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Roman hydraulic engineering: two Vitruvian problems

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The meaning of the word *colluviaria* and the stated purpose of release of *vis spiritus* has, for a long time, exercised the ingenuity of translators of Vitruvius. *Colluviaria* is clearly connected to *colluvio*, which means a heap of rubbish, or collection of unwanted material. *Vis spiritus* can be translated as 'breath (or wind) of force or violence', which could be interpreted as compressed air, but could also mean 'soul or essence of force' which might refer to the release of the hydrostatic pressure in the siphon. The Author points out correctly that drain valves, at the bottom of the pipe, would be essential for maintenance and repair of the siphon. His suggestion that some type of automatic air discharge valve would be necessary, particularly under reduced flow conditions, is less convincing. It is clear that some form of penstock or stop log for each individual pipe would be needed at both the upstream and downstream end of the siphon, to enable repairs to be carried out to one of the pipes without shutting down the whole system. Given such provision, it would be a simple matter to close off one or more pipes if air entrainment problems should arise because of inadequate submergence under low flow.

56. The remarkable accuracy with which the Roman engineers were apparently able to carry out their surveys remains a mystery. Both the *chorobates* and the *dioptra* depend on the ability of the human eye to align two nearby sighting marks with a distant target. It seems hardly possible that the gradient of part of the Nîmes aqueduct—0·07 m/km, or 7 mm in a sight of 100 m—could have been achieved in this way. The 'garden-hose' method suggested by the Author could, in principle, give this degree of precision, but it seems hardly conceivable that it could be extended over distances of many kilometers.

57. However, the greatest mystery of all is why the Romans thought it necessary to construct the Lyon system of aqueducts. This enormous project included the construction of some 250 km of access roads in rough terrain, numerous construction camps, the opening of quarries and the transport of more than 10 000 tons of lead and 500 000 m^3 of rock. It was constructed to supply water to the city of Lugdunum situated on a plateau some 130 m above the river Saône, near its confluence with the Rhône. The site was no doubt chosen by the predecessors of the Roman colonists for reasons of defence, but at the time the aqueducts were built, the surrounding areas had long been pacified. There would certainly have been port installations on the Rhône, and there was ample land available for development of a city on the river bank. The Romans were familiar with the waterwheel and the Archimedean screw pump, and could easily have supplied a city at such a location with water from the river, at far less cost and with greater security.

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58. Many other aspects of Roman technology are worthy of study by modern engineers. In particular, their design methodology, before the invention of algebra and with the handicap of a clumsy system of numeration, produced many elegant solutions and was often applied on the boldest scale. It is to be hoped that others will follow the Author in applying current methods of analysis to studies of the masterpieces of Roman engineering.

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W. G. Lockett has contributed a valuable and interesting Paper on aspects of Roman hydraulic engineering. It is exceptionally useful to have an analysis of the flow capacity of open-channels and inverted siphons, to notice the extent of the variations and to be able to appreciate the nature of the operational problems which must have arisen when open-channels and inverted siphons were coupled on the same aqueduct.

60. Nevertheless, the problem of Vitruvius's *colluviaria* remains troublesome. If air *were* entrained right to the bottom of an inverted siphon, I should be surprised if Roman techniques were sufficiently well equipped to release it at pressures corresponding to depths of 50–100 m and more. Mr Lockett supposes (§ 33) 'that similar conditions would have appertained at many siphon installations in Roman times; in other words, the phenomenon would have been widely observed.'. One must bear in mind, however, that in fact not too many inverted siphons were built by the Romans, as far as we know, so that experience of their operational characteristics must have been relatively limited. To my mind, the preferable explanations of ancient engineering problems are the simpler ones, not the more elaborate. In other words, if air entrainment did manifest itself as a day-to-day problem, I can envisage a much more straightforward solution, namely a progressive closure of the pipe inlets in the header tank to ensure a sufficient submergence of those pipes continuing in flow. Having air rattling about in a long, soldered tube was a phenomenon to be avoided rather than a problem to be solved. So how do we explain Vitruvius's statement? Given his dependence on Greek sources, it remains a possibility that his preoccupation with air-venting is based on a confusion between inverted siphons and true siphons, the latter being devices for which the classical world did recognize the air-locking problem.

