

Surveying Roman Aqueducts

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SUMMARY

As Roman civilization developed it faced an increasing challenge to supply water to its industrial and civil centres.

Roman aqueducts are amongst the most impressive and interesting remains that have survived from the Roman period. Although aqueducts as bridges are best known, the complete structure with basins, siphons, drop shafts and distribution stations are impressive feats of engineering even by today's standards. Over 800 roman aqueducts have been documented in the Mediterranean basin, with a total channel length of at least 5.000 km

What capacity was required?

How was the challenge met?

What Surveying techniques were required?

How were the aqueducts set out?

This paper is complementary with the paper given in 2009 on "How the Romans achieved straight roads" and looks at how roman surveyors achieved the precision required to build aqueducts up to 400km long whilst restricted to the vision of the naked eye.

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1. CHALLENGES FACED

1.1 General

Water supplies are a crucial factor in the development of urban communities. Prior to the Roman Republic (510 BC to 44BC) & Empire (44 BC to 476 AD) security of supply meant that most water was sourced from wells, or rain collected into cisterns and dams. The quality of water was generally poor. The “Pax Romana” allowed long exposed aqueducts to be built and maintained.

Much of the Mediterranean has dry summers, which meant that reliable sources were often located considerable distances from the cities.

1.2 Capacity required

1.2.1 Population Demand

Water was supplied to the cities as they grew. Water was used for public fountains, public baths, public toilets and then ran away to clean the sewers.

Water supplies fed into reservoirs, providing a hydrostatic head to the distribution system in the cities. These reservoirs were fixed locations; aqueducts supplying them were designed for continuous long-term use with flat gradients from good potable supplies, generally springs.

1.2.2 Industrial Demand

Water was supplied for hydraulic mining. Hydraulic mining was used throughout the Empire and required large volumes of water at high pressure. Gradients were generally steep with aqueducts being frequently relocated to suit the short-term demands of the mining face(s). Sources were local streams dammed to provide the volumes required. Water was also used to power mills, crushers, trip hammers and pumps.

1.2.3 Canals and Leats

Canals and leats were built to facilitate marine transportation and to provide power to mills. Sources were canalized rivers and streams.

1.3 Water Supplies

1.3.1 Quantity

Rome at its peak had 11 aqueducts supplying 300m.gallons (1.4m m³) a day to its estimated 1m. people. This equates to more than 1,000 litres per person per day.

The Nimes aqueduct discussed later added some 35-38,000 m³ per day for its population of about 30,000.

The Eifel aqueduct also discussed later added some 20,000 m³/day

It is estimated that the average person in developed countries today uses 500-800 litres per day (300 m³ per year) whilst water withdrawal in large cities is estimated at 300-600 litres per person per day.

1.3.2 Quality

The Romans preferred drinking water with a high mineral content. This was generally hard water, which, in-turn has left deposits in the aqueducts giving a guide to the volume and length of time the aqueducts were used.

1.3.3 Source

As described above the bulk of the 800 aqueducts known in the Mediterranean basin were supplied from springs.

1.4 Extent of Aqueducts

1.4.1 Period

The first aqueduct was built by the Romans to supply Rome in 312 BC, the last in 226 AD a period of some 540 years. The eastern empire continued to construct aqueducts for Constantinople from AD 350 to AD 500.

1.4.2 Extent

Some 200 cities in Europe were supplied via aqueducts. The longest aqueduct was 100 km and the highest 50m. The recorded length of aqueducts exceeds 5,000 km. The capital of the eastern empire, Constantinople, was supplied water by aqueducts into vast cisterns because of the variations in flow from the catchments areas. The longest (the "Valens aqueduct") from Vize to Constantinople was 250 km long with a total length of channels supplying the system exceeding 400km.

2. SOURCES OF INFORMATION

2.1 Historical records

2.1.1 Vitruvius

Book 8 of De Architectura by Vitruvius written about 45 BC has detailed guides to aspects of designing aqueducts.

