Eupalinos Tunnel - First Tunnel to be Excavated Simultaneously from Both Ends in the 6th Century B.C.

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ABSTRACT
The Eupalinos Tunnel is considered one of the most significant engineering achievements of antiquity as it involved simultaneous excavations from both ends of the tunnel. The tunnel was constructed between 550 and 540 B.C. on the Greek island of Samos and had an overall length of 1036 m. The tunnel measured approximately 1.8 m by 1.8 m with a 4 m deep, parallel trench system that contained a clay water pipe as part of the aqueduct system. This paper summarizes the instrumentation, challenges and techniques that were utilized in order to achieve such an engineering feat. Also included is the historical background, an assessment of the main geological features associated with the tunnel construction, the various tunnel design types and the relevant tunnel construction techniques that were utilized in order for the tunnels to meet within the intended tunnel alignment (within 1.8% accuracy).

RÉSUMÉ
Le tunnel d'Eupalinos est considéré comme l'une des réalisations techniques les plus importantes de l'Antiquité, car il impliquait des fouilles simultanées aux deux extrémités du tunnel. Le tunnel a été construit entre 550 et 540 av. sur l'île grecque de Samos et avait une longueur totale de 1036 m. Le tunnel mesurait environ 1,8 m sur 1,8 m avec un système de tranchées parallèles de 4 m de profondeur qui contenait une conduite d'eau en argile faisant partie du système d'aqueduc. Cet article résume l'instrumentation, les défis et les techniques qui ont été utilisés pour réaliser un tel exploit d'ingénierie. Sont également inclus le contexte historique, une évaluation des principales caractéristiques géologiques associées à la construction du tunnel, les différents types de conception de tunnel et les techniques de construction de tunnel pertinentes qui ont été utilisées pour que les tunnels se rejoignent dans l'alignement prévu du tunnel (à moins de 1,8 % précision).

1 HISTORICAL BACKGROUND

The Eupalinos Tunnel (or Aqueduct as it is referred to in selected literature) is located in present-day Pythagorion on the Island of Samos, Greece (Figure 1). It is the same Island as the birthplace of Pythagoras (who lived from 570 BC to 496 BC). Herodotus (484 BC – 425 BC) was an ancient Greek historian who was known for having written the book *The Histories*. *The Histories* contained a detailed record of his "*inquiry*" or "*historia*" in terms of the origins of the Greco-Persian Wars. He is widely considered to have been the first writer to have utilized a method of systematic investigation when dealing with historical people and events (Zambas,C.,2017). Herodotus describes the Eupalinian aqueduct in the *Histories,* 3.60. The quote within the Histories reads:

> *"I have dwelt longer upon the history of the Samians than I should otherwise have done, because they are responsible for … the greatest building and engineering feats in the Greek world: … a tunnel nearly a mile long, eight feet wide and eight feet high. This was the work of a Megarian named Eupalinos, son of Naustrophus"*

Without this insight, the tunnel may not have been discovered in the present day. This was the first time in history that anyone had ventured to undertake a project of such a magnitude without an analogous reference.

Figure 1. Location of Eupalinos Tunnel in present-day Samos Island, Greece. Meban, A. 2022.

Samos flourished in the sixth century B.C. during the reign of the tyrant Polycrates (570–522 B.C.), whose court attracted poets, artists, musicians, philosophers, and mathematicians from all over the Hellenic or Greek world. His capital city, also named Samos (present-day Pythagorion), was situated on the slopes of a mountain, Mount Castro (Figure 2), dominating the natural harbor facing the narrow strait towards Asia Minor.

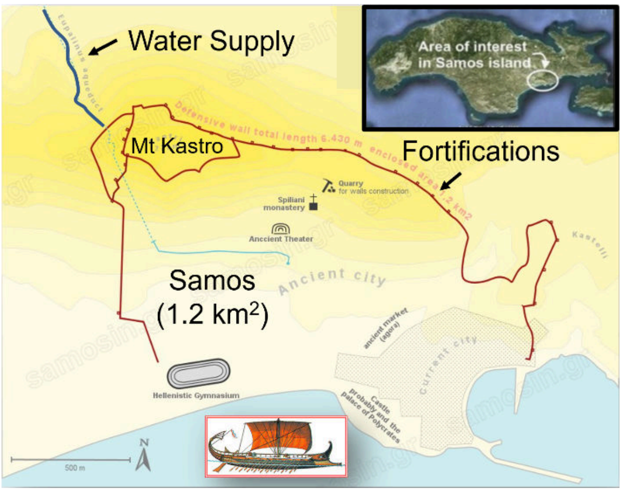


Figure 2. The Kingdom of Polycrates on the Island of Samos. Modified after: Greek Tunnelling Society, 2022.

