Levelling for Qanats, Aqueducts, Water Channels and Tunnels in Antiquity: Instrumentation and Accuracies

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SUMMARY

Accurate levelling was a requirement for major engineering works such as tunnels, aqueducts and water channels which have been successfully constructed in the last 1,000-4,000 years in various parts of world (Iran, West China, Middle East, Pharaonic Egypt, Greek and Roman World). Previous investigators have summarized information on the type of levels used, but the accuracies required and the precise techniques used to obtain such accuracies is a point that has been examined only in the case of qanats.

In this article, based on present-day experience and a systematic study of ancient works we try to pour some light to the techniques permitting high-accuracy levelling in combination with primitive instruments. In particular, (1) the use of stadias with a sliding target which, in combination with a constant stadia-to-rod distance, permitted high resolution sighting and minimization of refraction errors, (2) collimation-type techniques, and (3) redundant and repeated observations permitting randomization of systematic errors and minimization of other types of errors. These techniques permitted accuracies ranging between a few tens to a few cm per kilometre of levelling, highly exceeding the capacity of primitive levelling instruments.

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1. INTRODUCTION

In the last 4,000 years some impressive engineering works such as tunnels, aqueducts and water channels have been successfully constructed in various part of the world. Some examples are the qanats in Iran and in surrounding regions (Fig. 1), i.e. underground water channels, excavated at the bottom of vertical shafts (Wullf, 1968; English, 1998; Stiros, 2006); the early water channels in Egypt, ancestors of the 19th c. Suez Canal (Stiros, 2007); and tunnels, the most important example of which is the >1km long tunnel in Samos Island (Greece) excavated from both portals under the direction of Eupalinus in circa 530BC (Kienast, 1995).

A common nominator in all these works is their accurate leveling, which has been recognized as the most difficult part of the whole project, at least as far as qanats are concerned (English, 1998). This is because a qanat was made in three phases. First, a master well producing water at a certain distance from the channel output area was constructed. Then it was

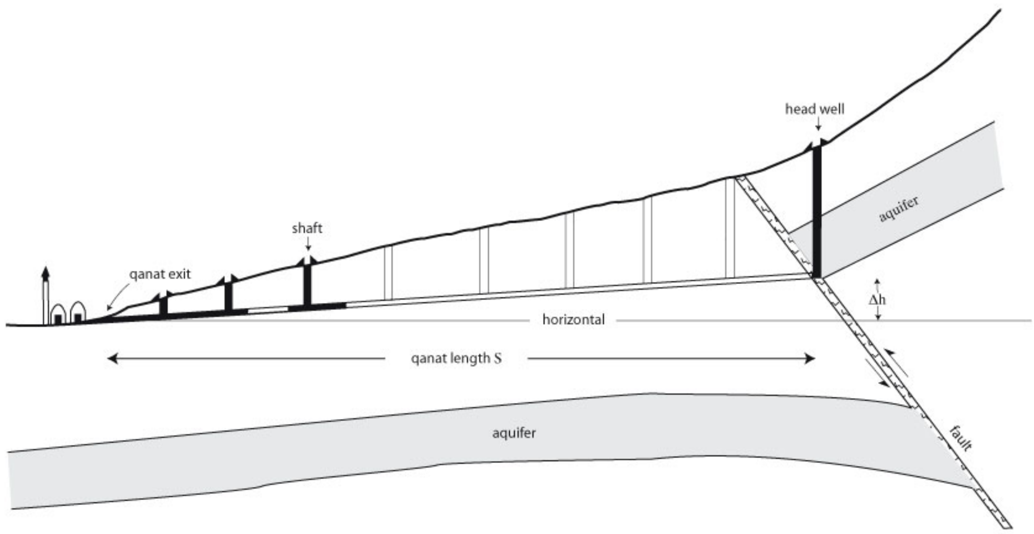

Fig. 1. Cross-section of a typical qanat in Iran. After a head well exploiting a productive aquifer is constructed, the qanat is designed on the basis of precise leveling. The tunnel excavation at the bottom of shafts starts from the exit of the canal and advances upwards, till the head well is reached. Excavated part is shown dark, while excavation debris is deposited around the shaft, giving the impression of lines of craters. After Stiros (2006).

measured the elevation of the water level in the well and the elevation of the output, destination area, usually a few to tens of km away, as well as the elevation of the ground along the future channel. Finally, the channel was excavated not from the master well downstream, but from the destination point upstream, until the producing main well was met. The project was successful if after a risky (death toll was not unusually paid) and long (usually several tens of years) efforts the underground channel arrived at the target level and the water was flowing freely along the water channel (English, 1998).

