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ORIENTATION AND ALIGNMENT OF THE 5th CENTURY BC TUNNEL OF EUPALINUS AT SAMOS (GREECE)

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ABSTRACT

In circa 530BC an about 1000m long tunnel was opened in Samos Island, Greece, as part of an aqueduct; this was the first tunnel ever excavated from both portals using strict surveying techniques. Despite detailed studies, there are some questions concerning the techniques used by Eupalinus, the chief engineer. One of these questions is the selection of the specific path for the tunnel, a selection which appears at a first view rather awkward, for it leads to a longer tunnel and a longer aqueduct. Our investigation revealed that Eupalinus' selection was constrained by two factors, one geotechnical and another geodetic. Eupalinus had first to avoid an area of weak rocks making unsafe, if not impossible the excavation, and second, to take advantage of a small valley, the only one existing in rocks suitable for the excavation, and define a baseline of the maximum possible length, necessary for the accurate alignment of the excavation from the two portals. This proves that Eupalinus had an excellent understanding of what we can describe as a practical theory of errors and of measurements.

KEYWORDS: Samos. Greece. Eupalinus. Tunnel. Error. Antiquity. Alignment. Qanat. Breakthrough. Baseline.

INTRODUCTION

Following the description of Herodotus, a famous 5th century historian, citizens of Samos, a semi-independent at that time island in the Aegean Sea, discovered in 1882 an ancient aqueduct bringing water to the town of Samos, a flourishing town-state in antiquity. Their finding confirmed the reports of Herodotus for an about 1000m long tunnel excavated from two portals in circa 530BC under the direction of Eupalinus (spelt also Eupalinos or Efpalinos); the first tunnel known to have ever been excavated from two portals using strict surveying techniques [**3**],[**4**].

The initial excavation and the subsequent studies revealed that the ancient aqueduct consisted of three segments (Fig.1). First, an about 900m long segment bringing water from the only important spring in the area to the tunnel north entrance. This segment was excavated first as an open trench and then as a qanat i.e. a channel opened in a trench and then as a qanat, where an underground sub-horizontal channel is excavated from the bottom of vertical shafts (see [**12**],[**10**]).

Second, a more than 1000m long, roughly linear tunnel, consisting of a main, horizontal tunnel with a section 1.8m x 1.8 m, opened from two portals, with the two fronts meeting with a small offset, about 50cm in the vertical. The water was flowing in a secondary, inclined channel made of ceramic pipes, in a qanat-type channel secondary tunnel at a depth of 4 to 8m below the main tunnel (Fig. 2a).

Third, an about 600m long qanat-type channel conveying water from the south portal of the tunnel to the town (Fig. 1).

Obviously, the tunnel was the most important part of the aqueduct and a subject of admiration in antiquity; a masterpiece of engineering, as the detailed studies of various archaeologists and architects, and especially of H. Kienast [**4**] reveal. Despite these detailed studies, there are still some questions remaining mainly concerning the

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geodetic techniques used to guide the excavation and permit for the first time in the world a successful breakthrough.

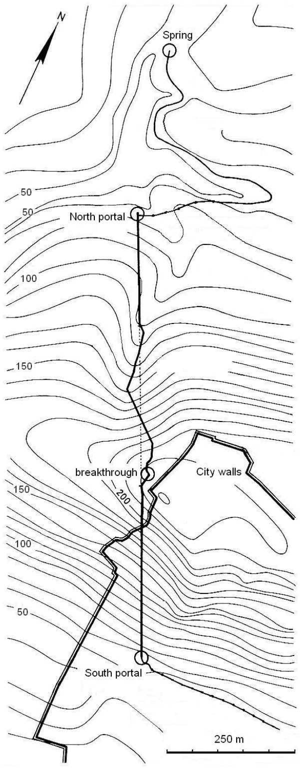

Fig. 1. Plan of the Samos aqueduct, consisting of three segments. (a) of a channel bringing water from the spring to the northern tunnel entrance (portal), (b) the tunnel and (c) a channel conveying water from the southern tunnel portal to a main cistern in the Samos Town. The tunnel was excavated from both portals, with excavation fronts meeting at the breakthrough point. The channel from the spring to the tunnel was constructed first in an open trench and then as a qanat (underground channel excavated at the bottom of vertical shafts, marked by dots). The segment from the southern portal to the cistern was also excavated as a qanat. After [**4**] with minor modifications.

One of the questions arising and still waiting for a convincing answer is why Eupalinus selected this specific path for his aqueduct, and especially for the tunnel, with the portal upstream fixed away from the spring and the portal downstream away from the destination cistern (Figs. 1, 3).

