THE ROMAN WATERMILL IN THE ATHENIAN AGORA
A NEW VIEW OF THE EVIDENCE

AMONG STUDENTS of ancient water power the work of Arthur Parsons is well known. During the early 1930's excavations in the Agora of ancient Athens revealed a most interesting and important specimen of a Roman watermill. Parsons produced an unusual and stimulating interpretation of the evidence,[1] skillfully comparing and illustrating his analysis and findings with the well-known text of Vitruvius.[2] The reconstruction of the mill, which sprang from his keen observations and understanding of the mechanical evidence within the building fabric, remains to this day a major contribution to our knowledge of Roman watermills.

To historians of technology the important and unique features coming from the Agora specimen are the critical dimensions of its water wheel, wheel-shaft journals, and driver gear. Parsons' interpretation of this evidence provides us with the only example of a watermill *geared down* in the manner which he believed to agree with the Vitruvian text. The relevant Latin text is as follows:

> Eadem ratione etiam versantur hydraletae, in quibus eadem sunt omnia, praeterquam quod in uno capite axis tympanum dentatum est inclusum. Id autem ad perpendiculum conlocatum in cultrum versatur cum rota pariter. Secundum id tympanum maius item dentatum planum est conlocatum, quo continetur. Ita dentes tympani eius, quod est in axe inclusum, inpellendo dentes tympani plani cogunt fieri molarum circinationem. In qua machina inpendens infundibulum subministrat molis frumentum et eadem versatione subigitur farina.[3]

> Mill wheels are turned on the same principle, except that at one end of the axle a toothed drum is fixed. This is placed vertically on its edge and turns with the wheel. Adjoining this larger wheel there is a second toothed wheel placed horizontally by which it is gripped. Thus the teeth of the drum which is on the axle, by driving the teeth of the horizontal drum, cause the grindstones to revolve. In the machine a hopper is suspended and supplies the grain, and by the same revolution the flour is produced.[4]

Although Parsons had doubts about the translation of the words *secundum id tympanum maius*, he took them to mean that the millstones revolved slower than the water wheel.[5] Morgan[6] and other editors of the Vitruvian text, however, agree with Granger that the description applies to a *geared-up* arrangement; i.e. millstones turning faster than the water wheel. Moritz questions this translation and suggests that its proper meaning related to a

[1] Arthur W. Parsons, "A Roman Water-Mill in the Athenian Agora," *Hesperia* 5, 1936, pp. 70–90 (= Parsons).

The author is grateful to Mr. Peter Saunders for the constructive criticism provided on the technical aspects of this paper and to Dr. Norman Smith for his encouragement and invaluable guidance on the development and structure of the analysis.

[2] *Vitruvius. The Ten Books on Architecture*, M. H. Morgan, trans., New York 1960.

[3] Vitruvius, *de architectura* x.5.2.

[4] *de architectura*, F. Granger, trans. (Loeb Classical Library), London 1962, pp. 304–307.

[5] Parsons, p. 77, note 2.

[6] Morgan (footnote 2 above).

geared-down arrangement (millstones slower than the water wheel).[7] More recently Norman Smith has pointed to the dangers of expecting Vitruvius' mill to be the one with which we are familiar from later periods.[8]

The present author intends to show that an alternative hydro-mechanical analysis can be derived from the Agora evidence to suggest that a "fast" water wheel existed, driving *geared-up* millstones, like all other vertical-wheel watermills. Integral to this analysis is a re-appraisal of the water-control methods, the wheel-shaft journals' alignment, and the millstones.

Water Control

With a constant flow of water onto the wheel, the interaction of such variables as the weight of the top millstone, its dress (sharpness and design of grinding face), variability of corn (moisture content, origin, type), and the rate of feed would affect the speed of the mill, sometimes considerably. Theoretically, a new and much thicker runner, say four times as heavy as the original, would require four times the power to maintain the same speed (all other variables being constant). But whatever the operating condition, the miller would most likely have operated the mill at the highest possible speed appropriate to the mechanical design and normal hydraulic conditions, subject to the qualitative limits of the product. To facilitate this he needed to be able to vary the volume of water flowing onto the wheel in order to control speed and also to stop the wheel altogether to effect repairs and carry out maintenance work on the machinery.[9] To provide control the water had either to be diverted from the headrace through a bypass or deflected from the wheel itself.

It is most fortunate for this analysis that substantial lengths of the headrace were found, allowing us to determine water levels and flow rates to the mill. When, in 1959, during further excavations some forty-five meters to the south beneath the pronaos of the Southeast Temple, the pit of another water wheel was found,[10] our knowledge of the waterways serving the lower mill (Parsons) was then complete. With such proximity the tailrace of the upper mill was the headrace of the lower mill. If a bypass existed serving the lower mill, it could be expected to be positioned close at hand so that the miller had the advantage of effecting quick changes to the flow rate. It was most unlikely to have been positioned any distance upstream of the mill because the delays in diverting water, especially in emergencies, would be unacceptable. No bypass channel or conduit has been found by archaeologists, however, and now that the entire watercourse between the mills is known and revealed we may reasonably conclude that none existed.[11] Perhaps we should also note that

[7] L. A. Moritz, "Vitruvius' Water-Mill," *The Classical Review* 70, 1956, pp. 193–196.

[8] N. A. F. Smith, "The Origins of Water Power: A Problem of Evidence and Expectation," *Transactions of the Newcomen Society* 55, 1983/1984 (pp. 67–84), p. 73.

[9] It is most difficult to envisage an alternative method of stopping the runner; swiveling out the footstep bearing to disengage the gears would be harmful with a rynd fixed to the spindle and the other "modern" methods of disengagement in both water- and windmill gearing either cannot apply to lantern gearing or are considered as being unknown or inappropriate to ancient technology.

[10] H. A. Thompson, "Activities in the Athenian Agora: 1959," *Hesperia* 29, 1960 (pp. 327–368), p. 349.

[11] Part of the headrace immediately behind the south wall of the wheel pit was removed by a well sunk in

the upper mill did not apparently have a bypass, for if it had existed, it would have needed to return the water back into the watercourse between the mills. In absence of a bypass arrangement, it is suggested therefore that the water control was effected within the mill, in the wheel pit.

Our experience tells us that in watermills without water storage a water-control device adjacent to the wheel must have in association the facility for the excess water to avoid the wheel. Within the confines of the Agora wheel pit, there are only two routes for the excess water, either between the wheel breast and the south wall of the chamber or taken over the wheel and discharged down towards the tailrace tunnel clear of the wheel. To facilitate a resolution of these alternatives, we must first examine the mineral deposits which thickly coat the pit walls.

Although lime deposits exist on the west wall of the pit, they are not so heavy or so extensive as those on the opposite wall. The east-wall deposits tell us much more, not just because of the invaluable scoring marks made by the revolving wheel but because they cover an entire vertical wall close and roughly parallel to the wheel side, unlike the west wall which is foreshortened by the maintenance ledge or catwalk at shaft level. The drawings executed by Travlos[12] give a fairly good representation of the distribution of lime deposits on the east-wall face (Fig. 1). The position and profile of these layers are consistent with their being deposited by water thrown with considerable velocity from the trough and revolving wheel acting in an overshot mode.