Still, these projects were made using primitive instruments, long before the telescope was invented. This raises the question how the geodetic design of these projects was made. This is a problem discussed by various investigators (Lewis, 2001; Kienast, 1995), but still a clear explanation has been presented only for qanats (Stiros, 2006). In this article we present some estimates of the accuracy in levelling in antiquity and explain which instruments and techniques ancient surveyors used

2. ACCURACY OF LEVELLING IN ANTIQUITY

Accuracy is a stochastic term, and the common approach of standard deviation defines an estimate with a probability of 66%. Obviously, the work of ancient builders and surveyors could not have been constraint by such an estimate: it would be out of place to design a qanat for instance, and after 30 years of work to recognize that the underground channel reached the main producing well is above the water level and the whole project failed!

Levelling in antiquity was therefore based not on the concept of the standard error as is the case in our days, but on the tolerance of measurements, which may be described as an error margin not to be exceeded with a probability of 99.9% for qanats or 95 to 99% for other projects. Hence tolerances correspond to the standard error multiplied by a factor of 2, 3 or 4, depending on the significance of the project.

The only case for which estimates of the accuracy of levelling in ancient surveys are available is that for qanats. In particular it was shown that adopting modern typology and the formula

$$\sigma = \sigma_o\sqrt{S} \qquad \text{(eq. 1)}$$

where S is the distance in km (Bomford, 1971; Vanicek et al., 1980), successful completion of these works requires a value of σ_o of the order $\sigma_o=25\text{cm}/\sqrt{\text{km}}$, with this value reaching the level of a few $\text{cm}/\sqrt{\text{km}}$ in exceptional cases in the maturity period of qanat construction (Stiros, 2006).

In the case of the Samos tunnel, it was noticed that the excavations from the two portals of this >1000m long tunnel led to an offset of about 60cm at the breakthrough point (Kienast, 1995). This is certainly an estimate of the tolerance of the ancient survey, which, as will be analyzed elsewhere indicates an accuracy level broadly similar to that of qanats.

3. INSTRUMENTATION

Geodetic instrumentation in antiquity, especially for levelling is not a mystery. Laborious work of various investigators (for instance of Lewis, 2001) have permitted to summarize the basic principles of ancient levels as in Fig. 2. The basic characteristic of all these instruments is that they were equipped with a simple horizontality system and a simple sighting system,

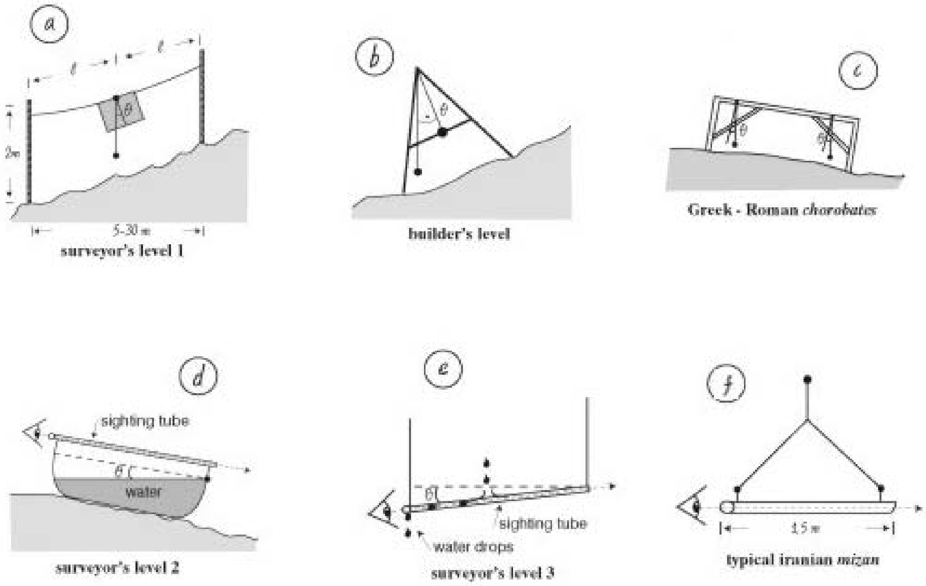

Fig. 2. Typical traditional and ancient leveling instruments. After Stiros (2006).

usually a tube or a V-shaped hollow. In addition, there were used stadias, but of much lower accuracy.