2.1.2 Frontinus

De aquaeductu by Julius Sextus Frontinus written about 45 AD describes the aqueducts of Rome and the problems associated with their maintenance.

2.2 Physical remains

Many aqueducts were not maintained after the fall of Rome but some are still in use and extensive remains are available for study.

2.3 Typical Aqueducts for Study

Two of the best-known aqueducts are: -

2.3.1 Nimes

The city of Nemausus (Nimes) was the capital of a local tribe before being conquered by the Romans in 118BC. It was developed until; in 42 BC it became a colony. The city prospered and by the first century AD had constructed a 6 km city wall, enclosing temples and an amphitheatre. The spring within the walls became insufficient and the Eure aqueduct was built.

The water supply chosen at Uzes was only 25 km directly north and most significantly only 11.8 m above the water distribution basin (castellum divisorum) in the city. The route however had to avoid the hills of the Garrigue de Nimes and had to pass in a large loop to the East extending the aqueduct to 50 km and requiring a crossing of the Gardon River (the Pont du Gard) and the draining of a lake.

To keep the length as short as possible a large number of bridges and tunnels were built. The mean gradient of the 50km aqueduct is less than 30 cm/km (0.03%); the maximum is 45 cm/km with a gradient of only 8cm/km (0.008%) in the long central section including the Pont du Gard. The Pont du Gard is nearly 50 m high, 350 m long with arches up to 25m wide. The 50,000 tons of limestone ashlar masonry has survived severe floods inundating the lowest tier. The aqueduct operated successfully from 100 to 250AD and was still in use until the 5th century AD.

2.3.2 Eifel

The city of Colonia Claudia Ara Agrippinensium (Cologne) also grew so that its source of water had become inadequate by the first century AD and an additional aqueduct was built to carry water from the springs of Eifel. The aqueduct built in AD 80 carried water the 95 km mainly in a concrete tunnel below ground. This subterranean design protected the supply from frost and gave some additional security. Including the spurs the system is some 130km and operated successfully until 260 AD.

It has been observed that the Eifel aqueduct was constructed in separate 15,000 roman foot sections (approx 4400m.) This would have required the surveyors to align and match the aqueduct at each joining points. By constructing the aqueduct in sections it has been calculated that 2,500 workers would have taken 16 months to carry out the construction once the survey and design were complete. A period of 1 year has been suggested for the survey and design.

3. SURVEYING

3.1 Problems faced

3.1.1 Terrain

To maintain an even and flat gradient the aqueducts generally followed the sides of valleys being constructed on side slopes. The contour line was maintained around any side valleys until a bridge crossing could be made. A detailed ground survey covering possible routes up to 100 km long would have to be made.

3.1.2 Levels

Monumental structures such as the “Pont du Gard” could only be constructed when the finished level was clearly established. The architecture of the “Pont du Gard” has equal width arches in the first and second tier and three arches aligned with the lower arches in the top tier. Little room is left for maneuver in height if the architectural appearance was to be maintained. The very shallow grades would leave little scope for error. Whilst some other aqueducts indicate that intermediate stilling basins were provided which would allow for regulation and provide some level tolerance the Nimes aqueduct would have required benchmarks and level control to maintain a fall of 4mm per 25m for kilometers..

3.1.3 Gradients

Gradients had to be adequate to ensure flow without creating any scour. Generally slopes of 1/600 to 1/300 were used. The flattest being 1/4,000. Vitruvius recommended a slope of not less than 1 in 200. To maintain these flat grades and to build the aqueduct in sections every structure supporting the channel would have to be brought up to a very accurate level. Heights of arches and regulating courses would have to be accurately predicted and installed.

3.1.4 Alignment

Once the horizontal alignment was established and pegged out small deviations in alignment would not be critical. Alignment of tunnels, shafts, and arcades would have to be precise. Vertical plumb of structures and shafts would have to be maintained, particularly because the aqueducts were fairly narrow structures.