On the south wall of the pit the lime deposits appear to reach a thickness of up to 12 cm. opposite the wheel breast, coming perhaps as close as 9 cm. to the face of the wheel (Fig. 2). Such a shaped deposit is clearly not the result of a ducted or constrained flow; no mortices or cavities exist here, nor profiles which suggest there having been a wooden chute or duct, taking the water downwards between the pit wall and the wheel. We may therefore conclude that the deposits have been created by (a) water thrown from the wheel by centrifugal force and (b) water falling from the headrace above. It is significant that the lower deposits are thickest where they are in line with the west side of the wheel as if they had resulted from water being thrown from that side of the wheel; but no similar profile exists in line with the other wheel face. We may conclude therefore that the greater part of the south-wall lime deposits originated from water coming from above in the headrace and running down the wall of the pit. Let us now examine the possible water-control arrangements.

The limitations provided by the archaeological evidence suggest that one of two possible methods could have existed. The first involves the use of two fixed water troughs, one above the other with a hinged flap or gate arranged to divert the water between the channels (Fig. 3). In this arrangement water in the lower inclined wheel trough would be controlled by adjusting the hinged flap in one of a series of fixed positions. Whether the "leading" or "trailing" mode is adopted matters little; both would encourage smooth flow without

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the Middle Ages. See Parsons, p. 74, note 2, also fig. 1. No water-control device could have existed here, for the reasons already given.

[12] Parsons, p. 74, fig. 5:A; p. 79, fig. 10:A.

FIG. 1. Lime deposits on the east wall of the water-wheel pit

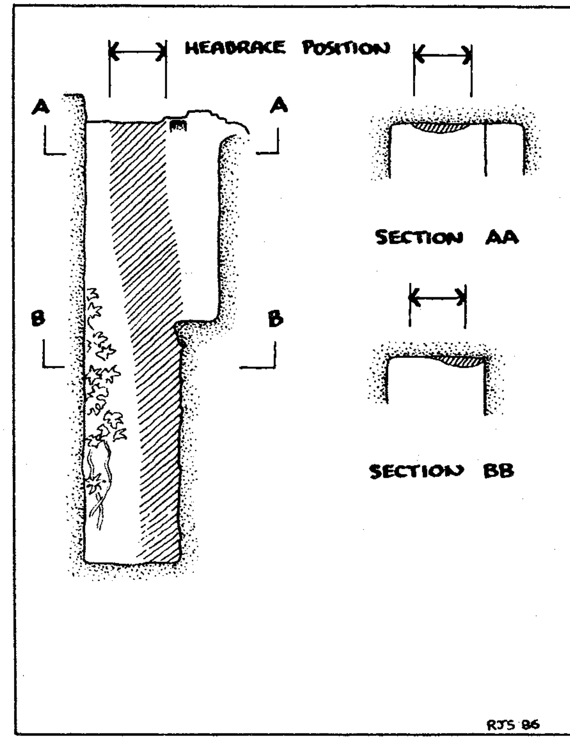

FIG. 2. Lime deposits on the south wall of the water-wheel pit

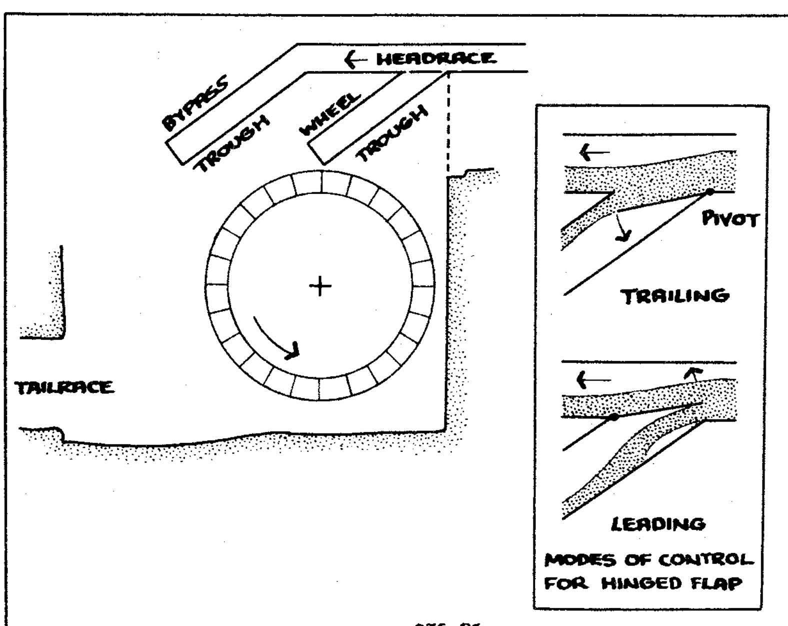

FIG. 3. Suggested water-control method with two troughs

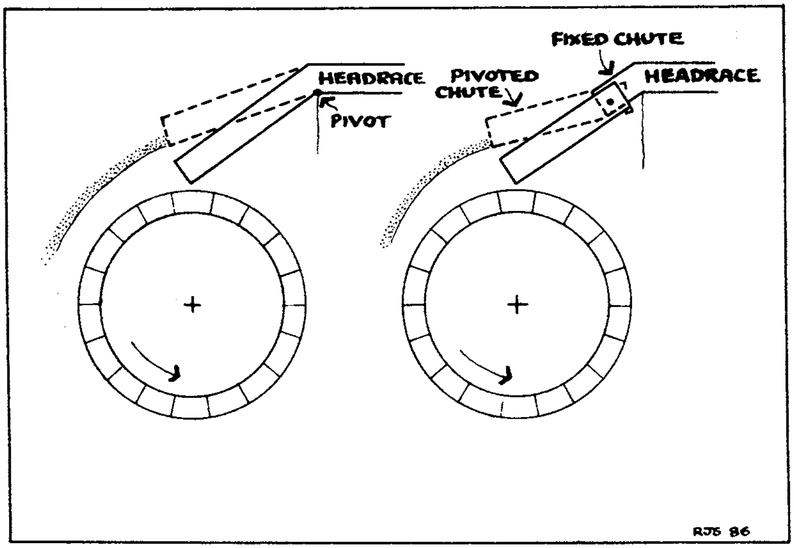

FIG. 4. Suggested water-control method with single pivoted trough

turbulence, although the trailing arrangement might require the top of the wheel trough to be boxed in. It also has the disadvantage that the hinge is permanently flooded.