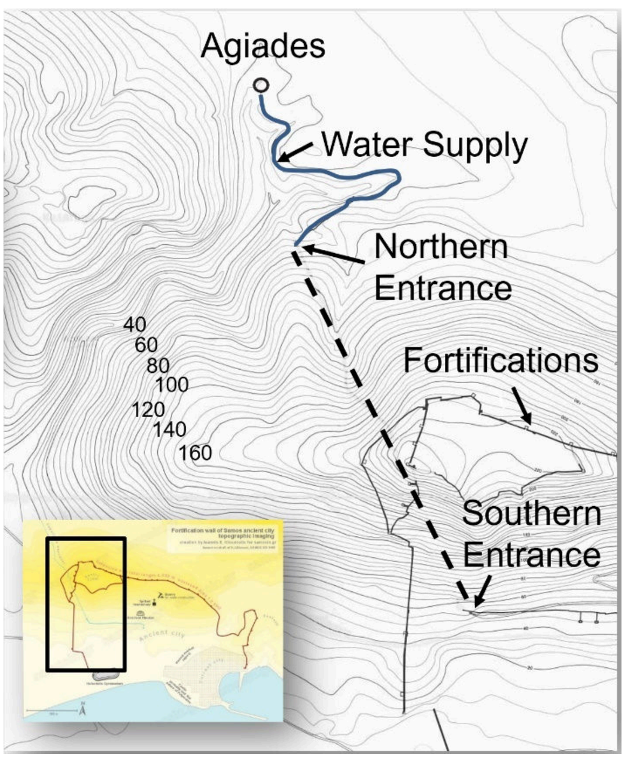


Figure 3. Topography and Rough Alignment (dashed line) of Eupalinos Tunnel. Modified after Apostol, T., 2004.

Polycrates had to fortify and protect his kingdom from pirates and others; Thus the requirement to wall and protect the city but also to safeguard the water that was being brought into his city. In Figure 3 we see the topography of the area. There is a natural river to the north of the Samos fortifications, the Agiades. Polycrates needed to provide water to the flourishing population of his city. As such, he decided to bring the water from the Agiades river to his city but needed to protect the source water. The gross alignment of the tunnel can be seen to stem from the Northern entrance of the Tunnel to the Southern entrance as shown in Figure 3 with the dashed line. The tunnel is approximately 1 km long and passes under Mount Kastro.

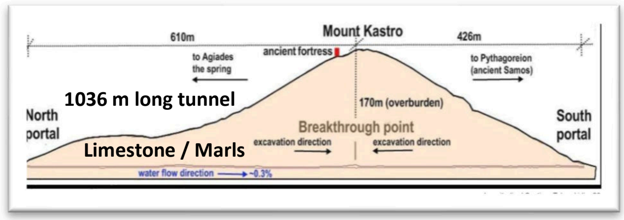


Figure 4. Idealized cross-sectional Tunnel Alignment of Eupalinos Tunnel. Modified after Greek Tunnelling Society, 2022.

In Figure 4 one can see the tunnel alignment in cross section. The tunnel is 1036 m long, has and overburden of 170 m and was excavated from the North and South side simultaneously. The breakthrough point (meeting of the two sides of the tunnel) was under Mount Kastro.

2 TUNNEL ALIGNMENT

For centuries, scholars have asked how the construction and alignment of the tunnel was achieved. No one knows exactly how Eupalinos accomplished this feat. However, most scholars seem to agree that the best probable explanation is the use of Hero's method. Hero, who lived in Roman Alexandria in the first century A.D. (i.e. 5 centuries later!), founded the first organized school of engineering and produced a technical encyclopedia describing early inventions together with mathematical solutions. Thus, the Eupalinos Tunnel is considered as the first underground project excavated with a geometry-based approach.

2.1 Alignment Techniques

Using Hero's method, one needs to start at a convenient point near the Northern entrance of the tunnel, and traverse the western face of the mountain along a piecewise rectangular path (indicated in red in Figure 5) at a constant elevation above sea level, until reaching another convenient point near the Southern entrance (Kienast, H., 1995). Therefore, using Hero's method, if one was to measure the total distance moved west, then subtract it from the total distance moved east one determines one leg of a right triangle, shown as a blue dashed line on the map in Figure 5. The triangle's hypotenuse is along the proposed alignment of the tunnel.

As such, one can then add the lengths of the north-south segments to calculate the length of the other leg, also shown as a dashed line. Once the lengths of the two legs are known, even though they are buried beneath the mountain, one can lay out smaller horizontal right triangles on the terrain to the north and to the south (shown in orange) having the same shape as the large triangle, with all three hypotenuses on the same line. Therefore, workers can always look back to markers along this line to make sure they are digging in the right direction.

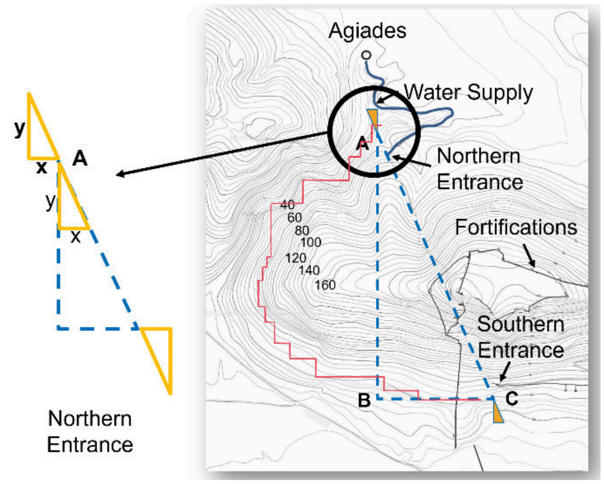


Figure 5. The use of Hero's method in order to determine the alignment of the tunnel. Modified after Kienast, H., 1995.

