tube stones

VIII. Aspects in the realisation of aqueducts then and now.

While transports water in our day through penstocks and height differences overcomes by pumping, ancient engineers mostly exploited natural slope to avoid consideration of the material characteristics of tubing

and high internal pressures.
Pressure lines were constructed to cross hollows. They were less expensive than high aqueducts. With this advantage one gained the disadvantage of tread by transients. Particularly at low pressure.
The lower the operating pressure, the higher the ratio of the pulse pressure to operating pressure, so higher the risk of damage. That demanded special measures by engineers.

IX. Holes in ancient pipes before VITRUVIUS

In this consideration beyond pressure pipes also are included partially filled and largely unpressurized lines.
In Greek culture area clay pipes were used not only for distribution lines, but as well for long mines to the cities. Fig.12. Many of the clay pipes were with holes cappedabove, which are usually considered to be openings for inspection, cleaning and repair.
Pipelines usually worked partially filled. In case of water surplus a normally partially filled line can run completely filled. This line is exposed to transients.

Fig. 12 Greece clay pipe with hole, Athens

The encountered holes in such lines could have been a means of limiting transients, when the tube once ran fully. Be it either as air chambers, or by deliberately throttled leaks at the top of the pipe, these means decreased suction waves as well as pressure waves.

X. Result of the investigation

VITRUVIUS and PLINY have left us the word *colliviaria* or c*ollis quinaria* for one thing, they have not described.
On the other hand there are archaeological findings, strange holes in ancient pipelines whose purpose was until now puzzling. Nowadays the function can not be checked at the object, because these pipelines are out of operation and they are only present in fragments. Here a thought experiment could be useful: We tried to assign the ununderstood word *colliviarium* too the ununderstood object, the hole in the pipe.
Engineers considerations and the recent archaeological findings (Susita) show that air chambers provide exactly what VITRUV describes as purpose of *colliviaria*.
For those holes we have found only two functions: inspection opening and damping of the shock waves. And the findings in Susita, the chamber in capstone has the function to form an air cushion. Thus, the previously mysterious holes in many preserved blocks of pressure lines can be identified as air chambers, as the *colliviaria* postulated by VITRUV.

XI. Summary

A more detailed review of the relevant citations in VITRUV showed, the purpose of ***colliviaria*** was to avoid water hammer damage. Based on the new findings better word translations for ***vis spiritus*** are proposed. The various functions of devices were analysed, which in rich secondary literature were discussed as possible *colliviaria*. Further considerations were made about phenomena of transients in pipelines. These considerations and the analysis of recent discoveries provide evidence to look enigmatic holes, particularly the sealed holes on the upper side of pressure lines as *colliviaria.* This can be the starting point for the study of other issues that arise in ancient aqueducts.

XII. Illustration of pressure waves and their damping by *colliviaria*

The phenomenon of transients eludes naturally simple observation. Only at consequences you see that ghostly and often destructive forces were involved.
In an analogous experiment with air in a pipe the effect of a pressure wave can be shown and how the pressure wave can be degraded by c*olliviaria*.
A tube is closed at one end by a plug. In the other end a piston is inserted. Subtracting the piston from the tube, the pressure drops in the pipe until the piston emerges and suddenly releases the opening. Air flows into the tube. Information travels much faster than the air flow, with speed of sound, 340 m/s, as a pressure wave along the pipe. The energy in the shock wave is so high, that the plug at the end of the line is forcefully expelled.
The c*olliviaria* are simulated by small pipe sockets closed with soft rubber teat. These soft elements in the air line are similar to the compressible air in the chambers of the aqueduct.
The experiment with the rubber finger cot *colliviaria* shows the decrease of transients: The plug is only weakly or not at all expelled.

Fig, 13
colliviarium simulated by pipe socket

XIII. Appendix
Sensitized by the Conference in Ephesus, where the new interpretation of c*olliviaria* was presented G. Wiplinger discovered in the excavation site under piled pipe stones of the ancient aqueduct of Ephesus some stones with *colliviaria*.
The holes are original closed with mortar sealed conical stone plugs.

Fig.14 Ephesus

The stone plugs do not reach to the tube profile. They form a cavern. The volume is small compared to the large one in Susita, but enough to mitigate the transients effectively. These archaeological findings are further evidence of the colliviaria hypothese from 2004.

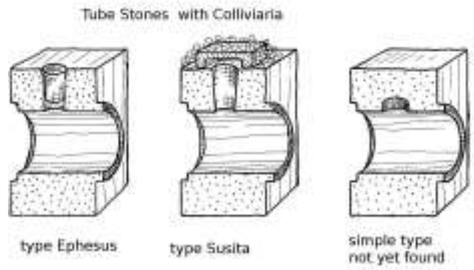
Fig.15. Cavern on top of tube

A special pipe stone in side position, found one museum grounds in Ankara, was described by M. Bildirici. The tube element also has the original Stone plug. An inside cavern can not be seen in the picture. - Visitors are encouraged to explorate inside-.

Fig 16 Ankara

Roman colliviaria were not standardised.

Fig.17 different types of *colliviaria*



If ancient stone cutters really understood the function of colliviaria, it would have been much easier for them to cut a tight small cave from inside in top position in one or the other tube stone before all ware fixed in line. Instead of holes with cemented bungs or cover stones. Perhaps those simple type cavities can be found now in ancient stone lines *in situ* by aids of pipe-tv.