This is a point raised especially by H. Kienast [**4**] who noticed the possibility of at least two alternative paths leading to a shorter tunnel or an overall shorter aqueduct (Fig. 3), i.e. to apparently more reasonable solutions. In particular it was noticed that Eupalinus could have fixed the northern portal closer to the spring in order to shorten the overall length of the aqueduct and hence excavate a slightly shorter tunnel (3-2' in Fig. 3); or he could have fixed the northern portal further downstream and excavate a substantially shorter (about 10%) tunnel (2-2' in Fig. 3). We can add the possibility of a third alternative tunnel path, proximal to the spring, marked 5-1' in Fig. 3. This last alternative, possibly a combination of a qanat (section 4-5) and of a tunnel (5-1') appears at first as the optimal solution concerning the minimum length of the aqueduct and maximum elevation of delivery point of the water, a point emphasized by [**4**].

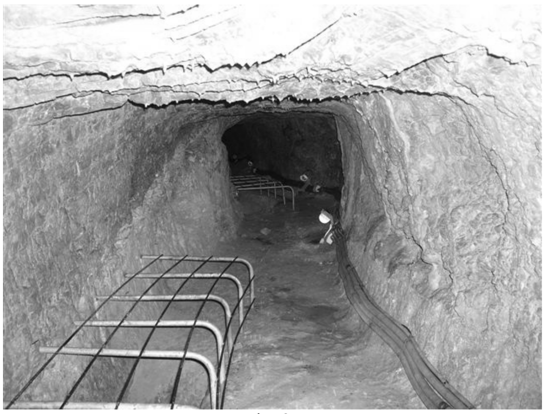

Fig. 2a

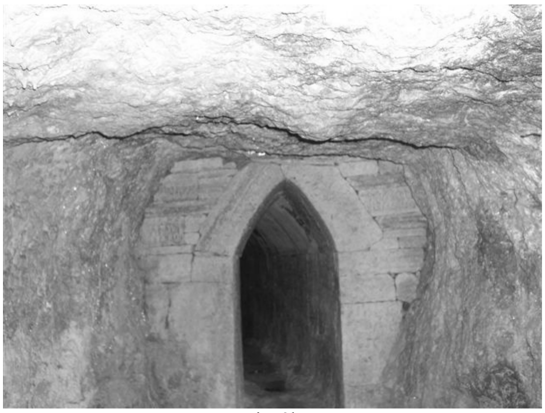

Fig. 2b

Fig. 2. Views of the Eupalinus tunnel. In most parts the tunnel is nearly square in section and without support (a). However, in some parts it was necessary to build a strong supporting wall (b). The void at the floor of (a) is the qanat-type excavation for an inclined, qanat-type channel through which the water was flowing.

The basic reason for the lack of a convincing explanation for the rationale of Eupalinus to select the existing path is that this ancient tunnel has never been studied on the grounds of geotechnical engineering and of geodesy. In this paper we try to shed light to this problem from the point of view of geodesy and explain that the orientation of the tunnel was partly dictated by the needs of a successful alignment of a tunnel opened from two portals in the existing geotechnical and topography conditions.

CRITERIA FOR THE SELECTION OF A TUNNEL PATH

In antiquity, there were three basic criteria to access the feasibility of an aqueduct tunnel and selection of its path, defined by its two portals:

First, that the tunnel is excavated through rocks with mechanical properties suitable for a safe and successful project according to the technology of the period. This limits the excavation to rocks of strength permitting a stable opening with no falling roofs, no closing "void", no squeezing rocks, no flow of high amounts of water, etc. (see [**5**], [**6**]), but not too hard, so that it can be excavated using the available tools (practically hammer and shovel) without need of explosives. Only local deviations from these conditions were possible; for instance, qanat builders had the possibility either to support certain weak sections or to make deviations to avoid very strong rocks (see [**12**], [**10**] and references therein).

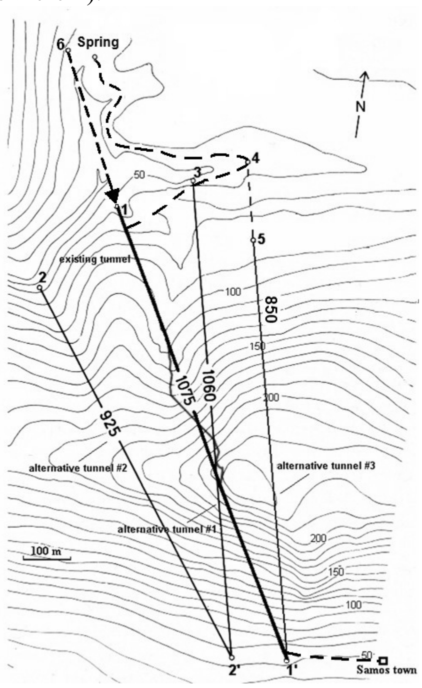

Fig. 3. The excavated tunnel (1-1') and three possible alternative routes. The axis of the existing tunnel is indicated by bold line and small scale deviations from this axis by thinner line. The aqueduct from the spring to the northern tunnel entrance and from the southern tunnel entrance to the town is indicated by a dashed line. A dashed line with an arrow (6-1) indicates the baseline inferred to have been used for the alignment of the tunnel. Numbers indicate the length of tunnels. Modified after [**4**].