The second arrangement involves a single inclined wheel trough, pivoting at its top end on the "apron" of the headrace. Control of the water would be effected by inclining the trough to a greater or lesser degree, thus directing more or less water onto the wheel. Its obvious disadvantage is the necessity of a leakproof hinge and side-wall sealing between the trough and masonry of the headrace. An improvement to the sealing is brought about by making the upper part of the trough fixed rigidly to the headrace and having the lower portion pivoting at its upper end (Fig. 4). If the lower section is made to slide outside the fixed upper section of the trough, with a suitable overlap the sealing is no longer a problem.

The single inclined trough was Parsons' interpretation of the arrangement and his method of control ". . . a simple trap in the floor of the channel above the south wall of the wheel-race [that] let the water fall directly to the floor. . .". He took the thick lime deposit on this wall as proof of this arrangement.[13] There are problems with this suggested trap control whether hinged or sliding, because in order to keep the diverted water from adversely affecting the revolving wheel (note that the buckets/floats are rising beneath the trough) it would surely require ducting downwards to below the wheel breast. We have already concluded that this arrangement probably did not exist.

Of the alternative methods of control proposed the author favors the single inclined trough as being most consistent with the pattern of lime deposits on the east wall of the pit. Assuming that the mineral deposits on the south wall were made during the operational life of the mill, the most likely position for the pivot of the inclined trough would be where it joined the headrace. The difficulties of making and maintaining a moving seal at this

[13] Parsons, p. 82.

position would explain the substantial lime deposits below on the south wall.[14] An obvious alternative explanation for the south-wall deposits is that they may not have been coeval with those elsewhere on the pit walls, for it is possible that they were created after the mill ceased working. If this were so, however, it would not affect the conclusion that has been reached concerning the method of water control and application.

Buckets or Radial Floats?

A preliminary hydraulic analysis of the Agora headrace and inclined trough shows that the velocity of application is high.[15] The table below gives the theoretical water velocities[16] due to different depths of water in the headrace.

Table

Depth of water in the headrace (inches)	Theoretical velocity of water into wheel (ft./sec.)	Theoretical flow rate (ft.^{3}/sec.)
15	24.78	10.9
12	24.30	7.8
9	23.72	5.1
6	18.67	2.8

It will be seen that when the headrace is 50–90% full the velocity of application can be taken as approximately 24.0 ft./sec. With an effective diameter of 9.44 ft. the wheel speed, assuming the floats or buckets to run at 50% of the water velocity, is close to 24 r.p.m. Even by modern standards, this is a "fast" overshot wheel. Having regard to the size of the upper millstones found at this site, this mill appears to have been considerably over-powered, even allowing for the unknown mechanical ratio of the gearing[17] and our partial ignorance of the operating friction between the millstones.[18] Of course, the extant stones, worn thin to the limits of their usefulness, represent the lightest load conditions.[19] Even with thicker and heavier millstones, however, the balance-of-power calculations support the inescapable conclusions that the water wheel was fast.

A hydraulic analysis shows us that if this wheel had buckets the useful effect of the water carried would diminish rapidly as the speed of the wheel increased. It would probably reach a maximum theoretical generated power of 8.5 h.p. at a wheel speed of approximately 18 r.p.m.,[20] and thereafter as the speed increased, the adverse effect of centrifugal forces

[14] It is difficult to suggest what sealing method the builders may have used. A flexible seal such as an animal skin might have provided a practical solution.

[15] This hydro-mechanical analysis forms part of Higher Research Degree studies undertaken by the author at the Imperial College of Science and Technology, London.

[16] Velocities which occur at the mean depth of the buckets/floats.

[17] Generally the greater the gear ratio the greater the friction losses, but even with a rudimentary form, such as a lantern gear, the total losses are a minor part of the whole system's friction.

[18] Part of the author's current research is devoted to establishing the coefficient of friction for operating Roman-style disk-type lava millstones.

[19] Parsons, p. 84, fig. 17: millstones b, c, and e should be ignored in this respect.

[20] At a flow rate of 10.9 ft.^{3}/sec. The power-generated figure is gross; there is no allowance for friction.

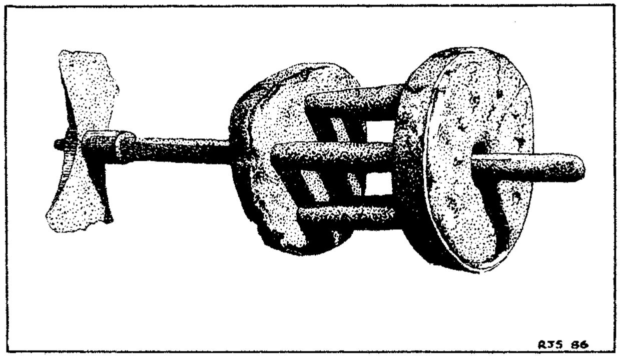

FIG. 5. The Zugmantel Roman lantern gear

would rapidly reduce the power of the wheel. Coincident with centrifugal losses are the losses due to splashing as the buckets pass through the stream of water entering the wheel.

With radial floats the wheel would behave rather differently; at lower speeds it would be unable to generate the power of a bucket arrangement, but at, say, 20 r.p.m. an improved performance is theoretically evident. Above this speed the impulse effect is very great whilst the power derived from weight is negligible. The balance-of-power calculations confirm that the mill was over-powered, which we may conclude manifested itself, when normal flow rates were applied to the wheel, in a relatively fast wheel. The Agora water wheel is therefore considered to have had radial floats within a shrouded rim and not buckets.

WHY SUCH A FAST WHEEL?

Without becoming entangled in the question of the Roman engineer's technical competence and skill, the answer to this question must surely be found within the advantages of using a fast wheel.

Let us assume for the moment that the mechanical ratio (MR) of the gears is unknown. It could lie anywhere in the range of as high as 8:1 to as low as 3:1 (driver:driven).[21] It is suggested that a lantern-type driven gear was probably used similar to the Zugmantel specimen, the only one to have survived from the Roman period[22] (Fig. 5).

[21] Although it would be possible to derive a theoretical high-speed limit from the rim velocities applied to millstones during the last century or so, the author prefers to be guided by the Zugmantel lantern specimen. Taking six cogs or staves as the least number as a practical operating limit, the Zugmantel gear pre-determines the pitch of cogs in the Agora driver. The resulting MR is close to 8:1. For the low-speed gear ratio it is suggested that an obvious and realistic limit of acceptance would be the speed of a large quern which in the Agora mill is compatible with an MR of, say, 3:1.

[22] This gear was found still attached to its millstone spindle; it was recovered from a well of one of the *vicus* houses at the Roman fort of Zugmantel on the Domitian *limes*. It is thought that these mill parts, including two millstones, were thrown down the well in the second half of the 2nd century after Christ. See H. Jacobi, "Römische Getreidemuhlen," *Saalburg-Jahrbuch* 3, 1912, pp. 75–95, 89, fig. 43. Also *idem*, "Kastell Zugmantel, Die Ausgrabungen," *Saalburg-Jahrbuch* 3, 1912, p. 54, figs. 17 and 18. The author is grateful to Dr. Baatz of the Saalburgmuseum for information on this matter.