Taking a closer look at the geometry associated with the alignment (Figure 5), one can utilize the alignment along the tunnel, within the mountain and determine how to site it from outside the tunnel. Maintaining the tunnel alignment and respecting its geometry one can determine the alignment outside of the tunnel in this fashion. One can respect the 'x' and 'y' lengths that correspond with the ABC triangle of the global configuration. The hypotenuse of yellow triangles in Figure 5 are aligned with the tunnel orientation. In this fashion, one can maintain their alignment and postulate the alignment towards the outside of the tunnel.

2.2 Instrumentation and Measurements

In the 6th Century B.C. there is no record of a magnetic compass, specific surveying instruments or topographic maps. Perhaps, then, the instruments that were used (among others) are the ones that are seen in Figure 6.

The first tool seen is a crude carpenters tool made of batons and pins and was used in order to measure right angles as per those required to map out the red alignment within Figure 5. Hero in the 1st century also described the use of a Dioptra to measure angles (instrument in the middle of Figure 6). It was a surveying instrument which was suitable for the precise measurement of horizontal, vertical and angular distances between two celestial or terrestrial points. It consisted of a stand which had a horizontal toothed base that could be rotated with the help of an endless screw. A precise system of aiming (theodolite) could be placed on the base. This disc was placed at the edge of the semicircular disc and had a crisscross turning aiming device. The operator of the instrument could aim any point in space and mark their angle position.

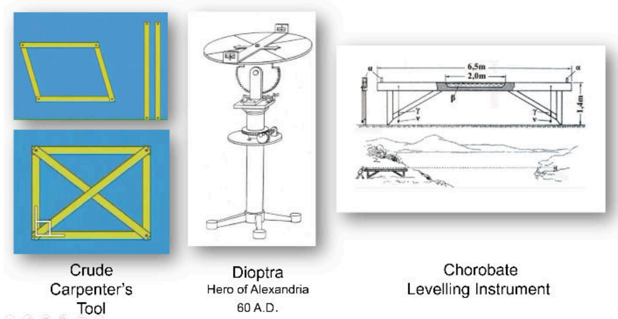


Figure 6. Potential instrumentation that was utilized in order to help determine the alignment of the tunnel during construction.

In terms of horizontal control of the tunnel excavation, a Chorobate could have been used. The Chorobate is an instrument that is 6.5 m long with a 2.0 m portion that was filled with water. The water was used to ensure that the instrument was level. As such, one could look through the apertures to make sure that the apertures were aligned while also focusing on the point of interest. i.e. the alignment of the tunnel floor. Alternatively, a Chorobate could be placed on the base of the Diaptra. Such instruments can be seen in modern-day, one can visit (in person or virtually) the Kotsanas Museum that is located in Olympia (the birthplace of the Olympic Games). There is also a Kotsanas museum location in Kolonaki, Athens, Greece. The Chorobate and Diaptra instruments are quite similar to modern-day instrumentation that are used in tunnel construction such as the automatic level and theodolite / total station respectively.

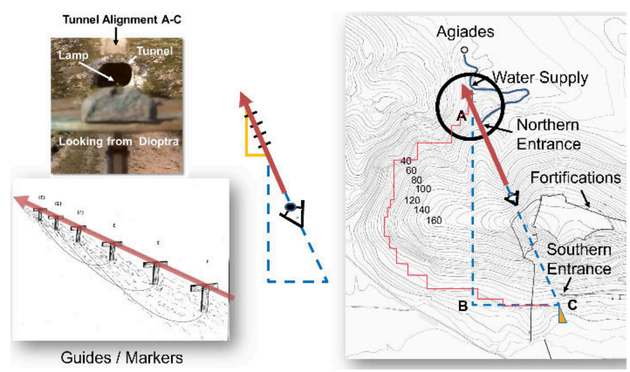


Figure 7. The use of the Dioprta and Markers in order to determine (and check) the alignment of the tunnel outside the periphery of the tunnel excavation.

Having determined the alignment outside of the Northern Entrance, one can then establish guides or markers along this alignment in order to monitor the construction works (Figure 7). We still use Boning Rods or Batter-boards for survey construction stake-outs to this day and they look very similar to those markers used in ancient times. These guides act as a point of reference in both directions. As the tunnel is being excavated, one can check the alignment from the tunnel as a "back bearing". In addition, while the tunnel is being constructed, the guides could be used to check the alignment with the surface alignment (A-C) that would have been also marked out from the Northern to the Southern entrance in a straight line (i.e. the hypotenuse of the triangle ABC).Within the tunnel excavation itself, lamps were also placed on the floor of the excavation along the center-line to help guide the construction works (Figure 8).