There are two points in instrumentation that are usually ignored. First, in some cases stadias were not simple graduated staffs, but they were equipped with a sliding circular target, adjusted to the sighting point (Fig. 3). And second, the level and the stadias were connected with wires of equal length, apparently forcing the distance-to-rod distance to remain constant, as is noticed for instance by Al Karaji, summarizing the state-of-the-art in the Arabic-Persian world at circa 1000AD (Lewis, 2001).

4. DISCUSSION

Professional surveyors and surveying educators know well that the quality of instruments is not the only parameter determining the quality of measurements, and the latter is primarily affected by the overall measuring procedure and the expertise of the measuring teams.
In addition, our present-day understanding of the accuracy in levelling, especially after the studies of the aseismic uplift of Southern California in the 1970's (Reilinger and Brown, 1981; Stein, 1981; Strange, 1981) indicate that levelling is affected by three primary types of errors: (1) sighting and calibration errors, (2) refraction errors and (3) accumulation of errors (Bomford, 1971; Vanicek et al., 1980).

The methodology proposed by Al Karaji, for instance, for a fixed distance between level and stadia representative also of techniques used in other periods and areas as well (Pharaonic Egypt etc; Lewis, 2001) permits to minimize the refraction errors, to a major degree

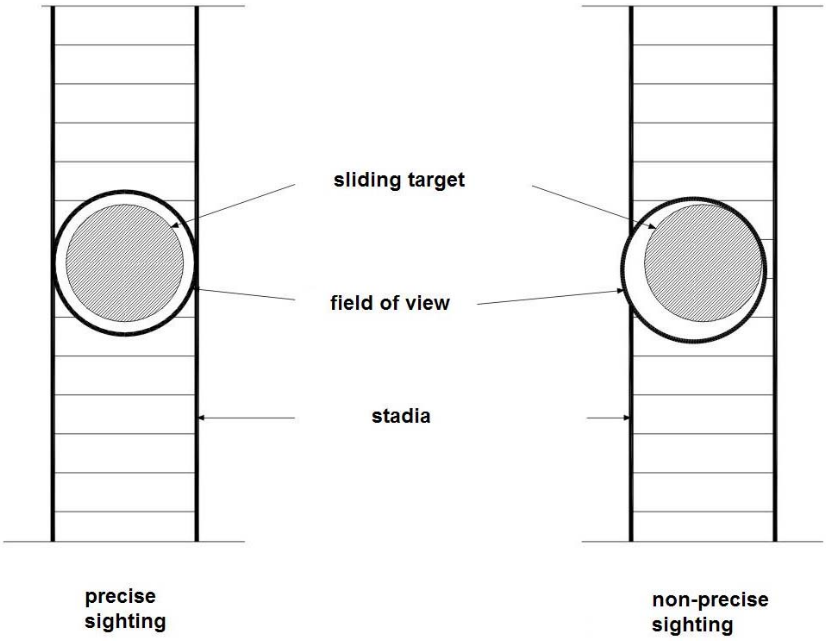

Fig. 3. Principle of accurate observations on a stadia equipped with a sliding target. This technique fully exploits the potential of human eye to identify differences better than absolute locations.

depending on the inequality between front-sights and back-sights. In addition, the sliding target on the stadia permits an optimum estimation of the elevation for two reasons: the human eye can estimate much better differences than absolute values (Fig. 3), especially since the diameter of the circular range of view through the sighting tube remains constant because of the fixed level-to-stadia distance. It was also likely that measurements were made on the stadia both at an upright position and then upside-down, and with the level first in one direction and then rotated 180^o along a vertical axis; these processes permit imperfections in graduations of the stadia and linearity-horizontality of the level to be to a large degree obliterated (collimation). Such simple procedures permit minimization, if not elimination of the first two types of errors described above.

