Levelling in antiquity: instrumentation, techniques and accuracies

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Certain major ancient engineering constructions, such as aqueducts and qanats, testify to high accuracies in the computation of elevation differences obtained using primitive levelling instruments. Based on the typology of ancient levelling instruments and the analysis of certain key ancient structures such as the (Eupalinos) tunnel at Samos Island (Greece), it became possible to specify the accuracy, and especially the measuring techniques and procedures of levelling in antiquity, ignored so far by non-professional investigators. Ancient levelling techniques were derived on the basis of trials and errors over past centuries and include standard length sighting distances (revealing that 'cord stretching' may also indicate levelling), stadias with fine focussing on sliding targets adapted to the level field of view, two-way measurement in levels and stadias, repeated and redundant observations in loops, measurements by skilled professionals. These techniques permit to limit and randomise systematic errors and to obtain accuracies up to a few centimetres per kilometre are likely to indicate a real theory of error propagation and are reminiscent of the techniques used in our days in extraordinary projects (the alignment of the CERN colliders, etc.).

Keywords: Levelling, Ancient Greece, Tunnels, Ancient instruments, accuracy, precision, qanat

Introduction

In the past 3–4000 years, some impressive engineering works requiring accurate levelling, tunnels, aqueducts and water channels, have been successfully constructed in various part of the world (Iran, West China, Middle East, Egypt, ancient Greek and Roman World). Some examples are:

(i) the first century AD, 50 km long Niîmes aqueduct in southern France, comprising 35 km of tunnels and bridge arcades up to 47 m high. This aqueduct had an average gradient of 34 cm km^{-1} (1 : 3000), while along long segments its gradient is null [**10**]

(ii) the 132 km long Carthage (Tunis) aqueduct, built in the second century AD [**11**]

(iii) various qanats (known also as qarez, qareez, foggaras or falaj), underground sub-horizontal water channels, up to 100 km long, excavated at the bottom of wells in Iran and many other arid regions [**8**], [**12**], [**25**], [**31**]

(iv) channels and tunnels to drain swampy land [**17**].

In addition, there have been made several efforts to excavate the 160 km long Suez Canal in antiquity [**26**].

All these constructions were made long before modern instruments equipped with an alidade and a bubble level were invented in the sixteenth century. Hence, three questions arise concerning levelling in antiquity:

(i) which was the accuracy of measurements and what was the understanding and estimates of the accuracy?

(ii) which instruments, main (levels) and secondary (stadias) were used?

(iii) which measuring techniques and procedures were used?

An answer to the second question was provided on the basis of the analysis of ancient Greek, Roman and Arab sources (see for instance [**18**]). In addition, there have been some efforts at reconstructing ancient instruments and testing their accuracy (see for instance [**2**], pp. 13, 23). Still, these studies faced two limitations. First, they were confined to spectacular buildings such as temples and the pyramids, testifying to accuracies of up to 1 cm over distances of ~300 m [**7**], [**2**], [**22**] (i.e. of small scale structures from the point of view of surveying). Second, they were usually made by non-professional surveyors, mostly historians, archaeologists and architects who cannot understand the overall measuring process ([**7**], is one of the few exceptions).

Concerning the first question, only recently, in a study of ancient qanats in Iran, it was found that the accuracy in levelling over distances tens of kilometres long was ranging between a few centimetres and a few tens of centimetres per kilometre [**25**], comparable to that of modern low order engineering surveys based on industrial equipment. Such accuracies were indeed realistic and absolutely necessary, for aqueducts tens

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of kilometres long were constructed in segments, independently from each other, the excavation of qanats was starting from the destination point and advanced towards the source (master) well, while certain tunnels were excavated from their two portals and led to a successful breakthrough [**11**], [**16**], [**27**]. On the other hand, there are known cases of unsuccessful ancient works, probably due to errors in levelling. For example, when an aqueduct failed to provide water to the town of Nicomedia, modern Izmit, the town affected by the 1999 Turkey earthquake, in view of the construction of a new aqueduct, the local governor asked the Roman emperor Trajan to send him a surveyor 'to prevent a repetition of what has happened' (Pliny, Letters X, 37, see [**18**], p. 344).