3.2 Instruments available

Alignment

3.2.1 Groma

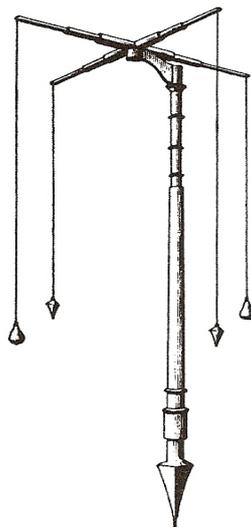
This was an instrument used as the basic tool for horizontal alignment

An archaeologist called Della Corte uncovered the metal parts of a Groma in Pompeii in 1912 and this is his interpretation of its appearance.

The Groma is recorded as having consisted of a vertical iron staff or “ferramentum” about 1.5m long pointed at the lower end.

The remainder has been proposed as a cross arm 25 cm long pivoted on a brass bearing which supported in turn, the main aligning elements – the revolving “stelleta” with arms about 1m across. A central plumb-bob known as an “umbilicus soli” probably hung from the centre over the control point. Records show that the instrument was difficult to use in windy conditions and recommendations include use of tubes or immersing the tips of the plumb-bobs in water to reduce movement.

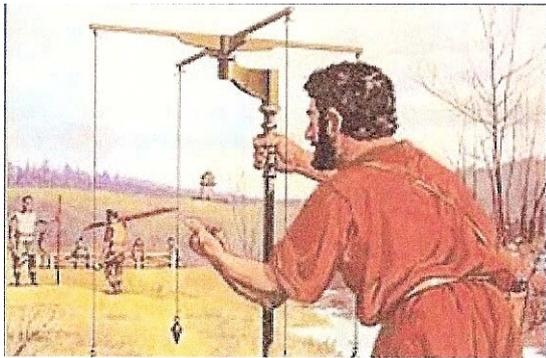
Unfortunately no record exists of the actual final assembly.



3.2.2 Application of the Groma

Roads in camps and towns were established by setting up over a point and using the Groma to establish a straight line or right angle. Straight lines on aqueducts and right angles in structures could be maintained from reference points once the centre line had been set out.

The Romans understood and used algebra and trigonometry based on Euclidian geometry. They were therefore able to re- calibrate the Groma using 3/4/5 triangles

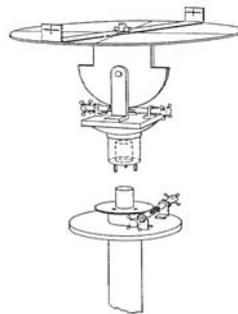


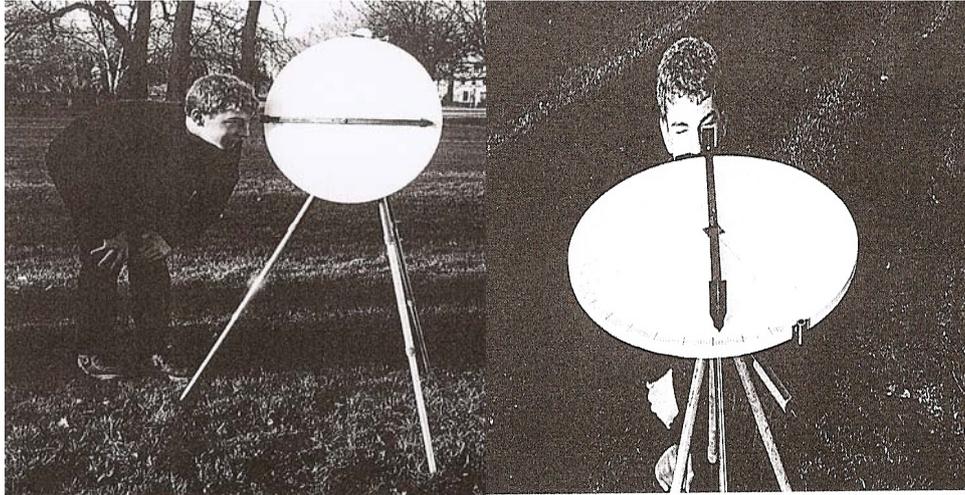
Alignment, Level and distance

3.2.3 Dioptra

The dioptra was a mechanical construction, without an optical eyepiece. It was invented by the Greeks and is included in reports by Romans although no records of its use survive. There was a discussion on its use at previous FIG history sessions.