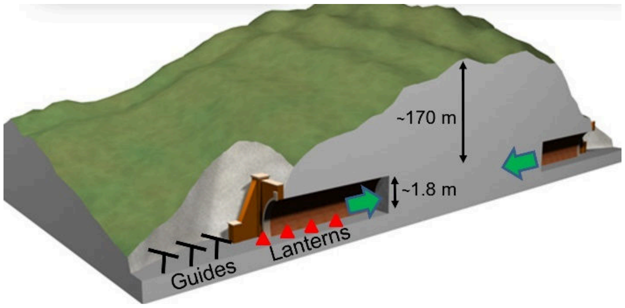


Figure 8. Idealized drawing of a tunnel cross-section depicting the use of guides outside the tunnel alignment and the use of lanterns within the excavated portion.

3 TUNNEL DESIGN AND CONSTRUCTION

The tunnel design consists of a 1.8 m by 1.8 m excavation for the passage of humans as well as a 4 m deep trough that housed the terracotta pipe (initially). The pipe sections were 72 cm long and 26 cm diameter. The pipe increases in depth over the course of the tunnel, from 4 m deep at the north end to 8.5 m at the southern end. Vertical shafts link this channel to the main tunnel roughly every 10 m (Figure 9). These were dug from the tunnel and then linked together to create the channel.

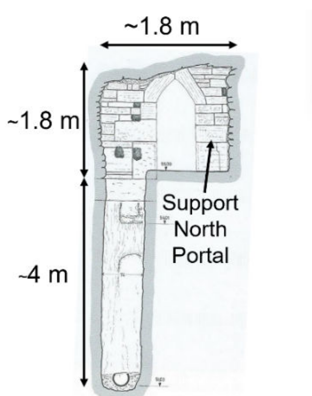


Figure 9. Cross-section of tunnel design (North Portal) consisting of 1.8 m x 1.8 m passage with 4 m deep utility shaft that housed a water pipe.

There were also a number of original, ancient symbols and letters painted on the tunnel walls at various locations in order to denote the tunnel chainage as well as the location of the vertical shafts (Figure 10). On the west wall, there are letters in alphabetical order at a regular intervals of 20.59 m, which indicate that this was the basic unit of measurement used by Eupalinos (this constitutes one fiftieth of the planned course through the mountain). The size of the opening allowed two workers to excavate at the face side by side. The process must have been exhausting and tedious given the underground conditions.

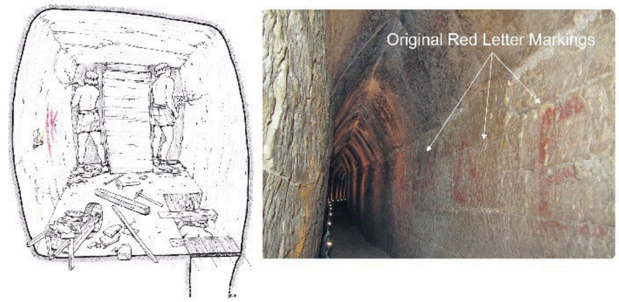


Figure 10. Left: Excavation by hand. Two workers working side by each. Right: Ancient symbols and letters painted on the tunnel walls to denote the tunnel chainage as well as the location of the vertical shafts.

If one is to look within the tunnel at various locations, one sees a heavily supported Northern Section with a typical arched profile (and at other locations Roman Profiles) which is characterized by a roof-shaped ceiling formed by stone slabs (Figure 11). On the southern portion of the tunnel, there is very little support (aside from the portal entrance) that has been introduced.

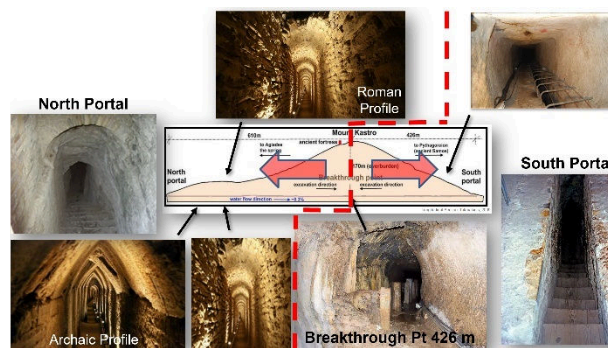


Figure 11. Various tunnel profiles, support and design details related to the overall tunnel profile. Vlachopoulos, 2018.

If one was to look at the present-day alignment of the tunnel in plan view (Figure 12), it is not a straight line from the Northern to Southern Entrance.

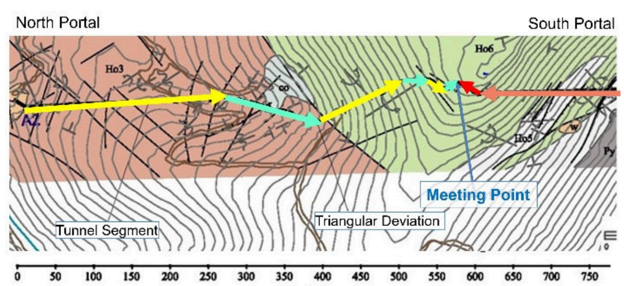


Figure 12. Plan view of tunnel alignment depicting the various courses of the tunnel.

After 273 m from the northern end, an area full of water, weak rock and mud forced Eupalinos to modify his plan and direct the tunnel to the west. Eupalinos planned his re-direction using an isosceles triangle with angles 22.5, 45, and 22.5 degrees. Measuring errors occurred and Eupalinos was slightly off course and/or significantly fractured and less stable rock was encountered that caused the re-adjustment. The North tunnel was once again redirected to the East at approximately the 400 m mark. There are 3 more corrections that occur are due to alignment re-adjustment as well as the geology encountered.