Concerning the third question, on the basis of the analysis of qanats, it has been proposed that accurate levelling was a product of the high skills of surveying teams, of the uniformity of the field work, as well as of redundant observations permitting minimisation and randomisation of systematic errors which usually affect levelling [**25**]. The details of the measuring process, however, were not specified.

It is hence obvious that an answer to the above three questions, especially the first and the third are still missing; an effort for an integrated answer to these three questions is the subject of this article.

Levelling accuracy in antiquity

Precision and accuracy in modern levelling surveys

The quality of various types of measurements is usually defined by their precision, which is a stochastic term. The common approach is to regard a measurement χ falling within a certain interval which is a function of the mean value of such measurements and of their standard error, $\bar{\chi}$ and σ respectively; for instance in the limit ($\bar{\chi}-k\sigma$, $\bar{\chi}+k\sigma$) with a probability of 66% for $k=1$, 95% for $k=2$, 99% for $k=3$, etc. This approach neglects systematic errors and underestimates 'true errors' (e.g. [**3**]).

However, in contrast to most other sciences, the quality of measurements in geodesy is defined not in terms of precision, but usually in terms of accuracy; the latter is possible due to geometrical constraints, for instance, the misclosure error in angle measurements in triangles, and the error in terms of accuracy can be several times higher than the error in terms of precision (see for instance [**6**] for an estimate of the difference between precision and accuracy in GPS).

Analysis of errors in numerous levelling traverses forming loops (i.e. providing geometric constraints to the quality of measurements) has led to the following well known formula specifying the standard errors in levelling

$$\sigma=\sigma_o S^{1/2} \tag{1}$$

where S is the distance in km of the endpoints of the levelling traverse and σ_o a parameter depending on instrumentation and measurement techniques used [**3**], [**28**], [**30**]. This formula merely reflects accuracy, but still defines σ as a stochastic variable.

Tolerance in ancient levelling

Ancient builders and surveyors were more concerned about the quality of their work than their modern colleagues: it would be completely out of place to realise for instance, that after 30 or more years of exhaustive and dangerous work with several victims (see [**31**], [**8**] and [**25**]), the qanat constructed failed to bring water because of an error (usually a systematic error) in levelling!

The only way to exclude such a possibility was to strictly follow techniques or guidelines which have proved successful, and to avoid those which proved non-successful in numerous, similar projects in the past. These techniques or guidelines can a priori be regarded as empirical specifications similar to those adopted in modern surveys (see [**28**] and [**30**]) and which permitted estimates of the accuracy and not simply of the precision of the ancient surveying work.

Still, we have no reason to believe that ancient surveyors were regarding the accuracy of their measurements as a function of a confidence level, as is the case with modern statistics. Based on empirical rules and cumulated experience they could only estimate the tolerance of measurements, i.e. upper and lower bounds of the estimated values.

This last approach, indeed, was quite usual at least in ancient Greek mathematics and physical sciences. For instance, there are known lower and upper bound estimates for the parameter π of the circle, for the length of the perimeter of polygons inscribed in circles, as well as for various measurements in astronomy (radii of planets, distances between the sun and planets, etc.; see [**13**]).

Since both modern and ancient surveyors were based on estimates of accuracy, at a first approximation we can relate the error margin or tolerance in ancient work with modern stochastic estimates assigning the confidence level to the significance of the project. For instance, for a long qanat in a nearly flat terrain and for nearly null gradient aqueducts, the tolerance of measurements can be assigned to a confidence level approaching 100% (practically 99·9%, $k=5$ or even more). For aqueducts with an important gradient, the corresponding confidence level can be regarded between 95 and 99%, $k=2$–3).