61. I agree entirely with the Author that setting the gradient of an aqueduct using water-levelling or an A-frame with plain sights (as has been a common method in relatively modern times) was not so critical as the original survey to determine the relative levels of source and delivery. However, I am less than certain that the Author is correct in supposing that Hero's *dioptra* was the best instrument for the job. Levelling with plain sights requires, above all, a long instrument, and notwithstanding Vitruvius's statement, possibly incorrect, that the *chorobates* water-level was a mere 5 ft in length, the 6 m overall length of the device is surely inherently more accurate than the 2 m of a *dioptra*.

62. Finally, I doubt that there is any great need to accept or refute the gradients recommended by Vitruvius or Pliny. Roman engineers had no more control over the topography than any other water-supply engineers. Getting water from source to city was a question of adapting gradients to the distance between rather than of slavishly trying to prove that such-and-such a slope was the one to use. Basically, the challenge was to make sure it was all downhill.

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The *chorobates* length of 6 m does not limit its usefulness for levelling to that length. Looking along the top surface, especially if notches are added, might extend the range to as much as 50 m. The level, horizontal line could have been transferred, as shown in Fig. 18. An error of as much as 5 mm every 50 m is only 1/10 000. That accuracy is probably attainable if levelling is done in self-closing loops and if, as is normal practice, errors are adjusted for. The *chorobates* could also be reversed to cover notch errors. The Roman engineers may have achieved the required accuracy of 1/5000 with a *chorobates*, provided that the user was slightly long-sighted.

64. The method would have allowed several kilometres of progress daily, which is quite sufficient for the original surveys.

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The most valuable use of an outlet at the bottom of an inverted siphon is to flush out sediment and debris which collects under gravity (the dregs and impurities (*colluvies*) of de Montauzan: §§ 14 and 15 of the Paper)—the word *colluvium* is used today to denote a random mixture of sedimentary material.

66. It can be surmised that common (Roman) usage led to aqueduct outlets being referred to collectively as *colluviaria* (the misuse of words persists today: e.g. borrow area—what confusion for the future; did they ever pay it back?).

67. The Author believes that Vitruvius may have been 'out of touch': and he may well have used this colloquial term for vents for releasing compressed air without regard to its literality. Nevertheless, thanks to Vitruvius, Lockett *et al.* for showing us that 'the more things change, the more they stay the same'.

Mr Lockett

Regarding Vitruvius's *colluviaria*, the remarks of all contributors underline the essence of our problem: the use of an unknown word for an obscure piece of gadgetry to deal with an apparently bizarre phenomenon. We are obliged to speculate, but in doing so, we must ensure that our explanations of the gadget and the phenomenon are compatible.

69. *Mr Daniell* and *Mr Duder*, like de Montauzan (see § 14), associate the word *colluviaria* with waste material. Mr Daniell goes on to argue that *vis spiritus* could be translated as 'hydrostatic pressure'. This being the case, there is no question that the device Vitruvius refers to is simply a drain valve used for the necessary

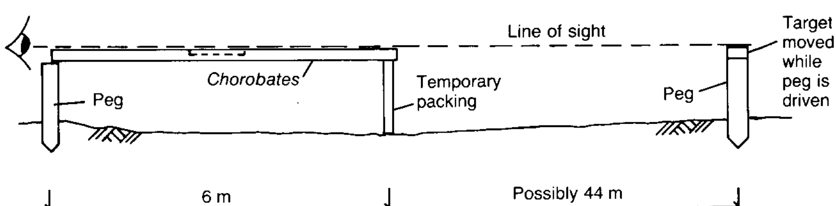

Fig. 18

emptying of the siphon for maintenance purposes. Had this interpretation of the Vitruvian text been generally accepted in the past there would surely have been no controversy.

70. While admitting the possibility that air could be entrained in the siphon, both *Mr Daniell* and *Dr Smith* suggest an alternative solution to the problem: having first determined the source of the entrained air, post a 'waterman' at the header tank of each siphon, with a standing instruction to maintain the water surface above the level at which vortices tend to form; this will be achieved by the plugging and unplugging of the inlets to the siphon pipes. Depending on the variability of the aqueduct flow, this could involve daily visits or a 24-hour watch. This eminently sensible explanation disposes of the *vis spiritus* problem, but leaves us in the dark as to what was a *colluviarium*.