On the other end, The excavation of the South tunnel was completely straight for 390 m after which it diverted East and met up with the Northern Tunnel.

Again, Eupalinos used a unit of 20.59 m for distance measurements and a unit of 7.5 degrees (1/12 of a right angle) for setting out directions.

Therefore, the geology of the area certainly dictated or influenced not only the alignment of the tunnel but also the construction techniques and support measures introduced. This will be explored in the following section. In this way, an observational approach (that we use today in tunneling) was utilized.

The tunnel took 10 years to construct and was in use for approximately 1100 years.

4 TUNNEL SITE-SPECIFIC GEOLOGY

The primary resources that were referenced for this paper (in addition to the on-site investigation by the author) came from Lyberis, E. et al., 2014, Dounias, G. et al., 2014, Georgios, A. et al., 2018. These investigations / assessments were the most relevant prior to the rehabilitation work associated with the tunnel. These assessments and rehabilitation works needed to be conducted prior to opening the tunnel to the public. As well, such geological assessments are best left to well-education and experienced Geologists.

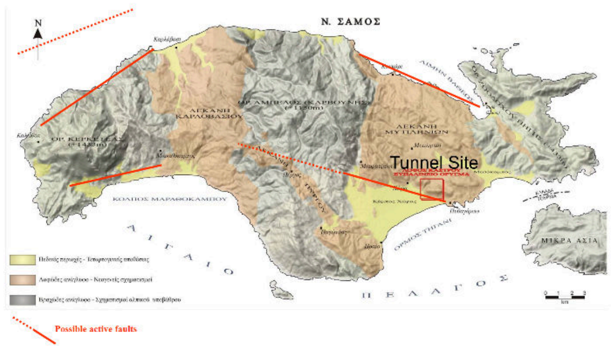
In terms of Geological setting (Figure 13), Samos Island is located within the within Mytilinii molassic basin, which was formed during Miocene and Pliocene (Epoch) age.

The aqueduct was bored mainly through: (a) medium-bedded to massive limestones, (b) alternations between marls, shales and platy limestones, and (c) tectonic breccia. These geological formations are members of Hora and Pythagorion (volcano-) sedimentary sequences of Mytilinii molassic basin.

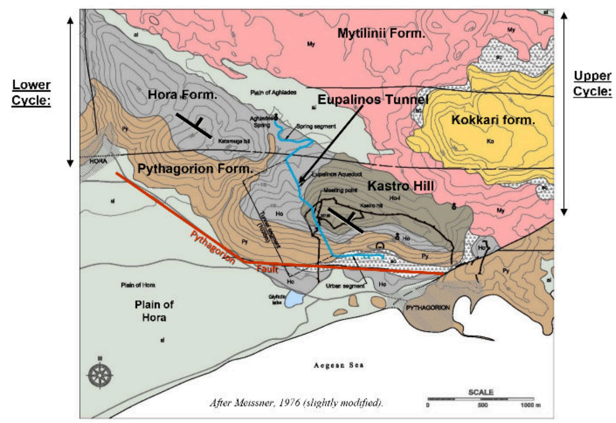
Pythagorion fault (outlined in red), which is considered active, controls the boundary with Hora plain. The NW-SE direction of this hill range is controlled by the dominant trend of strata of Pythagorion and Hora formations.

As seen in Figure 13c, the majority of the formations that are excavated through are primarily sequences of Pythagorion and Hora formations.

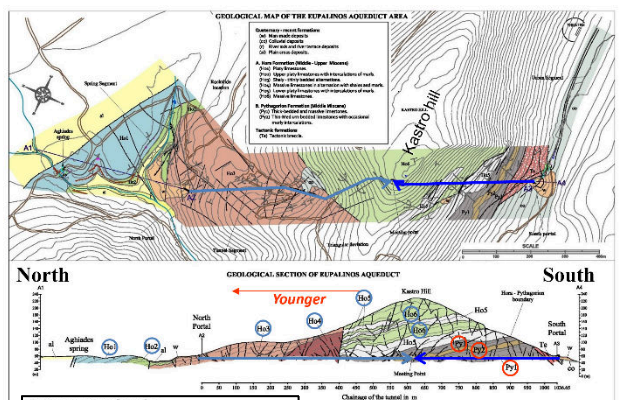
On the South Foothill the tunnel passes through Pythagorion Unit Py1 (thick bedded and massive limestone) and Pythagorian Unit Py2 (thin medium bedded limestone with occasional marly intercalations). On the Northern foothill, the tunnel passes through the younger Hora Units Ho1 to Ho6 successively, ranging from Platy Limestone to Limestone with intercalations with Marl to Shaly-thinly bedded alternations and massive limestones. Pythagorion Units Py1 and Py2 appear at the south foothill, while the younger Hora Units Ho1 to Ho6 successively appear towards the North.