Hence, tolerance t (or error margin) in ancient levelling is related to the accuracy in the stochastic, modern sense of the term by the equation

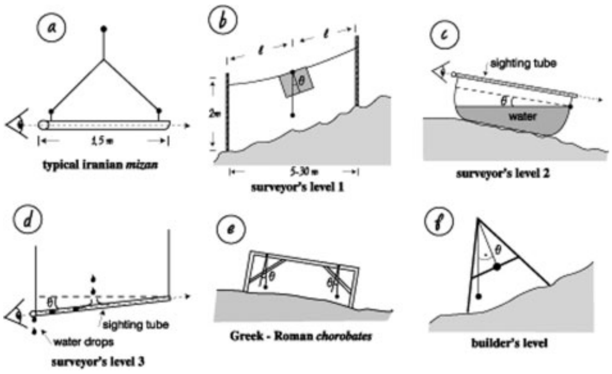
$$t\leq 2k\sigma \tag{2}$$

where k is the parameter defining the confidence level in the normal distribution and σ the typical (standard) accuracy error defined by equation (1).

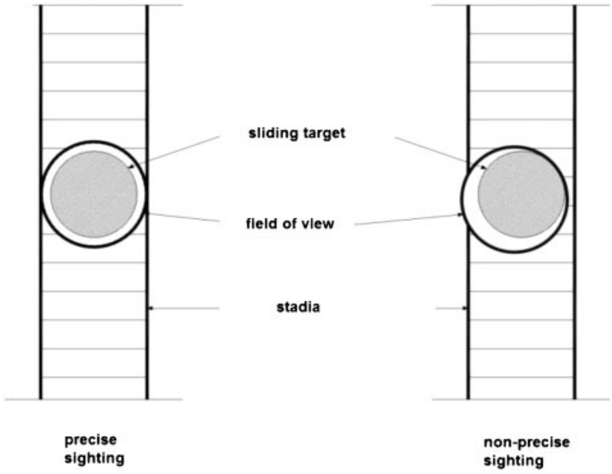
A limitation in this approach is that the modern statistical approach suggests that upper and lower bound values or errors are symmetrical relative to the mean value, while this was not necessarily the case in antiquity, as will be discussed below in the case of the sixth century BC Eupalinus tunnel in Samos.

Estimates of accuracy in ancient levelling

Estimates of the accuracy of levelling in ancient surveys are available for two types of constructions. First, of the pyramids, for which an accuracy of up to a few or even 1 cm over distances of ~300 m was calculated [**7**], [**2**], [**22**] and second of qanats.



1 Typical ancient levelling instruments (modified after [25]): several other combinations of sighting and horizontality systems were possible, for instance chorobates using hydraulic techniques



2 Principle of accurate observations on a stadia equipped with a sliding target. This technique fully exploits the potential of human eye to identify symmetry and differences in distances better than absolute locations. Field of view is shown circular, but it may have been triangular or square

For the latter, it was shown that adopting modern typology and the formula of equation (1), their successful completion required a value of σ_o of the order σ_o=25 cm km$^{-1/2}$, reaching the order of a few centimetres per square root kilometres in exceptional cases, most likely in the maturity period of qanat construction [**25**].

In the case of the >1000 m long Eupalinus tunnel in Samos Island (Greece), it was found that the excavations from the two portals led to a vertical offset of 30–50 cm at the breakthrough point [**16**]. Since this error derives from a levelling traverse at least ~2·5 km long (tunnel length plus traverse around the hill), applying equation (2) an uncertainty level for a k >3 to 4, an estimate of σ_o of the order of a few centimetres is obtained. This estimate is compatible with that of high accuracy qanats (see above and [**25**]).

Instrumentation

Laborious work of various investigators (for instance Lewis [**18**]) have permitted to identify and classify most types of ancient levels before the advent of the alidade in ~1600; these types are schematically summarised in Fig. 1.

The basic characteristic of all these instruments which remained in use for millennia, is that they consisted of:

(i) a simple sighting system, usually a 1·5–2 m long tube with a simple circular, triangular or square hollow. The shape of this hollow and the length of the tube determined the field of view, necessary to point to the stadias

(ii) a simple horizontality system, either mechanical (plumb line or symmetry around the vertical) or hydraulic (based on the level or the flow of water (Fig. 1).