With a Vitruvian mill, the speed of the upper millstone in relation to the water wheel can be increased permanently simply by using a higher MR. The torque is more or less constant, subject to the increasing friction losses associated with small gears. Of course, a faster water wheel will increase the millstone speed; but the fact remains that the operational speed can be selected by the MR of the gears. Why then build a fast wheel?

The most likely reason is that the miller wished to maximize the millstone speed, using a high MR combined with a fast wheel. We know with certainty that the driver gear was as large as the pit would allow: Parsons found where the iron hoop on its rim had scored the edge of the pit. If we assume a maximum MR of 8:1 and a water-wheel speed of say 20 r.p.m. the millstones would revolve at 160 r.p.m. Although this rotational speed is high by modern milling practice, the rim speed is still within the limits which we associate with an acceptable product and high meal temperatures. But we should beware of using these criteria; they are related to modern millstone practice with its own style of dressing: sharp, defined furrows and fine stitching on the lands, maintained regularly. Ancient millwrights did not reach this high standard of dressing. With less well defined dressing and a probable lower standard of maintenance, we may assume that the meal was coarser and the quality lower than modern standards. There is also a suggestion that the power required was disproportionally less. By making the water wheel smaller (thus making the head of water above the wheel greater) the builder achieved a higher speed. The alternative was to make the wheel larger and literally fill the drop from head to tailrace, which would have produced a slower wheel whose power would come from gravity rather than impulse. But the power generated would be roughly the same. If the power required is taken as being proportional to the product of millstone weight and speed, it follows that a pair of small-diameter and fast millstones could have the same throughput as a pair of larger diameter slower stones.

Perhaps we are near the truth, that the Agora stones were the size that the operators were familiar with and that their tradition and experience did not include working with larger stones. And so they intentionally sought to build a mill to run them at speeds to the limit of their acceptance, whatever criteria they used.

We may tentatively conclude that the design of this watermill, in particular the creation of a relatively fast wheel, was intentional and probably the product of an evolutionary process of design and operational improvement. We can readily identify several advantages of such a water-wheel arrangement. The building of a smaller wheel was an easier task, involving less material and a more simple design, and not so difficult to install compared with a larger and heavier wheel. It is suggested that they were conscious of the advantages of using radial floats inherent and consequent to the adoption of a high head onto a small water wheel, an impulse wheel. Radial floats are easier to construct than buckets, within a shrouded rim, requiring less material and having more simple jointing; moreover the need for effective water sealing associated with buckets was avoided. Bearing loads are less. The impulse wheel, with its higher speeds, also had the singular advantage of smaller, faster millstones, achieved without excessive gear ratios.

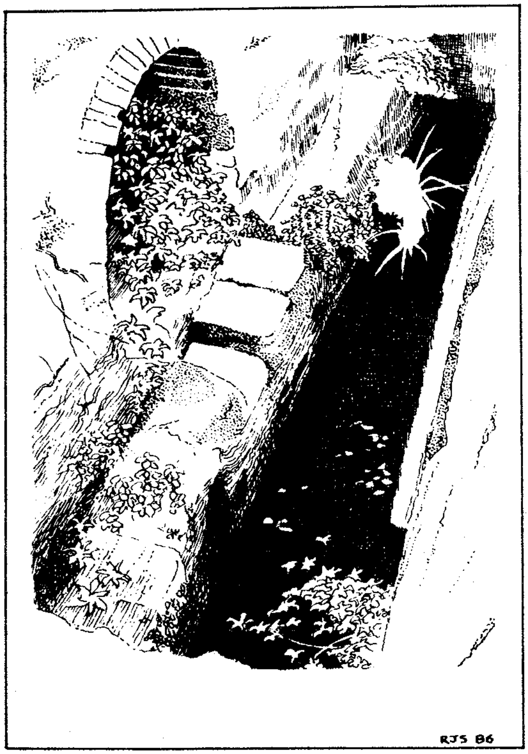

FIG. 6. West bearing-support stone

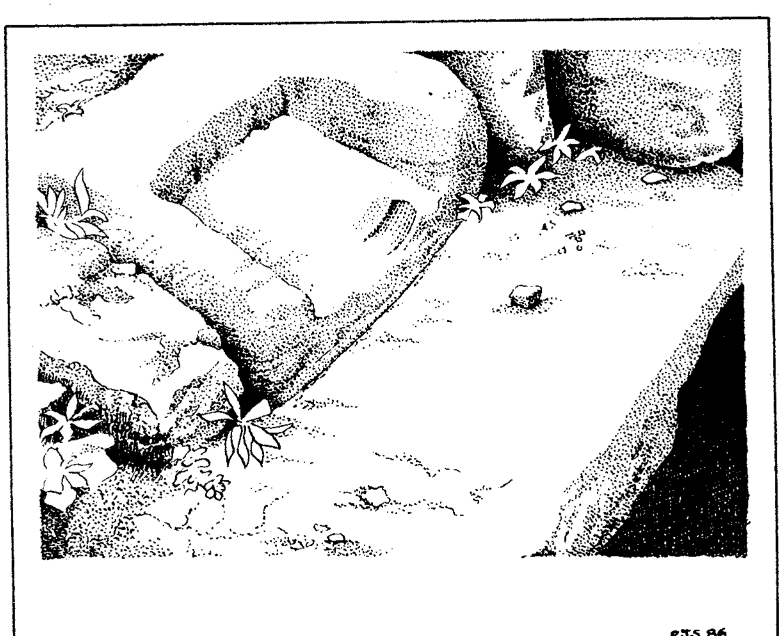

FIG. 7. East bearing-support stone

The Wheel Shaft: Problems of Alignment

To help analyze the problems of wheel-shaft alignment we must first examine the bearing stones and their supporting fabric.

The wheel shaft's west bearing block is large (approximately 0.84 × 0.60 m.) and could be interpreted as the equivalent of a combined plummer block and sole plate. Being fitted into the base of the arched maintenance recess behind the water wheel,[23] it is firmly locked into the building fabric and serves well its primary functions of spreading load, absorbing the wheel's continuous vibrations, and providing a most rigid and stable platform (Fig. 6).

The east bearing support has a different arrangement. Its base area is only one half that of the west bearing-support stone, and it is wedged with smaller stones into an emplacement, well back from the edge of the gear pit[24] (Fig. 7). Between this support stone and the gear pit is the marble slab that Parsons identified as supporting the millstone spindle bridge.

This marble slab passes below the socketed bearing stone, and careful exploration with a narrow steel probe suggests that it continues to the back of the bearing stone. The bearing stone is let into the surface of the marble slab, fitting into a shallow mortice at least one centimeter in depth,[25] which can be clearly seen along the front edge of the bearing stone and detected by probe along the beginning of each side. The large packing stone on the north side and other smaller stones adjacent all appear to have yielded in position, the smaller stones having dropped and the larger relaxed towards the bearing stone leaving a gap in places of 2–3 cm. Moreover, the packing stones on the south side are very irregular in shape and crudely wedged in position.