Second, that the tunnel gradient is kept within certain limits, usually <1% to permit slow flow of water but no turbidity which may lead to erosion; and that the overall gradient of the aqueduct permits delivery of the water above a certain critical height.

Third, that the portals are in areas permitting accurate orientation and guidance of the excavation; this is especially important in the case of an excavation from two portals (Fig. 4). Misalignment (Fig 4b), indeed, was not a threat just for ancient engineers only (see below) but remains a threat for modern tunnels as well (see [**2**], [**6**],[**7**], [**9**], [**11**]).

Obviously, the first criterion is on the grounds of engineering geology and geotechnical engineering, while the two other criteria are basically geodetic.

REQUIREMENTS FOR A SUCCESSFUL TUNNEL ALIGNMENT

Correct alignment of the excavation of a tunnel from two portals is a major and difficult task, as been demonstrated in the case of a 2^{nd} century AD, 430m-long tunnel at Saldae, present-day Bougie or Bejaia in Algeria; in this case a slight error in the determination of the two baselines led to excavations from two portals deviating from their theoretical axis, and not meeting (Fig. 4b). This led to failure of the whole project, and a long, additional survey work from the engineer who made the initial study until the misalignment error was identified and the tunnel was successfully completed [**3**].

Orientation and guidance of a tunnel opened from both portals requires a baseline at the first portal defining the orientation of the tunnel. From this baseline a second baseline at the other portal is established using various surveying techniques (Fig. 4a). These two baselines are subsequently used for the guidance of the excavation and represent its axis (or a line parallel to it).

In the case that the two main baselines are not collinear due to survey errors, the two advancing excavation fronts will not meet (Fig. 4b); this is the case of the Saldae tunnel in Algeria mentioned above.

As is explained in the Appendix, the error (accuracy) in the orientation of a certain baseline is inverse proportional to its length (eq. 5), and this error is obviously magnified by the survey work to establish the second baseline following the law of error propagation [**11**], [**8**]. This indicates that the ambitious project of Eupalinus *required a baseline of the maximum possible length*.

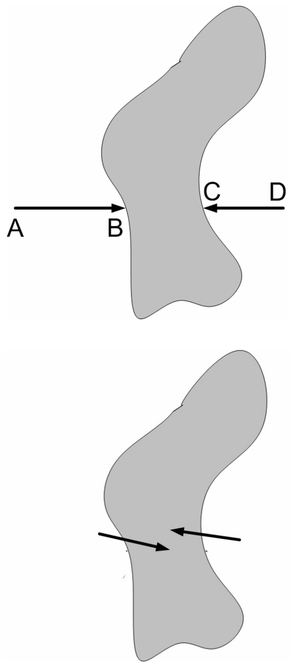

Fig. 4. (a) A sketch to show the two baselines necessary to guide the excavation of a tunnel from two portals through a rock mass indicated by shading. Accuracy in their alignment is critical. For the Samos tunnel the misalignment is of the order of 0.5^{o} [**4**].
(b) Misalignment of the two baselines leads to non-converging segments. This was the case of the Roman tunnel at Saldae (Algeria, see text for details and [**3**]). Smaller scale breakthrough errors are not unusual in modern tunnels as well [**2**], [**6**],[**7**],[**9**].[**11**].

ORIENTATION OF THE SAMOS TUNNEL

Fig. 3 indicates that because of the smooth topographic relief, close to the spring, the area favourable for a long baseline is at the extension of lines 4-1’, and perhaps of 3-2’. Still, rocks in this area are unfavourable, not permitting a safe excavation (Fig. 3). For this reason Eupalinus had to shift the tunnel north portal and the whole tunnel as much as possible west of line 3-2’. From the geotechnical point of view, the ideal solution would be line 2-2’, corresponding to a shorter tunnel, as noticed by [**4**], cutting through higher quality rocks. Still, in this case the portal would be in a gulch and the necessary geodetic baseline would be too short (less than 100m), and the risk of misalignment of the baseline at the south portal and of failure of the whole project would be too high.