A main difference between modern and ancient levels is that in the latter measurements could be made from both edges; this was because of the absence of lenses, objective and eyepiece which characterise modern instruments and permit sighting from one edge only. A certain advantage of the ancient levels is that measurements from both edges permitted to counteract certain systematic errors.

Ancient stadias were either simple graduated staffs, like modern stadias, or in addition, they were equipped with a sliding target, usually circular (in the case of levels with a circular field of view), adjustable to the height of the sighting point (Fig. 2). These targets are key points to understanding levelling accuracy in antiquity, as will be explained below.

Measuring techniques

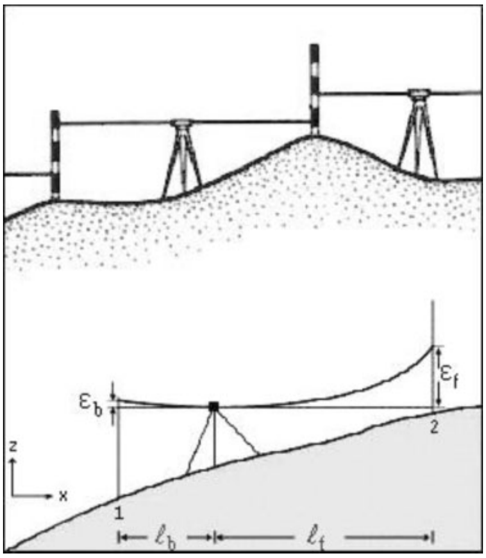
A characteristic of the reports of ancient and of modern authors concerning ancient geodetic technology is that they usually describe only the instruments and ignore all the 'boring details' of the measuring procedure. For instance, the 'chorobates' (see Fig. 1*c*) was regarded by the famous Roman writer Vitruvius (the first century AD) as the most accurate levelling instrument (see [**18**], p. 305), but it was not specified how it was levelled, how long the sighting lines were, with what kind of stadias it was used, how many measurements were taken each time, etc. Yet, such details may be inferred on the basis of experience with modern instruments and the study of the literature on ancient constructions.

Collimation techniques

In order to avoid errors induced by imperfections of the instruments (mostly non-verticality of the sighting tube of primitive instruments as those shown in Fig 1), measurements were made several times, reversing each time the instrument; this was possible because of the symmetry of instruments in absence of lenses (see Fig. 1). Such a primitive collimation technique was most probably used for stadias as well. Measurements in each stadia were most probably made twice, with the stadia first erect and then upside down; this reduced calibration and verticality errors.

Equality in back- and fore-sight distances

Al Karaji, an authority in qanat engineering in the Arabic-Persian world at circa 1000 AD, mentions that the back- and front-sight distances were kept equal throughout the whole levelling line with the rods and level tied with cords of equal length (see [**18**]). This ignored detail can be evaluated in the framework of the specifications for similarity of the back and fore-sight



3 The ray path in levelling is a curve (bottom), and in the case of unequal back-sight and front-sight distances (top) a systematic error is introduced in the measured elevation difference: accumulated errors of this type over long traverses may reach several metres[21], [24], [29]

distances in modern surveys (see [**27**]) and especially the experience gained from the repeated South California levelling measurements in the 1970s: asymmetry in the back- and front-sight distances in levelling has led to systematic errors (Fig. 3) cumulating to high values (see [**21**], [**24**] and [**29**]). A remedy to this systematic error is to keep the level-to-staff distance constant using cords of standard length, as suggested by Al Karaji in his treatise on levelling 1000 years ago (see [**18**]).

Stadias with sliding targets at fixed distances

As already noticed, ancient levels were not equipped with lenses, and hence the section of the stadia by the horizontal plane defined by the level axis could not be precise. For this reason, there were necessary some techniques to increase the resolution in height measurements on stadias even at short sighting distances. The sliding rule [**18**] shown in Fig. 2 for a circular target was a smart solution based on the ability of the human eye to identify more easily differences in distances than absolute positions of points.