Below the marble slab is a massive stone foundation block, some 37 cm. thick, slightly wider than the gear pit. Its north end has an accurately cut, vertical face which butts up to the lower stone and brick courses of the north wall of the pit. This wall has been rendered (Fig. 7) up to the corner of this lower stone block. According to Parsons' drawings there are other stones under this foundation stone, but they are now lost to view below 35 cm. of earth deposits in the pit.[26]

It is interesting to note that the width of the marble slab is the same as that of the west bearing stone, and having regard to its position at the edge of the pit and its area, it is tempting to identify the slab as the obvious position for the mill-side wheel-shaft bearing rather than the spindle bridge. There can be no escaping the fact, however, that the east bearing-support stone was found *in situ*. But why should the east stone be so much smaller than the west stone? The most obvious answer is that their areas reflect the loads upon them, for there can be little doubt that the west bearing took perhaps three quarters or more of the combined journals' load.

The scoring on the edge of the gear pit together with that in the bearing-support stone were probably coeval, created by the same wheel-shaft alignment. Parsons' restored plan

[23] Parsons, p. 84, fig. 16:4.

[24] Parsons, fig. 16:1.

[25] Parsons, p. 79, fig. 10. Section YY purports to show this arrangement as does fig. 16:3, but it is a pity that Parsons did not mention it in his text.

[26] Parsons, p. 79, fig. 10: Section YY. Also p. 74, fig. 5.

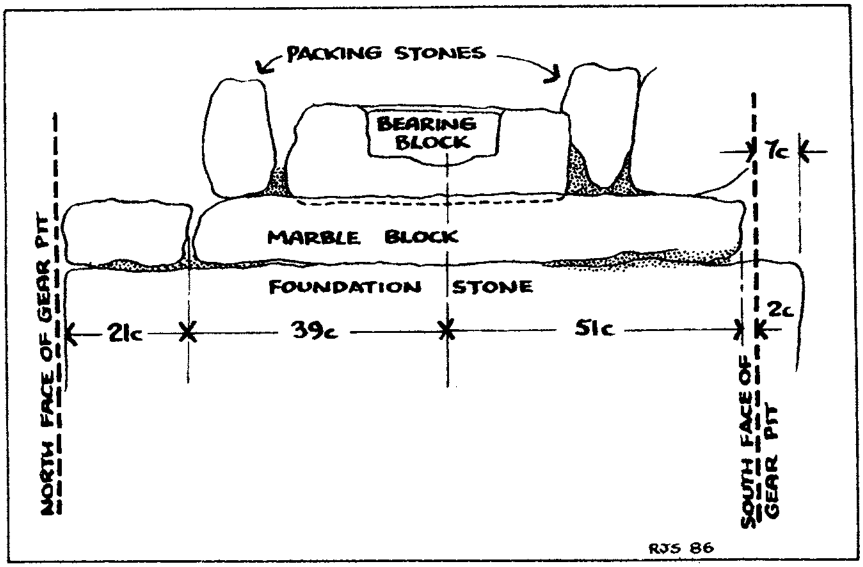

FIG. 8. Elevation of the east wheel-shaft bearing-support stone

(Travlos' drawing, fig. 10:A) depicts this and suggests that it was coincident with the wheel rim making concentric grooves in the heavy lime deposits on the wall of the wheel pit. Parsons attributed this "mis-alignment" of the water wheel to a builder's blunder, which required the wheel to be set over at a slight angle to the walls of the pit in order to take the water as squarely as possible.[27] He was mistaken; the explanation of the wheel's scoring is attributable to a quite different defect.

First, accepting the accuracy of the reconstructed plan by Travlos (fig. 10:A) and allowing for a vertical water wheel, the center of the wheel is only some 2 cm. out of alignment with the headrace. Such a small misalignment could be taken up by the inclined wooden trough delivering water to the top of the wheel, which was 2.3 m. long. But this is a false trail. Careful examination of the plan shows that the axis of the west bearing, the barrel vault for the wheel shaft, and the gear pit all lie on a straight line normal to the axis of the headrace as it approaches the mill. Only the east bearing-support block is misaligned by some 5 cm. off this center line to the south, and it is not easy to suggest why this should be so.

Looking at the bearing-support arrangement (Fig. 8),[28] one wonders whether or not the sole plate had moved at some time towards the south and perhaps the bearing block was not originally set in a rebate on the sole plate. On the subject of stability and rigidity of the east bearing block, it should be noted that a floor drain enters the northeast corner of the gear pit

[27] Parsons, p. 80.

[28] Dimensions taken on site confirm that the position of the shaft axis and bearing stone are correctly shown on Parsons' figure 10:A, but the position of the marble block is in error. It would appear that a simple mistake has occurred and that the dimensions from the shaft axis to the north and south ends of the marble block have been unwittingly transposed. This has not affected the interpretation.

passing on the north side of the bearing block (Parsons, fig. 4: *v*; fig. 7; it does not show in fig. 10:A). This was identified with a probable grain-washing position in the northeast corner of the mill which Parsons considered to be out of use in the last phase of the mill.[29] He noted that the drain outlet was blocked by a stone set in to brace the bearing. Perhaps here is a clue to the causes of movement of the bearing stone; either (a) the passage of water could have weakened the structure, or (b) the bearing was positioned to one side to allow the admission of the drain to the gear pit, or both. The packing stones definitely suggest that movement of the bearing towards the south had taken place, which may have been caused by the insertion of the drain, or by the continual vibration of the mill in response to the side thrust of the gearing, or both; which, we cannot ascertain.

What does seem likely is that the bearing block was originally on the center line of the pit, but we cannot be sure if the marble sole plate was ever centrally positioned. One might suggest that it was pushed southwards to admit the drainage channel, but this was not necessary because the drain was apparently above the slab and blocked by a stone resting on the marble slab set in to brace the bearing-support block. Assuming that the marble slab was always in this position, it would seem probable that the bearing block was rebated into the slab, sometime during the working life of the mill, to stop it moving southwards.

We have seen that the west bearing, barrel vault, and gear pit were aligned on a single axis normal to the headrace axis and that the east bearing misalignment, as shown on the drawing, is only one degree off this axis. The essence of this plan is obvious, the builders made no error, indeed their work is quite accurate. The walls of the wheel pit are quite another matter, however, for neither of them is aligned with the headrace axis and they are not parallel to each other. But this is unimportant because they take no part in guiding water to the wheel or constraining it during its passage through the chamber.

The scoring of the wheel rim on the chamber wall might be due to the build-up of lime deposits, which eventually extended to touch the wheel. Unless the miller attempted removal of these deposits, the thickness now seen is the result of a century's operations. The scoring must have occurred at the end of the mill's life, perhaps over several years; otherwise it would have been covered by further deposits. Indeed on the basis of a constant rate of deposition, the depth of scoring, or more accurately the envelopment of the wheel, as detailed by Parsons[30] suggests that it had been rubbing the wall for a decade or even two.[31] But

[29] Parsons, p. 87.