Hero of Alexandria has best described the Dioptra. It was used for both horizontal and vertical measurement. A properly built Dioptra would have involved significant engineering with threaded vertical and horizontal adjustment and a water level. Calibration and skill were required in its use.





The dioptra had an alidade or sight, which could be arranged to read vertically or horizontally. The Greeks describe exercises for measuring distant heights, lengths and widths and these exercises are repeated in the guild surveying (Corpus) handbook..

Combined with a staff, which had a sliding target, the instrument could be used as a level. Used flat it had the properties of a plan table.

It may well be that a chief surveyor for a legion could have retained and understood such an instrument.

Even woodworking tools were passed from artisan to artisan from generation to generation.

A dioptra is likely to have been a high status possession

A Dioptra could have assisted in producing the initial survey, the initial route alignment and the setting up of any primary level controls.

Level

3.2.4 Chorobates

Another instrument mentioned by Vitruvius is the “core ab beh tez” or land walker.

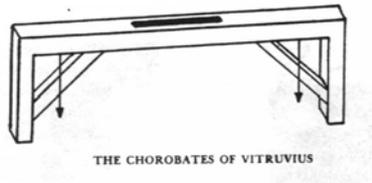
It is described as a rod 6m long with duplicate legs attached perpendicularly at each end.

Diagonals connect the rod and legs.

Both diagonal members have vertical lines scribed in them over which plumb bobs hang. When the instrument is in position and the plumb lines strike both the scribe lines the instrument is level.

If the wind interferes the water level at the top of the horizontal is used. Vitruvius instructs the groove should be 1.5m long 1 digit wide and 1.5 digits deep.

Using two or more chorobates set up horizontally, the vertical height could be established by sighting along the uphill instrument. The decempeda [or ten foot surveyors rod] could be used as the staff or target.



The corebbehtez was a rugged instrument and it is therefore most likely that army surveyors used it to maintain level control of aqueduct gradients, cross drains and culverts and support structures.

Sighting along a 6m straight edge would not have been a very accurate way of measuring fine level tolerances.

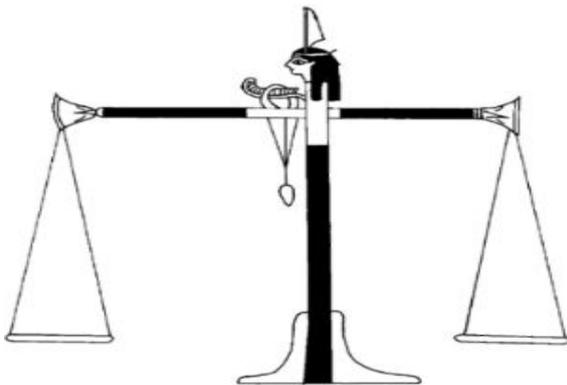
3.2.5 Application of other instruments

Quoting Vitruvius, who you will remember was writing some 100 years before the construction of many of the aqueducts.

'levelling is done with dioptras or *librae aquariae* or the chorobates'

The Corpus books 350 years later still refer to a libra aquaria.

A very speculative sketch of a librae aquarie by J Lewis is shown.



The suggested arrangement is that a tube 2m long is set up as a balance. Use of a long tube increases the distance the unaided human eye can focus over.

When the tube is in balance the surveyor is looking along a horizontal and can check levels against a targeted staff. The small weight could have been used for calibrating the balance by fore and back sights.

This instrument, if it has been correctly described, would, most probably, have been used for the very close level control required for the initial survey and establishment of benchmarks. Aqueducts were built by the military and the best surveying techniques would have been known and available to the Military. Sighting over the relatively short distances required without optics would have eliminated any corrections for curvature of the earth.