Examination of Fig. 3 indicates a bending of contours at the northward extension of line 1-1' forming a small valley. This means that this area offers the possibility of an at least 300m long baseline roughly in extension of line 1-1' (dashed line 6-1 with arrow in Fig. 3). The error of orientation of such a baseline is at least several times smaller than that of a baseline in the extension of line 2-2'. In addition, the errors induced by transferring this direction to the baseline at the second portal would be much smaller at 1-1' relative to 2-2'.

It can therefore be concluded that the orientation of this valley, i.e. the local topography and the requirements of the geodetic alignment controlled not only the selection of the north portal, but the selection of the path (orientation) of the tunnel, and of the whole of the aqueduct.

DISCUSSION

Apparently the selected solution was a compromise between the geotechnical and the geodetic design. Eupalinus adopted this solution (path 1-1' in Fig. 3) knowingly that he would pay a toll: because this path is close to the area of unstable rocks, he had to support the excavated opening with a strong wall along a distance of about 100-200m (Fig. 2b). This obviously increased the cost, the duration of works and risks for failure in the tunnel. In addition, he had to construct longer channels between the spring and the tunnel and the tunnel and the town of Samos.

Still, his decision was the result of a cost-benefit analysis. A relatively small risk and higher cost saved him from a failure due to misalignment of the two tunnel branches.

The question arising is whether Eupalinus was in a position to understand such accuracies. This is a problem partly examined by [**10**] in the case of levelling. What is certain, however, is that Eupalinus had at least an excellent, most likely empirical understanding of errors in geodetic measurements and of their propagation; in particular the need for a long baseline. Without such knowledge it would be absolutely impossible to complete such as demanding project, and in fact because of this knowledge the project was successful: modern measurements revealed a deviation of only 0.5^{o} in the orientation of the two tunnel segments and the Samos tunnel became a subject of admiration in antiquity and modern times [**4**].

A final point to mention is the importance of the geodetic design in underground works, as is known in the case of qanats [**10**].

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APPENDIX

Let us assume a segment AB of length S, and ΔX, ΔY the differences of coordinates of points A and B in a certain Cartesian coordinate system. The orientation α of line AB will be given by the formula

$$\alpha = \text{arc sin}\,(\Delta X/S) \tag{1}$$

Assuming for simplicity that ΔX and S are uncorrelated, we may apply the simplified form of the law of propagation of errors ([**1**],[**8**],[**10**]) in eq. (1) and estimate the standard error σ_α of α as a function of standard errors $\sigma_{\Delta X}$ and σ_S of ΔX and S, respectively

$$\sigma_a^2 = \left(\frac{\partial a}{\partial \Delta X}\right)^2 \sigma_{\Delta X}^2 + \left(\frac{\partial a}{\partial S}\right)^2 \sigma_S^2 \tag{2}$$

Equation (2) yields

$$\sigma_a^2 = \left(\frac{\partial a}{\partial \Delta X}\right)^2 \sigma_{\Delta X}^2 + \left(\frac{\partial a}{\partial S}\right)^2 \sigma_S^2 \tag{3}$$

or

$$\sigma_a^2 = \left(\frac{1}{\sqrt{1-\left(\frac{\Delta X}{S}\right)^2}}\right)^2 \left(\frac{1}{S}\right)^2 \sigma_{\Delta X}^2 + \left(\frac{1}{\sqrt{1-\left(\frac{\Delta X}{S}\right)^2}}\right)^2 \left(\frac{1}{S^2}\right)^2 \sigma_S^2$$

$$\sigma_a^2 = \frac{1}{1-\sin^2 a}\left(\frac{1}{S}\right)^2 \sigma_{\Delta X}^2 + \frac{1}{1-\sin^2 a}\left(\frac{1}{S^2}\right)^2 \sigma_S^2$$

$$\sigma_a^2 = \frac{1}{1-\sin^2 a}\frac{1}{S^2}\left(\sigma_{\Delta X}^2 + \frac{\sigma_S^2}{S^2}\right) \approx \frac{1}{1-\sin^2 a}\frac{\sigma_{\Delta X}^2}{S^2} \quad (4)$$

because $\sigma_s << S$. Hence

$$\sigma_a^2 \approx \frac{1}{1-\sin^2 a}\frac{1}{S^2}\sigma_{\Delta X}^2 \quad (5)$$

Angle α depends on the coordinate system and ΔX and $\sigma_{\Delta X}$ on the measuring techniques. Hence, equation (5) indicates that the accuracy (or error) in orientation of line S is practically inverse proportional to its length S.

Empirically, a similar conclusion can be inferred from a line graphically determined from two points: the accuracy in the orientation of the line increases with the distance of the two points.