(a)



(b)



(c)

Quaternary - recent formations
(w) Man-made deposits
(co) Colluvial deposits
(r) River axis and river terrace deposits
(al) Plain areas deposits.
A. Hora Formation (Middle - Upper Miocene)
(Ho1) Platy limestones.
(Ho2) Upper platy limestones with intercalations of marls.
(Ho3) Shaly - thinly bedded alternations.
(Ho4) Massive limestones in alternation with shales and marls.
(Ho5) Lower platy limestones with intercalations of marls.
(Ho6) Massive limestones.
B. Pythagorion Formation (Middle Miocene)
(Py1) Thick-bedded and massive limestones.
(Py2) Thin-Medium-bedded limestones with occasional marly intercalations.
Tectonic formations
(Te) Tectonic breccia.
Legend

Note: Larger Geological Cross-section with details also included in Figure 14.

Figure 13. (a) Geological Map of Samos., (b) Geomorphological Map of Tunnelling site (as cited in Lyberis, E. et al., 2014), and (c) Geological Map and Cross-Section. Modified After Lyberis, E. et al., 2014.

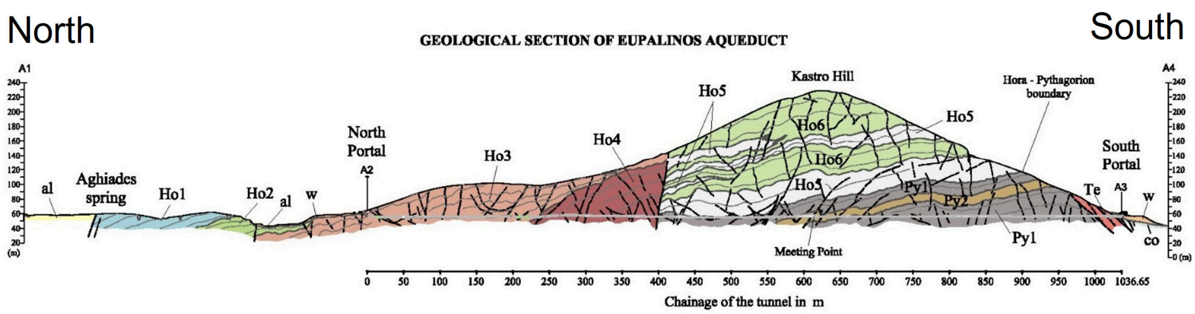
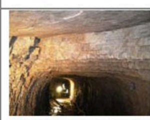
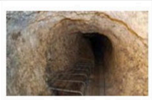
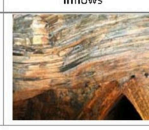
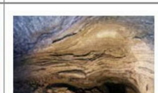
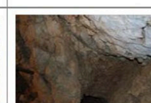


Figure #14. Geological Cross-section of Eupalinos Tunnel. Modified after Dounias G, 2014.

Table 1. Engineering Geological Characteristics of Rock Types and Formations, Modified after, Dounias G., 2014 and Lyberis, E. et al., 2014.

Lithofacies / Char/stics	a. Massive & thick-bedded limestone	b. Medium-bedded limestone	c. Brecciated limestone	d. Platy limestone	e. Platy limestone and marls	f. Shales and marls	(Te) Tectonic breccia
Stratigr. Unit	Pythagorion & Hora	Pythagorion	Pythagorion & Hora	Hora & Pythagorion	Hora (mainly)	Hora	Pythagorion & Hora
Structure	Rock	Rock	Rock	Rock – locally Soft rock	Rock – Soft rock – locally Soil	Soft rock – locally Soil	Rock – Soft rock – locally Soil
Strength	Strong to Medium	Strong to Medium	Medium	Medium to Weak	Medium to Very weak	Very weak	Strong to Very weak
RQD range	70-100%	70-100%	25-70%	10-50%	0-30%	0-20%	0-40%
GSI range	60-70	50-60	35-45	30-40	25-35	15-25	20-35
Tectonism	Small	Small – Medium	Medium – Intense	Medium – Intense	Intense	Intense	Intense
Inhomogeneity	Small	Small	Small – medium	Medium	Medium – High	High	Small – High
Anisotropy	Small	Small – Medium	Small – medium	High	Very high	Very high	Small
Susceptibility to weathering	Small	Small	Small – Medium	Medium	High	Very high	Small- High
Permeability	Medium – High	Medium – High	Medium – High	High	Small – Very small	Very small	Medium- High
Failure Hazard	Small	Small	Small – Medium	Small – High	Very high	Very high	Very high
Common Failures	Local gravel and small block falls along highly fractured zones	Local gravel, small block & rarely platy fragment falls along highly fractu-red zones	Gravel and block falls along highly fractured zones	Platy fragment falls and detachments of platy rockmass	Platy fragment falls and detachments of platy rockmass	Platy fragment falls, detachments and rocksli-des of platy rockmass	Gravel, block of gravels and block falls
Excavation difficulty in antiquity	Very difficult excavation – Stable cross section	Very difficult excavation – Stable cross section	Difficult excavation – Generally stable cross section	Medium to difficult exca-vation – Moderately stable cross section – Local water inflows	Medium to Easy excava-tion – Presence of insta-bilities – Local water inflows	Easy excavation – Pre-sence of instabilities – Local water inflows	Easy to difficult excavati-on – Presence of instabili-ties – Local water inflows
Photos							

The main geological and ensuing geological engineering characteristics are shown in Figure 14 and Table 1 respectively. In total, six (6) alternating lithofacies plus one tectonic facies compose the main geological units as seen in Table 1. Each lithofacies has similar lithology and similar engineering geological characteristics and behaviour in the tunnel. The lithofacies in blue are medium-bedded to massive limestones. The lithofacies in brown and green are marls, shales and thin-bedded limestones.