[30] Parsons, p. 80, fig. 11; p. 79, fig. 10:A.

[31] In a footnote (Parsons, p. 83, note 2) Parsons reminds us that wooden machinery was liable for replacement during the life of the mill (90–120 years), a fact that all engineers should bear in mind when interpreting the remains of watermills, ancient or modern. Of equal significance are the developments and improvements which may have been made to the machinery, processes, or building during the mill's life. When a modification was made to the machinery it may have coincided with a maintenance problem such as an element breaking or wearing away. It is entirely possible that the builder did not get the arrangement he had hoped for or intended and equally likely that he learnt either from his own operating experience, by direct observation of other watermills, or by information from others, of improvements that could be made. Our experiences with watermills tell us that at least three machinery elements must have needed replacement several times during the Agora mill's life: wooden cogs and bearings, and far more noticeable to a miller, millstones. And so our interpretation of these artifacts should be influenced by the possible developments and sequential variations that the machinery may have taken.

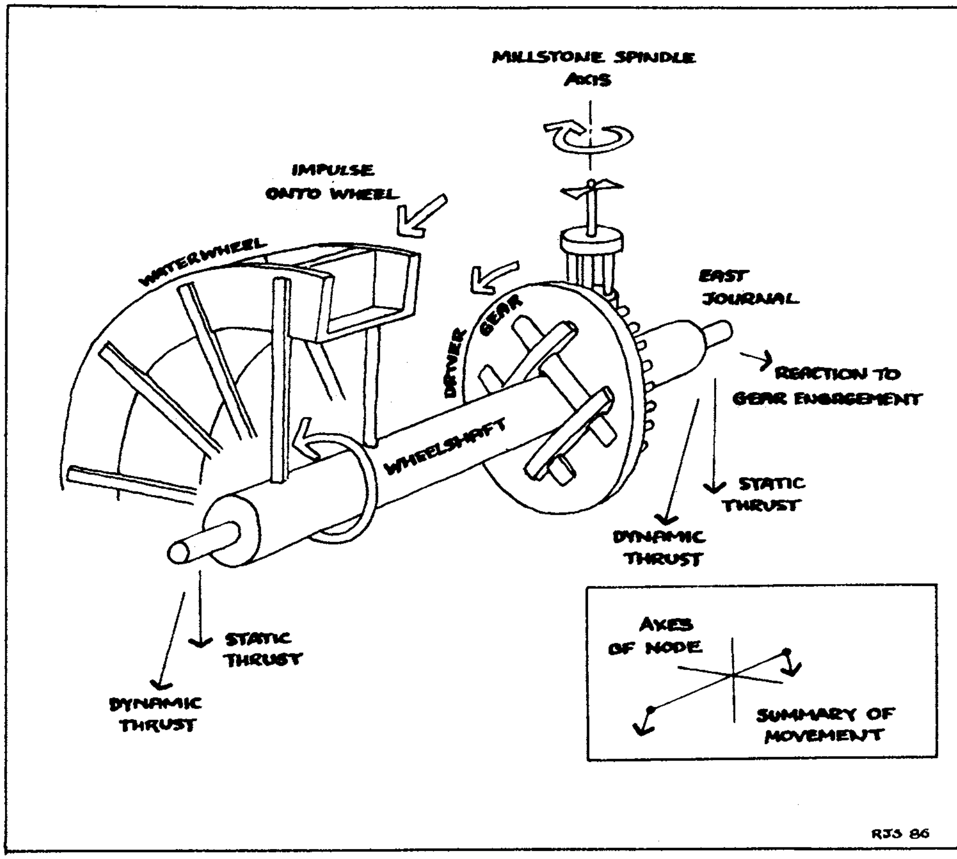

FIG. 9. Bearing-forces diagram

the creation of these concentric grooves was not solely due to the build-up of mineral deposition; the wheel rim slowly moved towards the wall at the same time.

The cause of this movement was the forces acting on the wheel-shaft bearings. Take the west bearing first. Under static conditions the thrust due to the weight of the shaft, wheel, and driver gear is vertically downwards. When shaft rotation occurred the dynamic conditions of the bearing were quite different. There was a tendency for the journal to climb the bearing (its north face), and simultaneously, the centrifugal force of the wheel combined with the thrust of water against the floats would have resulted in a reaction inclined northwards and downwards.[32] The bearing wear would have displayed this reaction, the journal moving northwards as it sank into the bearing.

The east bearing was also subject to out-of-balance dynamic forces, the major one being the reaction from the gears. When in motion the driver gear would tend to move the wheel shaft towards the south as it transmitted its torque to the driven gear above. The journal in the east bearing would therefore move southwards as it sank into the bearing. This

[32] It should be possible to generate a force diagram to resolve the reaction.

movement is confirmed by (a) the position of the scoring caused by the iron hoop[33] on the shaft end within the east bearing block (Parsons, fig. 16) which appears to be some 2 cm. off center to the south, and (b) the scoring of the driver gear on the pit edge.

All these bearing forces would be represented by a single, albeit complex, force diagram (Fig. 9). For the purposes of this paper, however, we may conclude that the whole assembly (water wheel, wheel shaft, and driver gear) in plan view rotated about a node, positioned somewhere along the shaft.[34]

And so the scoring of the lime deposits by the water-wheel rim was caused by a combination of movements involving (a) a long-term build-up of material deposits on the surface of the wheel-chamber wall, (b) a shorter term, clockwise rotation in plan view of the main shaft and water wheel as a result of bearing wear, and (c) the east bearing-support block having vibrated from its original position or been moved purposely to accommodate a water drain.

The Gearing Ratio

Parsons' conclusions concerning the gear ratio of the mill rest solely on his interpretation of the marble slab below the east wheel-shaft bearing block as being the support for the millstone spindle bridge.[35] As a preliminary observation this is not unreasonable, but because the conclusion is so important and far-reaching (we should remember that this is the sole example of a gear ratio of specific value claimed for ancient watermills), a closer examination is worthwhile.

Parsons concluded that the gear ratio had been 1.11:1.36 (driver:driven). In other words, the top millstone rotated at some 82% of the wheel speed. We will now see that an alternative interpretation may be placed on the evidence.

First let us give definition to the position of the footstep bearing and then identify the primary mechanical functions that are associated with the millstone spindle.