The technique adopted is based on the fact that the sighting field from a hollow horizontal tube is a circle with diameter depending on the distance of the target from the instrument. If the distance between the level and the stadia is kept fixed using a stretched rope of standard length, the circular target of a standard diameter would fit to this circle leaving around it a margin of standard width. The circular target may be adjusted with fine up and down movements of the target on the stadia and with rotations to the left and right of the sighting tube so that the margin around the circular target is symmetric (Fig. 2). Because of the ability of the human eye to identify very precisely differences in lengths, margins of equal width were left around the target, which is set exactly at the axis of the level. For a trained eye this procedure permitted the trace of the horizontal sighting axis on the stadia to be defined with a resolution of up to 1–2 mm at a maximum distance of 15–20 m, the optimum possible value.

Using the well-known formula

$$\sigma = r\theta \tag{3}$$

where σ is the linear uncertainty in a direction normal to the sighting distance, r the distance and θ the uncertainty (error) in the angle measurement in rads, the above estimate testifies to an angular error of 0·7–0·25°, which is a very reasonable estimate, given that the astronomical orientation of the Egyptian pyramids was made with an accuracy of 3′ [**22**], i.e. 5–15 times higher.

Using the estimate of σ=1–2 mm for each sighting, we may compute analytically the accuracy of levelling traverses. First, we compute the accuracy of elevations differences between backward (back-sight) and foreward (front-sight) measurements for a single set-up using the formula $y=x_1-x_2$ and the hypothesis of uncorrelated variables. Applying the law of propagation of errors for uncorrelated variables

$$\sigma_y^2 = \left(\frac{\partial f}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial f}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \ldots \tag{4}$$

where the elevation difference for one stadia set-up is estimated $1\times 2^{1/2}$ to $2\times 2^{1/2}$ mm.

Assuming that the height difference y between two points 1 km apart is computed by ~30 segments each corresponding to one set-up of the level covering a distance of 30–40 m, a function of the type

$$y = x_1 + x_2 + \ldots + x_i i = 1, 2, \ldots\ 30 \tag{5}$$

is formed. Assuming that all x_i's are of the same accuracy computed previously, $1-2\times 2^{1/2}$ mm and uncorrelated, applying equation (3) to (4), the standard error σ_y of y is of the order of 1–2 cm.

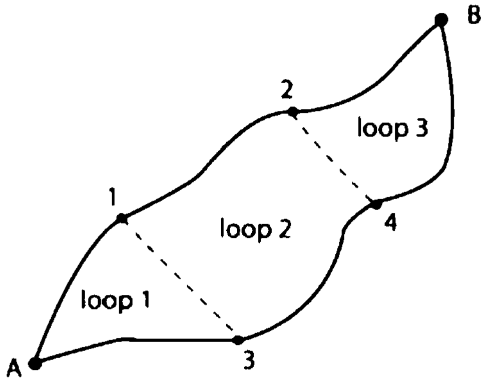
Recently, Arnold and Isler [**2**] in their study of ancient levelling techniques made experiments with a simple 2 m long tube, i.e. an imitation of an ancient level. What they found is that an elevation difference of 1 cm can be recognised with difficulty at a distance of 40–45 m.

Analytical estimation of the standard error of levelling for about 11 segments corresponding to a level-to-stadia length of 40–45 m and a standard sighting error of >1 cm following the same approach as above, leads to a standard error of the elevation difference in 1 km, >5 cm, i.e. several times higher than for short sightings.

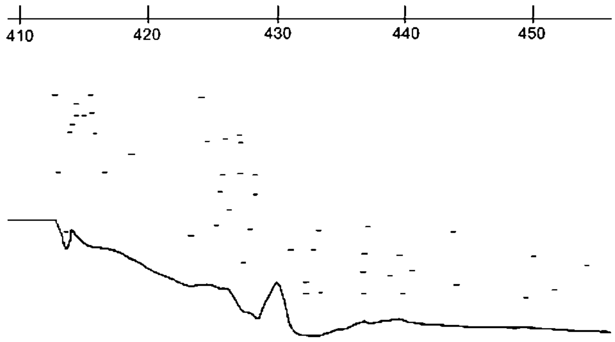
Long (>15–20 m) level-to-stadia lengths are unlikely for another reason as well: it would have been very difficult to manipulate 40–45 m long stretching ropes required for levelling (see above). Even in modern surveying, tapes longer than 30 m are rarely only used.