Each unit of the cross-section has its unique geological characteristics and ensuing strength, fractures / discontinuities, and predicted behaviour due to excavation. In order to highlight selected issues and tunnelling considerations, one section of the overall alignment will be showcased here. Other geological engineering character-istics and considerations of remaining sub-sections of the overall tunnel alignment are contained in the references provided in this paper herein. Angistalis, G. 2014 & 2018.

One of the most challenging sections is the Southern Portal Section. The Southern Portal Section of the tunnel is outlined with the blue rectangle in the Geological Cross-Section in Figure 15a. In Section 15b, one can see the geological details of this Southern section. The construction of the south portal of the tunnel penetrates the Pythagorion fault zone. This is definitely not the most ideal of conditions to begin the tunnel excavation. The first 36 m of the tunnel are characterized by tectonic breccia and colluvial deposits, as well as by human-made deposits consisting of rock that have been excavated.

Approximately 21 m of arched and modern lining were constructed in this region demonstrating the stability problems that must have been encountered during excavation around and beyond this section. At this location, one can see the fault plane as well as the separation of the massive limestone from the tectonic breccia. As such, the tunnel at this position along the alignment is characterized by uneven morphology and cave-ins. It should also be noted that additional failures such as fall of gravels and blocks are also possible based not solely on the geology but also on the geometry of the opening and confinement provided Figure 15c). In this section, the arched lining (as

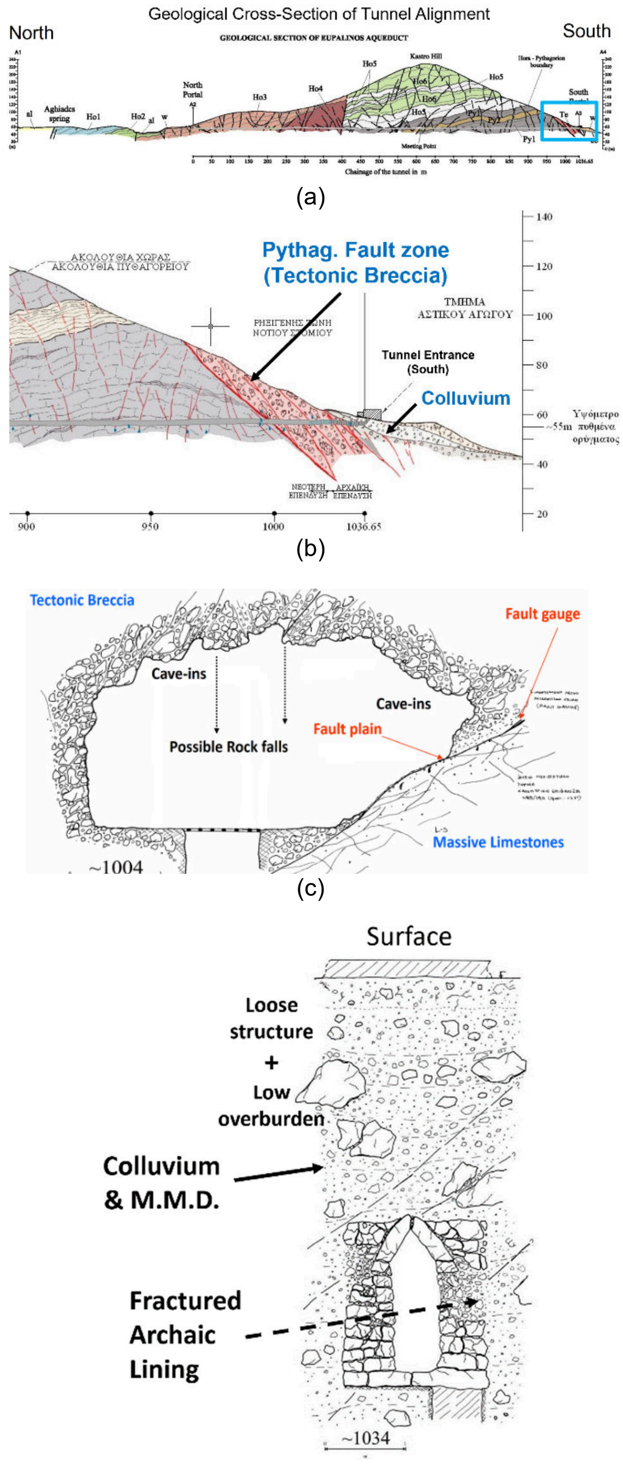


Figure 15. (a) Tunnel Cross-Section highlighting Southern Portal, (b) Pythagoran Fault Zone Dominating Southern Portal Region,(c) Cross-section of tunnel opening depicting potential risks and the need for support / confinement, and (d) Schematic of Arch Lining at Southern Portal. Modified after, Dounias G., 2014 and Lyberis, E. et al., 2014.

seen in Figure 15d) is covered by colluvial and man-made deposits (MMD) and locally undergoes deformation and fracturing, mainly due to the loose structure of the deposits and the low overburden. These conditions provide low self-support of the formation and susceptibility to earthquake movements, leading to overloading on the lining.