[33] Parsons is of the opinion that the projecting ends of the wooden shafts were ". . . worked down to form the bearing . . ." (Parsons, p. 82) and supports his view with the comment ". . . this is exactly the way in which such wooden shafts are treated today . . ." (p. 82, note 2). If Parsons is correct, and we should credit him with being a good observer, this arrangement is contrary to our experience of bearing materials. Moreover, drainage wheels with metal shafts have been found in Roman mines (see R. E. Palmer, "Notes on some Ancient Mine Equipments and Systems," *Trans. Inst. Mining and Metallurgy*, 26 1926/1927, p. 256; the axle of the Rio Tinto wheel (reg. no. 1889 6–22.1) in the British Museum is apparently copper, and three bearing stones from the Romano-British watermill site at Ickham near Canterbury were clearly intended for metal journals (R. J. Spain, "An Analysis of the Millstones and Quern Fragments from Ickham, Kent," 1977 [an unpublished report]; R. J. Spain, "Romano-British Watermills," *Archaeologia Cantiana* 100, pp. 101–128). Even if wood journals had been formed from the original shaft the author submits that it would have been a logical development for an iron or bronze journal to have been substituted, morticed into the shaft ends and bound with an iron hoop. This would have avoided replacement of the whole shaft. A further improvement would have been to employ winged gudgeons, but perhaps we should admit that this arrangement, common to wooden wheel shafts of the last three centuries, may have been developed in response to much greater shaft loads and improved bearings.

[34] If the gear reaction and the water impulse are resolved as torque applied to the axis of a rotating mass, we are dealing with gyrostatic motion, in which case the wheel shaft suffers precession.

[35] Parsons, p. 83.

The axis of the millstone spindle should be vertically above the wheel-shaft axis or close to it to avoid imperfect engagement between the gears. On the reconstructed plan, its distance from the driver gear will determine the gear ratio; the closer its axis to the driver gear, the higher the gear ratio. When all other factors are constant, the gear ratio will determine the millstone speed.

The millstone spindle which carried the driven gear projected through the stationary lower or bed stone to drive the revolving top stone. Its lower end rested in a footstep bearing, usually a stone, which took the weight of the spindle and driven gear. This footstep bearing would have been arranged to have vertical movement up or down and to have such adjustment readily and easily effected. In modern water- and windmills, millstone spindles have their footstep bearings adjustable also in a horizontal plane. This is facilitated by the toe brass being positioned by four adjusting screws, one in each side of a square, open, cast-iron bearing box. The spindle could then be adjusted to be exactly vertical, the operation called "brigging the spindle". Such accuracy was probable not necessary in ancient mills, but it was nevertheless desirable to be able to adjust the horizontal position of the footstep bearing to ensure the best "running fit" of the mill rynd in the cavity. Adjustment in the Agora mill was probably by hardwood wedges around the bearing stone.

In corn milling the footstep bearing rests on a horizontal beam called a bridgetree which is pivoted at one end and adjustable vertically at the other. The Agora arrangement must have involved a horizontal wooden beam aligned north-south over the wheel shaft to support the millstone spindle. Parsons interpreted this bridge as being supported from the marble slab between the gear pit and the east wheel-shaft bearing. Thus he is suggesting a short, presumably rigid, wooden bridge standing astride the wheel shaft.[36] Wedges driven beneath the footstep bearing appear to be the only way of providing vertical adjustment, but access would have been very difficult. Not only were they below the millstone platform but immediately underneath the driven gear. Imagine crawling into the gear pit and trying to adjust wedges without headroom with the cogs rumbling around within inches of your head! Even if Parsons' short-bridge method was the original arrangement (there is good reason to doubt this), the miller would surely have soon searched for a more practical and far less dangerous method of adjustment.

The obvious method of supporting the footstep bearing was to install a bridgetree which extended across the width of the millstone platform frame (Fig. 10). Pivoted at one end, the other could be raised or lowered by wedges or levering perhaps effected by a vertical wooden rod[37] passing up through the millstone platform, which would bring the control close to hand to an operator working on the platform.

It is interesting to note that the conclusion we have reached of a pivoted bridgetree spanning between the sill beams of the millstone platform is essentially the same arrangement

[36] Parsons, p. 79, fig. 10: section YY. It is a pity that the bridgetree is not shown on the plan in fig. 10 where its arrangment would have been much easier to follow.

[37] This could be identified as the "brayer" in the lever system of a modern corn mill.

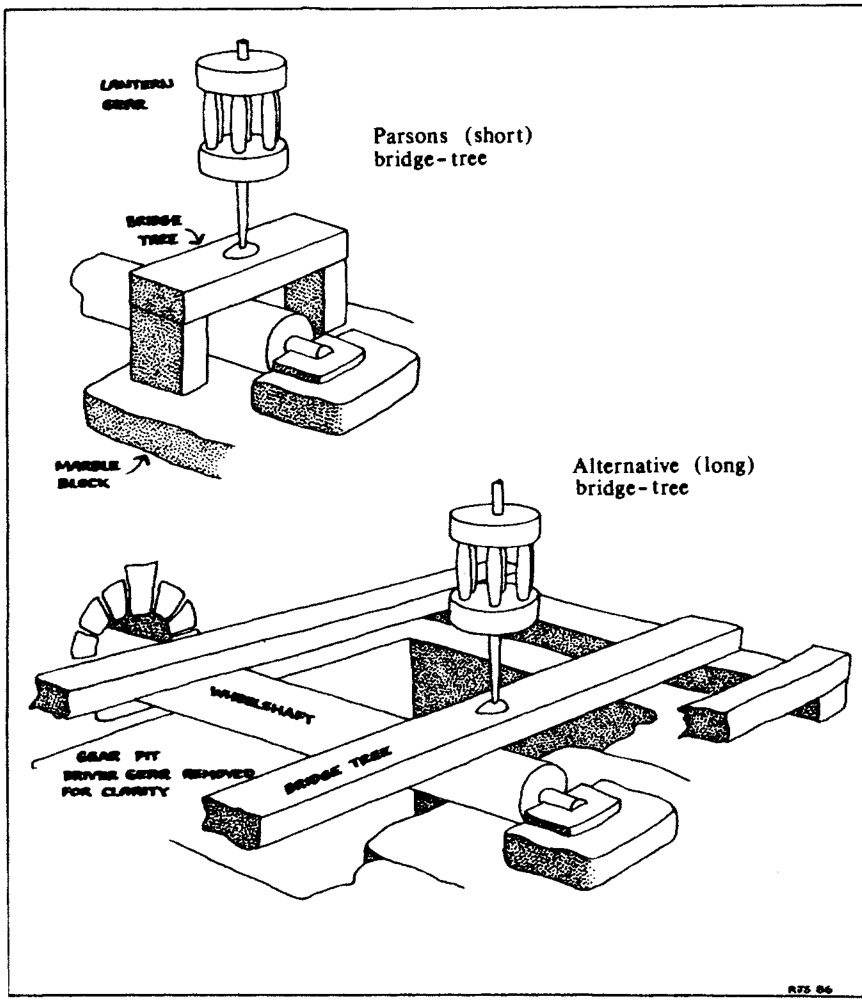

FIG. 10. Bridgetree arrangements

embodied in traditional hursting (millstone framing), i.e. that the bridgetree and support posts are integral with the millstone support frame.[38]

If we accept this arrangement of the bridgetree, it fundamentally affects what we know about the gear ratio on which Parsons was so firm. In fact, because we are now unable to ascertain the position of the millstone spindle and therefore the diameter of the driven gear, the gear ratio cannot be determined at all. There is no longer a case to be made for the Agora

[38] Only one other Roman watermill has provided evidence of the timber frames supporting the bridgetree and millstone platform. In the 2nd-century (after Christ) watermill found at Ickham an attempted reconstruction of the wooden structure has suggested that the supporting frame for the bridgetree and millstone platform was not completely integrated. See R. J. Spain, "The Second-Century Romano-British Watermill at Ickham, Kent," *History of Technology* 9, 1984 (pp. 143–180), p. 172, figs. 3 and 6.

mill being "geared down". Instead we may now view it as possibly having a conventional[39] smaller driven gear, perhaps a lantern gear, to produce a higher millstone speed.