Hence, the combination of stretched cords fixing the level-to-stadia distance at about 15–20 m and of sliding targets fitting to the level field of view permitted accuracies in height differences much higher than those expected in levels without lenses. In addition, this process minimises systematic errors imposed by asymmetries in back- and front-sight distances, i.e. the errors which represent the real threat for levelling (see above).

Interestingly, our estimate for a the level-to-stadia distance for high-quality measurements of 15–20 m is also compatible to that used in the twentieth century first class levelling [**3**], [**28**].



4 Redundant measurements of elevation difference between two points A and B, measured by two traverses A–1–2–B and A–3–4–B, as well as transversal segments 1–3 and 2–4. Misclosure in the three loops permit to identify erroneous measurements and to derive some estimates of the accuracy, in analogy to the well-known Ferrero formula



5 Levelling marks surviving on the walls of a 40 m long segment of the Eupalinus tunnel at Samos Island, Greece, the first probably tunnel excavated from both portals in circa 530 BC. These levelling marks correspond to only one of the several types of levelling marks used and reveal repeated or redundant observations and different surveys. Line indicates the reference level at the tunnel ceiling, undulating due to local rock instability. Vertical exaggeration ×40 (after [16])

Repeated and redundant observations

As has been analysed in [**25**], a basic characteristic of ancient surveys was the repeated and redundant observations. Multiple observations tending to reduce collimation errors have already been noticed above.

Repeated observations of whole segments, tending to reduce random errors were most probably also used. However, it is believed that ancient surveyors were based on high redundancy observations and geometric constraints. This is exemplified in Fig. 4. In order to measure the height difference between A and B, the simple way is to form a levelling traverse, for instance follow the route A–1–2–B. In this case, the accuracy of results will be low. Measurement of another traverse, for instance along route A–3–4–B, would certainly increase the quality of measurement. However, measurement of a complex system of traverses which include transversal segments forming closed loops would significantly improve the results, because of the possibility to control misclosure errors along each loop. This would permit to identify gross errors, to randomise systematic errors and minimise all errors affecting measurements. In addition, it would permit some statistics of misclosure errors, a primitive Ferrero-type formula for height differences and estimates of the accuracy of the levelling traverses.

Furthermore, repeated measurements, probably in different ambient conditions (for instance in spring, in summer and in winter with ground and plants affecting the near-ground refraction index of the lowermost atmosphere) would have permitted a mean value of elevation differences of higher accuracy.

These conclusions are not arbitrary, and they can be supported by two arguments. First, measurements in antiquity for large scale projects such as tunnels and aqueducts were lasting long, usually for years. There is clear evidence for that for qanats, with the geodetic design described as the most difficult and perhaps time consuming part [**8**], [**25**], [**31**] and for a Roman aqueduct at Saldae (modern Bejaia) in Algeria [**11**].

Second, at the famous >1000 m long Eupalinus tunnel at Samos Island, excavated in circa 530 BC from both portals [**27**] remains of numerous levelling marks of at least five types (thin lines, thick lines, horizontal lines with a tick, etc.) can still be observed in certain spots (Fig. 5 [**16**]). These marks undoubtedly indicate multiple and redundant measurements which permitted a low-error budget and a successful breakthrough.

The most likely interpretation for these multiple benchmarks is that Eupalinus had planned a complex system of levelling routes inside the tunnel, as if for instance several traverses of the type of A–1–2–B and A–3–4–B of Fig. 4 were confined to nearly the same path: a technique followed recently in the alignment of accelerator colliders (see the section on 'Discussion').