5 MEETING ALIGNMENT

Referring back to Figure 12 and the plan view of the overall tunnel alignment, each deviation was due to the mainly geological conditions encountered at those various courses. The question still remains, how did the two diametrically opposed excavations meet in the middle even with all of those courses and deviations?

On the horizontal plane, Eupalinos calculated the expected position of the meeting point in the mountain. Since two parallel lines never meet, an error of more than two meters horizontally meant that the north and south tunnels would never meet. Therefore, Eupalinos changed the direction of both tunnels, as shown here. The north tunnel was turned to the left and the south tunnel to the right. This gave a 17 m wider catching width, so that a crossing point would be guaranteed, even if the tunnels were previously parallel and far away (Figure 16). Kienast, H., 1995.

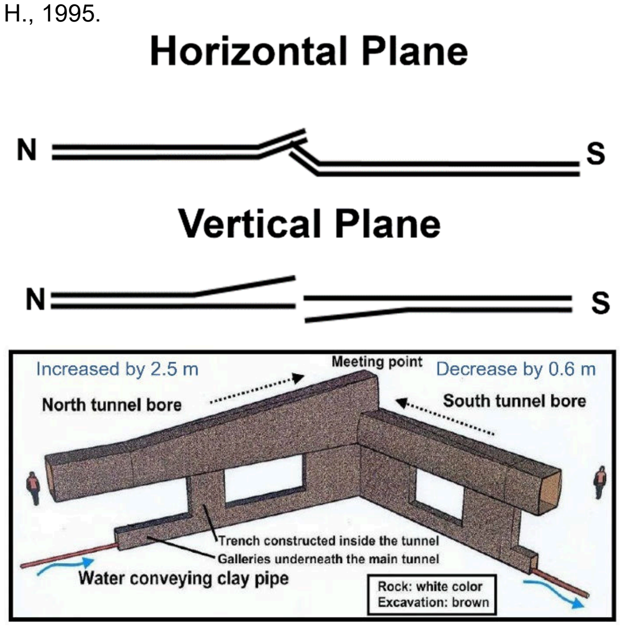


Figure 16. Horizontal and Vertical Plane alignment of Eupalinos Tunnel. Modified after Kienast, H., 1995.

In terms of the Vertical Plane, at the start of work, Eupalinos levelled around the mountain as discussed previously in order to ensure that both tunnels began using the same elevation. In order to compensate for any errors in elevation due to the constriction process and the measurement technique, he increased the possibility of the two tunnels meeting each other by increasing the height of both tunnels at the point near the calculated meeting point. In the north tunnel he kept the floor horizontal and increased the height of the roof by 2.5 m while in the south tunnel he kept the roof horizontal and lowered the level of the floor by 0.6 meters. His precautions as to this vertical deviation proved unnecessary since measurements show that there was very little error in the vertical direction. At the rendezvous, the closing error in elevation for the two tunnels was a few millimeters. (Hanzl, V. and Horak, V., 2012). The bores met in within 1.8 % accuracy (Figure 16). A photo of the meeting point of the two bores is seen in Figure 17.

Figure 17. Success! Meeting Point of the Two Bores.

6 REDISCOVERY AND RESTORATION WORKS

The aqueduct was functional for approximately 1000 years but then filled in and buried and forgotten for about 1500 years. (Stiros, S. and Kontogianni, V., 2010). The tunnel was rediscovered in the nineteenth century and many investigations have occurred; From 1971 to 1973 the tunnel was excavated by the German Archaeological Institute and H.J. Kieast has published the results in a Samos series of articles (Yoshitake, R., 2012).

The Greek government also commissioned studies more recently in order to open the tunnel to the public. As such, the design works of the aqueduct commenced in 2009, following the approval by the Ministry of Culture of Greece, financed by the Ministry of Public Works. (Angistalis, G. et al., 2018). The tunnel was restored to its current condition and opened to the public in April 2017.

7 SUMMARY

The Eupalinos Tunnel was and is an engineering marvel. The techniques that were used in ancient times are still applicable and used today by tunnel construction engineers, contractors and professionals. These historical works and techniques can serve to inform, aid and inspire current geotechnical, geological and tunnel engineers and practitioners in the way that they approach their unique tunnel and excavation project requirements. To this day, the acknowledgement and relevance of such an achievement is honoured: The current tunnel is designated as a UNESCO Heritage site and also has been acknowledged by the American Society of Civil Engineering (ASCE) as an international heritage site.

8 RECOMMENDATION

It is recommended that the Canadian Geotechnical Society consider acknowledging the Eupalinos Tunnel as an International Historical Tunnelling Landmark as per other societies and organizations (i.e. American Society of Civil Engineers, International Tunnelling Association, UNESCO among others). The author volunteers to take the lead on any such plan should such an initiative be endorsed.

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