The Millstones

In the southwest corner of the mill among the growth of weeds and wild flowers were several millstone fragments and leaning against the wall near by, the dark lava bedstone that Parsons found at the site (stone d).[40] This millstone was still in one piece, apparently as originally found, and the swirling pattern of furrows on the convex grinding face could only be clearly seen when the stone was brought out from the shadow of the mill wall and arranged so that the bright sunlight struck acutely across the face.

Parsons noted that the pattern of the swirling was arranged so that the upper stone turned against, not with, the swirl of the furrows.[41] He concluded this from his gearing reconstruction, for the Agora mill was a right-hand mill,[42] i.e. the top stone rotated clockwise viewed from above. This is rather surprising for, if this millstone was operated in a right-hand, clockwise fashion, then the meal would tend to be worked into the "breast" (middle third of the radius) and only centrifugal force would keep the stones from being choked. The depth of the furrows is shallow, only a few millimeters, perhaps because when they were abandoned they were not in fresh-cut condition; and we must remember that they have apparently been out in the elements for 50 years. Measurement on the grinding surface shows the height of inclination from rim to eye as approximately 1 cm. (1.9°), and the underside of this stone is rough dressed and flat.

Although Parsons rightly draws attention to the apparent negative dressing of this stone, it is worthwhile pointing out that we know of other Roman millstones exhibiting similar anomalies.[43] This shows that (a) whilst many Roman stones have a high standard of design and dressing on their grinding faces at least some millers were unaware of the disadvantages of negative dressing and (b) such stones nevertheless worked, suggesting that our knowledge of stone and meal behavior is incomplete.

The Agora millstones are all shallow stones which fits in well with the general theory that the later Roman millstones were flatter; but we should be cautious: their shallowness could simply be a product of the maximum utilization of stone which results in working the bed stone down towards its base.

[39] When exploring Roman technology the word conventional is probably misused and should be avoided; the intention here, however, is to pay some regard to the fact that in all mediaeval and modern Vitruvian-style watermills the millstones revolve faster than the water wheel.

[40] Parsons, p. 84, fig. 17, stone d; p. 86.

[41] Parsons, p. 34, note 2.

[42] Of this there can be little doubt because for the axis of the millstone to be on the wheel side of the driver gear is most unlikely; it would leave no room between the "vat" or "tun" casing around the millstones and the mill wall, even with a small-size driven gear.

[43] From Ickham, Kent: Stone no. 24 (find no. 1589), 45 cm. diameter, the bottom stone of a rotary quern. Stone no. 1 (1799), 86 cm. diameter, millstone used as a top then bottom stone. Stone no. 3 (1663), 88 cm. diameter, bottom millstone. See Spain, 1977 (footnote 33 above).

Among the fragments was stone c (Parsons' notation), which Parsons identified as a top stone from its smooth concave grinding face and the remains of rynd cavities.[44] Definition of the cavity shape proved difficult, and it was not possible to confirm with certainty the form of rynd cavity shown by Parsons. This fragment weighed 41 lbs., and so the entire stone would have weighed approximately 136 lbs. On its concave face there is a circular furrow or groove 4 cm. away and parallel to the rim. Its purpose is a mystery. The convex face of this stone was dressed with fine, somewhat irregular furrows, radiating rather crudely from the eye of the stone, and this surface of the stone is worn smooth. Testing the radial section with a straightedge shows that the convex profile had axial symmetry. Most fortunately the profile had a flat section at a constant radius from the axis which was readily identified with a straightedge.

This shows that the millstone had been used finally as a bed stone following its original use as a top stone. The significance of this, apart from the suggestion that the miller used as much of the stone as possible before it became useless or fractured, is that it could explain the extreme thinness of these millstones.[45]

Conclusions

Interpretation of the archaeological evidence, especially the lime deposits, proves that the Agora example was an overshot water wheel controlled most likely by a hinged trough whose delivery of water could be varied. A hydraulic analysis shows us that the wheel was "fast" and probably had radial floats. The alignment of the west bearing, the wheel-shaft vault, and the gear pit is near perfect; only the east bearing is displaced from this axis, a movement which probably occurred during the life of the mill. This axis is normal to the center line of the headrace approaching the wheel. The unique evidence of bearing wear, together with the rubbing of the driver gear on the pit wall, and the water-wheel scoring on the lime deposits of the wheel-pit wall, can be interpreted as being mainly due to movement of the rotating machinery about a vertical axis in response to the combined forces of (a) thrust upon the wheel from the water applied, (b) reaction from gear engagement, and (c) dynamic bearing conditions.

An alternative and more practical solution for supporting the millstone spindle has been suggested with the result that the gear ratio is now indeterminable.

The fragment of the single upper millstone found on site shows evidence of its having been used as a bed stone. This dual function could explain the extreme thinness of some of

[44] Parsons, p. 84, fig. 17, stone c.

[45] Stones b and e, which are remarkably thin, were not available for examination by the author when he visited the Agora in April 1985. A request has been made to the American School of Classical Studies at Athens for specific technical observations to be made on these millstones. The subject of thin millstones brings to mind an interesting parallel from oral traditions within the English corn-milling industry. After the turn of the last century, when rural milling was in decline and millers suffered increasing economic hardship, it was not uncommon for them to continue to use their millstones until they broke from being too thin. Often the meal had to be passed again through the stones to produce an acceptable product. Roman millstones that have been used as a top stone and subsequently as a bottom stone have been found at Ickham (stones nos. 1 and 33; see footnote 43 above).

the Agora millstones which hitherto have been assumed to be top stones, an assumption which was regarded as supporting Parsons' theory of the Agora mill being geared down.

This study of the Agora watermill and review of Parsons' valuable work has proposed alternative interpretations of the evidence. Accuracy of the building layout as reflected by the headrace, gear pit, and wheel shaft have suggested that the builders carefully followed an intentional design. A hydraulic analysis confirms the archaeological interpretation of a fast over-shot wheel which, combined with the suggestion of a gearing ratio allowing the millstone a higher rotational speed than the water wheel, supports the notion that the designer of this mill was conscious of technical and operational criteria, the product of an evolutionary process born of operations and maintenance.

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