Distance

3.2.6 Decempeda

The **decempeda** was a calibrated measuring rod made of hard wood with metal ends. It was probably about 3m or 10 roman feet long and could be joined with another to allow end over

end measurement. Decempeda were used to measure horizontal distances. They were used on slopes with plumb-bobs. They appear to have been the roman surveyors preferred distance-measuring device and would have been robust but slow.

3.2.7 Other Instruments

As identified above the range of Roman instruments was restricted to the vision of the naked eye, there were no optical instruments.

There is no report of the use of the compass.

Large-scale maps were produced although these were distorted in the E-W direction because of the problem of locating relative longitude

The Greeks recorded using specialist human pacers to measure distances. These measurements were probably accurate enough for mapping purposes.

The Greeks used **ropes** for measuring distance and these may have been used by the Romans although there is no record. Ropes were pre-stretched to reduce variation and may have been used with tensioning devices and plumb-bobs on hills. The corpus records, only show, cords being used for alignment purposes. They were stretched between stakes and hung with weights to eliminate further stretch. Tests carried out with Jute ropes 40m long with knots/beads and braids as markers at 30cm intervals have shown variations in measurement of about 2%.

Dioptra were capable of being used to measure distance and could have been used for traversing.

References are made to certain wagons having special circumferential wheels and cogs, which dropped a small stone or “calculus” in a box every roman mile as a type of **Odometer**. This would have been suitable as a locating device on tracks or roads.

Large-scale maps were produced. A few bronze copies have survived. These maps were distorted in the E-W direction because of the problem of locating relative longitude. Latitude could be calculated by observing the inclination of the sun. Historians do not acknowledge use of the compass, although the surveyor Veru’s workshop in Pompeii was reported as having a portable sundial.

Sundials could provide the local solar time at the particular longitude. Vitruvius refers to sundials in book IX of his de Architecture. A portable sundial could have been used like an astrolabe.

The Romans certainly used gnomon – the shadow making part of a sundial, which could establish the latitude.

Roman astronomers had astrolabes, which could have enabled them to measure latitude and longitude from the stars

Although the range of Roman instruments was restricted to the vision of the naked eye, Roman surveyors were trained in astronomy and cosmology and could therefore have derived the orientation between established points.. Historians however separate astrologers and consider that terrestrial surveyors used similar triangles to calculate orientation.

3.2.8 A Surveyors Workshop

The surveyor Veru had a workshop in Pompeii, which was uncovered and still held a portable sundial, a measuring rod, a folding ruler and bronze compasses.

3.2.9 Artisans

A tool called a libella has been shown on a number of tombstones as a carpenter/masons tool, which was a precursor of the modern spirit level. It was probably used for laying stones and day-to-day construction. Some pictures show it as an a-frame with a plumb bob suspended from its top used as a level. Others a straight edge with a plumb bob suspended from a small frame giving a horizontal alignment to the base of the straightedge. Carpenters had rulers, compasses; plumb bobs, squares and levels. The concept of half a bubble level used by 20th century drain layers could have equated to a constant offset on a libella.

4. SURVEYORS

4.1 Military

Most critical infrastructure was constructed or supervised by the military.

Military Surveyors although part of the Army had a special status as “Immunes”. Immunes were experts in their various fields and exempt from the more tedious or dangerous soldiers tasks. Immunes included surveyors, doctors, engineers, and priests. Their intelligence allowed them to rise quickly in the ranks and they were ranked as Praetorian Guard in the hierarchy of the Army. Military Surveyors were the most skilled surveyors, involved in all the major structures of the Roman world.

4.2 Civilian

Surveying was a skilled profession, which developed over hundreds of years. The civilian surveyors or Agrimensors had their own professional organization with dedicated training programmes including astrology and geometry.

5. CONSTRUCTION

5.1 Typical Sequence

5.1.1 Preliminary Survey

Water engineers would locate suitable sources before the surveyors would carry out a survey between the source and demand points. Most likely this survey would be with the quicker instruments the Dioptra and possibly Libae, would not be very accurate but cover all possible routes.