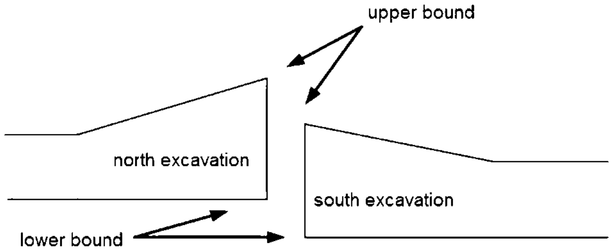
Simple techniques and well-trained parties

Rapid technological changes in the twentieth century led to dramatic changes in surveying instrumentation and techniques, which were slowly evolving since the industrial revolution. On the contrary, in antiquity, instruments and measuring procedures remained unchanged for centuries and millennia, and the reports of Vitruvius (the first century AD) for the Roman World and of Al Karaji (the eleventh century AD) for the Arab-Persian World, probably cover in basic terms all periods in antiquity, despite the small changes which occurred (for instance, hexadecimal or decimal measuring systems, etc).

A basic characteristic of surveying in antiquity is that it was confined to certain groups of experts, types of guilds or even of hereditary professionals in certain towns (for instance, qanat engineers in the Yazd town in Iran [**31**], [**8**]) who followed simple, precise rules developed on the basis of the trial-and-error approach over past centuries and millennia. This strict uniformity in operations by highly experienced professionals permitted to successfully complete important projects and minimise the possibility of failure and of death toll.

Tolerance in ancient levelling: evidence from the Samos tunnel

Different lines of evidence, observations in successful surveying projects project and an analytical approach



6 Vertical sections (not in scale) of the excavations near the breakthrough point of the Eupalinus tunnel at Samos based on the data of [16]. Increased height of galleries indicates predicted upper and lower boundaries of measurements. A 30–40 cm offset in the floor of the galleries indicates the misclosure along a >2·5 km long levelling path

discussed above indicate that the accuracy in levelling in antiquity could reach a few centimetres per kilometre.

Still, evidence from the ancient tunnel at Samos gives evidence that 2500 years ago Eupalinus, its master engineer, and obviously other ancient chief engineers had an excellent understanding of the error distribution in levelling in terms of upper and lower bounds of errors.

Until some tens of metres before the breakthrough point of the >1000 m long Samos tunnel, the two galleries were kept horizontal and their height constant, typically ~1·8 m. However, at the southern branch (i.e. the gallery from the southern portal), ~30 m before the predicted breakthrough point, the floor was kept nearly horizontal, but the elevation of the roof was gradually increased to ~120%, and then the excavation stopped waiting for the breakthrough from the other excavation front. Similarly, in the northern branch the tunnel section was kept nearly horizontal and with a similar, typical section, but for ~25 m before the expected breakthrough point the height of the tunnel was gradually increased until doubled (see Fig. 6 and [**16**]). The two galleries met with a vertical offset of 30–50 cm.

The likely explanation for the increased gallery height just before the breakthrough is that Eupalinus believed that his measurements perhaps underestimated the true elevation, but certainly did not overestimate it; for this reason, he had to increase only the elevation of the gallery ceiling (Fig. 6). It can hence be deduced that he had in mind a lower and an upper bound of the range of the real elevations, following the dominant approach in mathematics and in physical measurements at least in the ancient Greek World (see the section on 'Introduction'). His error estimates could derive from a combination of multiple measurements deduced from the spread of benchmarks shown in Fig. 5 and of empirical laws developed over the past centuries and perhaps by Eupalinus. This clearly indicates an ancient theory of error propagation, for which no written evidence exists.

Still, there is the possibility the change of the tunnel height schematically shown in Fig. 5 to reveal only 'blind' guiding of the tunnel by the sounds of hummer in rocks in the vicinity of the breakthrough point; an effect well known in mining. This explanation is, however, not likely for two reasons.

First, the height difference between the two tunnel segments was too small to permit the precise identification of the source of noise in the other gallery.