The third constituent of the error budget, accumulation of errors, is the most serious in levelling, especially in long traverses (Reilinger and Brown, 1981; Stein, 1981; Strange, 1981). Minimization of errors in every single sighting (using short and equal sighting distances) definitely permits to reduce this error. However, the basic strategy to limit this error, mainly related to systematic effects, is a technique currently used in high accuracy tunnelling: redundant, repeated observations permit to randomize systematic errors and increase the accuracy of results (Chrzanowski et al., 1993; Stiros, 2006). Ancient surveys were based indeed on this simple technique, ignored by most previous investigators of the ancient technology, in their majority non-professional geodesists. This technique was systematically applied in antiquity, as can be derived from two lines of evidence:

First, the duration of geodetic work in antiquity, usually lasting for years (English, 1998; Grewe, 1998; Stiros, 2006). Second, traces of numerous levelling surveys surviving along the walls of the Samos Tunnel (Fig. 4).

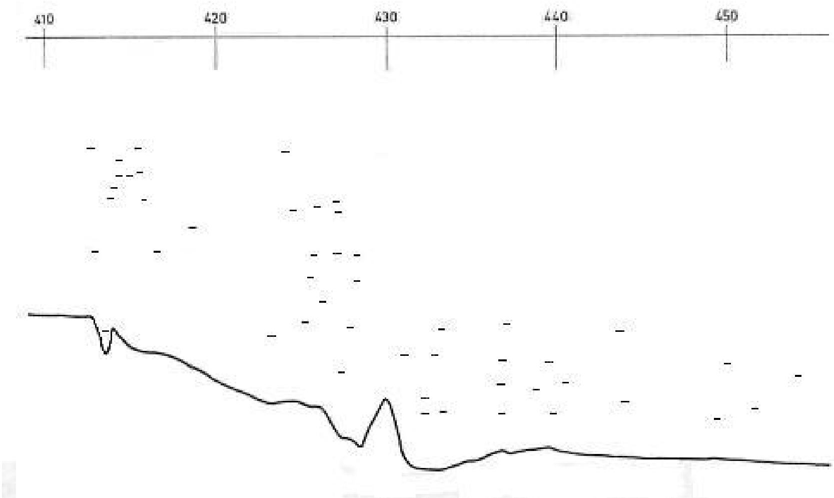

Fig. 4. Levelling marks surviving on the walls of the Eupalinus tunnel at Samos (circa 530BC) indicating repeated or redundant observations. Line indicates the reference level at the tunnel ceiling. Vertical exaggeration 40X. After Kienast (1995).

Still, a basic requirement of high-quality results was the expertise of the surveying teams, using standardized and measurement techniques tested over decades and centuries and permitting minimization of all types of errors.

A final question arising is how we can explain the reported gross errors (about 10m) in levelling which prevented from completion of major water channels such as the Suez and the Corinth (Greece) Canal in antiquity. The answer is that reported erroneous estimates of the height differences between the two exits of the future Canals were used by opposed social, economic and political groups to block such works; it was not a question of accuracy, but a question of politics (Stiros, 2007)!

5. CONCLUSION

Large scale engineering works such as tunnels, aqueducts and water channels have been successfully constructed in the last 1,000-4,000 years in various parts of world (Iran, West China, Middle East, Pharaonic Egypt, Greek and Roman World; see Grewe, 1998). Some of these works are at a scale of tens or even of one hundred kilometres, and obviously required high accuracy levelling, i.e. standard errors of a few tens to a few cm per root of kilometre of traverse.

Such accuracies are clearly up to one order of magnitude lower than those obtained by modern instruments in engineering short-length traverses, but they were obtained using primitive instruments. The type of levels used in antiquity are broadly known and summarized in Fig. 2. The accuracy of levelling, however, depended not on the instruments, but on the measurement procedures. The latter involved first, well-trained parties using techniques developed by experience and tested in numerous projects for centuries. And second it involved techniques simple but effective: for instance, measurements on stadias equipped with sliding targets, measurements based on fixed rod-to-level distances, and most probably double measurements (with stadias in upright position and then upside down, as well as with the level in one direction and then rotated 180^o) to eliminate certain systematic errors induced by instrument imperfection (collimation). These techniques, mostly ignored in the past, in combination with repeated and highly redundant observations permitted quality in measurements highly exceeding the typical specifications of primitive instruments.

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