Having surveyed the terrain, maps or models would be produced and the best alignment established. This would have to take account of the hydraulic requirements which would have required detailed analysis of gradients, shutters and stilling basins, steps, drop shafts and waterfalls.

Hydraulic structures such as seepage galleries, collection basins, dams/wiers and the supply channel would all have had to take account of the generally uncontrolled nature of the flows and variations on the time of year. Limited control was possible at stilling basins, which could regulate flows with undershot or overshot gates, and stop gates could be used for temporary repairs. In the final approach to a city the aqueduct was raised on arches to provide a head for the cistern, which supplied the city.

5.1.2 Main Survey

Having established the hydraulic profile the chosen route would be cleared, surveyed and line and level controls carefully established. This would most probably have been by dioptra used by the chief surveyor with level benchmarks established by Libra aquaria.

5.1.3 Construction Methodology

Conduits were generally covered trenches with some 80% of the length below ground built on a cut & cover basis. Some tunnels had stone or clay pipes within. Channels were typically 1m wide x 2m deep. Materials used included: - stone blocks, concrete, waterproof plaster, lead pipes used for siphons and distribution system and terracotta surrounded in concrete

Substructures for the channel were designed as walls up to 2m high, and arcades when the height was greater than 2m. Bridges were built across rivers or gorges with tunnels no more than 800m long. Manholes for inspection and maintenance were allowed at one or two actus centers (35m or 71m)

Low-pressure pipes provided the distribution within the city from the Final storage reservoir.

5.1.4 Construction Surveying

In a very similar manner to today the surveyors would establish setting out reference points, establish lines & levels for construction and monitor these lines and levels during the works. Chorobates were used for day to day leveling and one can imagine the crews of assistants required to control the 6m long instruments. Groma, plumb – bobs and libella would all have been used to monitor the works.

There was less distinction between engineers and surveyors and the surveyor/engineer would have been involved in ensuring that the aqueduct was built as planned. The success of these aqueducts is apparent from the robust structures which still exist and which in some cases are still in use.

6. CONCLUSION

Aqueducts were a major investment by the Romans requiring approval and support from the emperor.

Aqueducts were technically challenging, although the Romans were not great innovators they were supreme technicians in the use of existing technology, which was demonstrated over hundreds of years.

The Aqueducts tested Surveyors skills, work could not commence until the surveys and design had been completed. Rapid progress on adjacent sections would have required discipline and oversight from senior military figures.

Aqueducts needed a secure environment to allow maintenance and continuity of service. The fall of the Roman Empire led to cutting off of water supplies and was a major contributor to the collapse of the cities and the city state. Water supplies to today's cities where most people live must be considered as equally vulnerable.

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BIOGRAPHICAL NOTES

Richard Hucker MBE BSc. (Hons) FICE, F.Inst.CES, F.ZwE. ICIOB is a Chartered Civil Engineer who has been involved in the Development & Construction of Civil Engineering Projects, for over 40 years. Richard graduated from City University and worked on a variety of different projects in the UK before becoming an Agent for a major UK contractor. Richard then moved to the Middle East on a heavy civil project progressing through UK, Europe, Oman, Zimbabwe, Botswana and Malaysia as Country Manager before setting up a Project Management company in Egypt. Richard has been involved in the development of skills through his involvement in local institutions, setting standards for membership and sitting on panels reviewing national standards. Richard presented a paper in 2007 at the Hong Kong working week on Planning & Development in Northern Iraq having been awarded an MBE in 2006 for his services to British business in Iraq. Richard also gave papers in 2008 in Stockholm on Recruitment & Retention of Surveyors and on the Alignment of Roman Roads at Eilat in 2009. Richard is a member of the Management Panel for the Institution of Civil Engineers is a Fellow of the Chartered Institution of Civil Engineering Surveyors and Chairman of FIG working Group "10.3 - Project and Programme Management." Richard currently works for Costain as a Senior Manager leading Proposal and Estimating teams for Major Projects.

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