Second, in the vicinity of the breakthrough point, rocks are homogeneous and isotropic travertinoid limestones (see Fig. 7) which are expected to transfer the sound between neighbouring points linearly. For this reason, if the excavator had the impression that in the north gallery (segment) the sound produced in the south gallery was coming from a higher level, he would have increased the height of the ceiling of the north and would have lowered the floor of the south gallery in order to adapt to the excavation to the direction of the sound; he would definitely not have kept both floors horizontal and would not have increased the ceiling heights of both galleries. Hence, the hypothesis of 'blind' digging is not consistent with the existing evidence.

Discussion

Previous analysis summarises the answers given to the three questions posed in the introduction, i.e. which was the accuracy and the concept of accuracy in antiquity, and with which instruments and measuring techniques such accuracy was obtained. What is surprising is that on the basis of experience cumulated over past centuries or millennia, ancient surveyors had developed certain simple techniques which permitted to surpass the limits of the primitive instruments, and at the same time to avoid the pitfalls of levelling along long distances, i.e. to control systematic errors and cumulating errors.

A main parameter controlling the accuracy of ancient surveys was the repeated and redundant measurements using geometrical constraints, a technique indeed adopted in our days for highly demanding projects such as the alignment of the particle accelerators, including that at CERN, which also forces modern surveyors to surpass the potential of modern instruments [**1**], [**5**], [**14**], [**15**], [**19**]. For this reason, high accuracy survey work in antiquity lasted for years, perhaps to cover different ambient conditions and hence randomise systematic errors [**26**].

An implication of the previous discussion is that the accurate measurements and control of systematic errors was based on the technique of stretched cords of equal length between the level and the stadia. This may indicate that 'cord stretching', as was known surveying in ancient Egypt [**18**], [**4**], may not only indicate distance measurements, but elevation measurements as well.

Another parameter permitting high accuracy work in antiquity is that measurements were made by highly trained professionals strictly following standardised techniques and procedures tested for centuries and millennia, and techniques and procedures which could minimise, if not exclude, the possibility of blunders and of systematic errors. This was partly due to the fact that in antiquity changes in the instrumentation technology were slow if not null, and experience for successful and non-successful works was incorporated in professional practice; this is a completely different situation from that in our days characterised by a rapid technological progress, with new rules for new instruments continuously introduced, and with the old experience ignored!

A result of the success of ancient surveyors, in many cases identified also as geotechnical and hydrological engineers, is that they were persons and groups highly esteemed in ancient societies. For instance, tombs of several surveyors with frescos providing some glimpses of survey measurements are known from pharaonic

7 The >1000 m long Eupalinus tunnel near the breakthough point; the two segments met at a high angle. Mark the homogeneous and isotropic character of solid limestones neat the breakthrough. Metal fence was added about 20 years ago to cover small shafts leading to a qanat-type gallery, in which the water was flowing, 4–8 m below the tunnel floor. *a* view form the south gallery (segment) showing a vertical offset, about 30–50 cm; *b* view of the breakthrough point from the north gallery (segment): south gallery continues to the right of the edge of the tunnel segment shown

Egypt, indicating that these surveyors were high-rank officials (see [**22**] and [**4**]). The name of Eupalinus, the chief engineer of the famous Samos tunnel was mentioned with admiration by the fifth century BC historian Herodotus, and following this information the ancient tunnel was found in 1882 (see [**16**] and [**27**]). It is also possible that ancient hero Hercules can in fact be identified with a highly esteemed early engineer and surveyor, responsible for major works, mostly channels (I. Mariolakos, pers. comm.).

A final question arising is how we can explain the reported gross errors (~10 m) in levelling which are reported to have interrupted the construction of major water channels such as the Suez and the Corinth (Greece) Canal in antiquity, for fear of flooding of low-lying coastal areas. The answer is that reported erroneous estimates of the height differences between the two exits of the two future Canals can in no way reflect erroneous measurements (a 10 m error in the 6 km long Isthmus of Corinth was totally out of place), but tricky arguments, which were successfully used by social, economic and political groups to block the construction of the Canals. Hence, it was not a question of accuracy and of errors in the technical sense, but a question of politics [**26**]!

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