71. I still have difficulty with *Dr Smith's* suggestion that Vitruvius might have been confusing the pipe systems used to convey aqueducts across valleys with the conventional Greek 'siphon', which was used for emptying wine bottles and is rarely, if ever, discovered in aqueduct systems. I have not found that Vitruvius uses the word 'siphon' in the context of aqueducts, and its appropriation, with the qualifier 'inverted', to describe a U-tube must surely have occurred long after classical times.

72. My approach was to examine the possibility that Vitruvius meant exactly what he is commonly assumed to be saying: i.e. that devices are to be provided in the *venter* to release the compressed air (or relieve the air pressure). This required demonstrating that air could be entrained in inverted siphons and, if so, that the circumstances under which this could occur appertained in the real situation of a Roman aqueduct. In the absence of any refutation, the claim can then be made that there could have been a *vis spiritus* problem. But I acknowledge that I have no grounds (other than the circumstantial evidence of Castelli's experiments) for insisting that the Romans solved this problem by making an elaborate air-valve which they called a *colluviarium*. In fact, if classical scholarship could confirm the interpretation, *Mr Daniell's* is the most straightforward explanation yet.

73. Some supplementary comments about the phenomenon of trapped air (*vis spiritus*) appear to be relevant. The Ragged Chute inverted siphon for generating compressed air (see § 18) incorporates a vent pipe which, according to an unpublished description, periodically 'blows the compressed air and water to a height of over 100 feet'. In the early 1950s, I was informed that a similar outburst of water and air apparently occurred in the vents from the vortex chambers incorporated in the side-stream intakes of the Affric development in Inverness-shire, the model experiments for which were described by Wilfred Eastwood *et al.*[24] I would suggest that any air which *might have been* entrained in the Roman aqueduct siphons would most likely have drawn attention to itself in a somewhat dramatic fashion.

74. *Mr Daniell* raises the question of why the Romans went to the enormous expense of constructing the Lyon aqueducts in the first place. This is, of course, a historical problem rather beyond the scope of the present Paper. However, it cannot be denied that the construction of the water supply to Rome itself was a similar massive undertaking which was, in fact, carried out over the course of several centuries. Both Rome and Lyon are located on the banks of rivers from which water could indeed be obtained by a variety of known devices. The fact is that for their public baths and fountains, as well as for consumption, the Romans seem to have preferred water drawn from wells or springs, or at least from small

streams which presumably were less polluted than rivers used for navigation and for the disposal of sewage.

75. Regarding the mystery of how the Romans surveyed their aqueducts, all commentators point out correctly that the accuracy of a levelling instrument depends on the length of the sighting line, and the *chorobates* is admittedly about three times the length of the *dioptra*. Furthermore, as *Mr Scopes* states, there would be no difficulty, given clear reference marks or notches, in sighting forward up to 50 m. But the first requirement remains that the sighting line, whatever its length, must be horizontal. Vitruvius seems to prefer the plummet method of setting up the *chorobates*, rather than the water trough which he would use when 'the wind disturbs'. However, to achieve an accuracy of 1/5000, a plummet 1·5 m long would have to be set within 0·3 mm. Could a (long-sighted) Roman surveyor accomplish this? My own tentative preference for the *dioptra* is based on my conviction that some form of U-tube water level was the most accurate way known of establishing a horizontal line. The suggestion of a 'garden-hose' device was, of course, pure speculation, but at least this would have enabled levels to be carried forward in lengths of, say, 20 m per 'set-up' without involving any sighting whatever.

76. Of the two sources of error in surveying—systematic and random—my opinion is that the Romans probably knew enough geometry to eliminate many of the systematic errors by the normal methods of instrument reversal, reciprocal sighting, etc. Presumably, they would also have repeated their traverses a number of times, but how would they have dealt with a 'scatter' of results which might *not* reduce with an increased number of repetitions? Given our present knowledge of the theory of errors, some indication of the precision of Roman surveying instruments could be obtained by carefully conducted field tests of replicas. Such a project might be suitable for a class of students in the History of Technology. In the meantime, the manner in which the Romans planned and set out their aqueducts must remain a mystery.

Reference

24. W. Eastwood *et al.* Scale model experiments on high-head siphons and vortex chambers connected thereto. *Proc. Instn Civ. Engrs*, 1953, Part I, **2**, No. 5, Sept., 556–584.