Outline of the Restoration Designs of Eupalinos Tunnel, Samos Island, Greece

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ABSTRACT: The Aqueduct of Eupalinos has a total length exceeding 2.5 kilometres involving a bored tunnel 1036m long, ~1.8m x 1.8m wide under a 170m overburden of mount Kastro. Its purpose was to supply the city of Samos with water and was built in the mid-sixth century B.C, on the island of Samos that lies in the archipelago of north Aegean Sea. Herodotus (481-425 B.C.) was the first historian to refer to the monument. He mentions Eupalinos, son of Naustrophus, born in the city of Megara as the engineer responsible for the design and construction of this ancient project. He also describes the method of construction that makes this monument unique: “…One is a tunnel, under a hill one hundred and fifty fathoms high, carried entirely through the base of the hill; its excavation started from two portals (ἄρξάµενον, ἀµφίστοµον) …”. Part of the aqueduct was constructed as an open trench ~60 cm wide and of a variable height of some metres. Parts of the trench are covered with big orthogonal hewn stones and parts with an arched shaped roof. Another part of it was constructed using the qanat method which involves the construction of underground interconnected vertical shafts. The most interesting part of the aqueduct is the main and 1036m long bored tunnel that “hosts” the canal and the water conveying ceramic pipeline. Almost 230m of it are lined with a dry masonry made of high quality hewn stones. The roof is made of big slightly curved stones that form a triangular roof. Today parts of the monument suffer from deterioration and instabilities. Egnatia Odos S.A. (see note 1, chapter 7) in cooperation with the Prefecture of Samos and the Ministry of Culture initiated a multi-discipline design study to protect and restore the monument. In the context of the surveying design works the monument was mapped in a three dimensional space using both conventional and laser scanner techniques. The surveying data produced were processed with an advanced state-of-the-art software. The geophysical survey has given insight to the geological structure behind the lined part of the main tunnel and provided information on the thickness of its lining. The geological and geotechnical designs involve a detailed engineering geological mapping and reporting of the area along the monument. It also includes the dimensioning of the support measures proposed to strengthen the rock mass around the tunnel’s excavation perimeter where potential ground instabilities have been recorded. These measures include rock reinforcing systems with the use of stainless steel rock bolts and flexible netting of a different capacity. The structural design includes the works to restore the stability of the monument’s structural elements mainly those on its lined parts. The electrical and mechanical design includes the lighting design, the illumination plans and the equipment so as to provide a comfortable environment in the tunnel and to highlight its engineering and historical features. Finally, the architectural design combines elements such as accesses, parking areas, footways and restrooms, information places, etc along the monument.

Keywords: Herodotus, Eupalinos, ancient tunnel, lining, restoration

1 Introduction

Herodotus’ (see note 2) reference to the tunnel of Eupalinus, (485 - 421/415 B.C.) in his third Book Thalia is the following: «Ἐµήκυνα δὲ περὶ Σαµίων μᾶλλον, ὅτι σφι τρία ἐστὶ µέγιστα ἀτάντων Ξλλήνων ἐξεργασµένα, δρέος (=mountain) τε ὑψηλοῦ ἐς πεντήκοντα καὶ ἐκατόν ὄργυιας, τούτου δρυµη (=tunnel, trench) κἀτωθεν ἄρξάµενον (=upon being begin, wiki Lexikon), ἀµφίστοµον (=with double mouth, Henry George Liddell, Robert
George Liddell, Robert Scott, A Greek-English Lexicon.

ßπανῶν νησωλήνων παραγίνεται ἀπὸ μεγάλης πηγῆς. Ἀρχιτέκτων δὲ τοῦ ὄρυγματος τοῦτοῦ ἐγένετο Μεγαρεύς Εὐπαλίνος Ναυστρόφου. τοῦτο μὲν δὲ ἐν τῶν τριῶν ἔστι, δεύτερον δὲ περὶ λιμένα χώμα ἐν θαλάσσῃ, βάθος καὶ ἔκοσι ὀργυιέων· μήκος δὲ τοῦ χώματος μεζὸν δύο σταδίων. τρίτον δὲ σφί ἔξεργασται νής μέγιστος πάντων νησίων ἡμείς Ιομέν· τοῦ ἀρχιτέκτων πρῶτος ἐγένετο Ροῖκος Φιλέω ἐπιχώριος. τούτων εἶνεκεν μᾶλλον τι περὶ Σαμίων ἐμήκυνα.» Following translation:

“I have dwelt the longer on the affairs of the Samians, because three of the greatest works in all Greece were made by them. One is a tunnel, under a hill one hundred and fifty fathoms high, carried entirely through the base of the hill; with a mouth at either end. The length of the cutting is seven furlongs - the height and width are each eight feet. Along the whole course there is a second cutting, twenty cubits deep and three feet broad, whereby water is brought, through pipes, from an abundant source, into the city. The architect of this tunnel was Eupalinos, son of Naustrophus, a Megarian. Such is the first of their great works; the second is a mole in the sea, which goes all round the harbour, near twenty fathoms deep, and in length above two furlongs. The third is a temple; the largest of all the temples known to us, whereof Rhoeucus, son of Phileus, a Samian, was first architect. Because of these works I have dwelt the longer on the affairs of Samos.” (Herodotus. Histories. III translation by George Rawlinson; http://classics.mit.edu/Herodotus/history.3.iii.html)

2 General information

The Aqueduct of Eupalinos has a total length greater than 2.5 kilometres including a bored tunnel 1036m long. It was built in the mid 6th century B.C. at the island of Samos in the archipelago of the northern Aegean sea. The point where Samos and the ancient land of Ionia (present day Turkey) are nearest is less than 2 kilometres away and it is called the straights of Mycale. At this point in summer 479 B.C. the allied Greeks confronted King Xerxes the Great of Persia in the last battleship of the second Greco-Persian war. Samos has been inhabited for more than 2½ thousand years. It boasts the honour to be the birth place of some of the most famous ancient Greek philosophers and mathematicians such as Pythagoras, Aristarchus and Epicurus.

Herodotus (481-425 B.C.) is the first historian who makes an enthusiastic reference to the monument. He names Eupalinos as the engineer responsible for designing and building the ancient project. He also describes the method of construction that makes this monument unique: “...One is a tunnel, under a hill one hundred and fifty fathoms high, carried entirely through the base of the hill; ὄρξαμενοι (=upon being begin, wiki Lexikon), ὑμισσόμονι (=with double mouth, Henry George Liddell, Robert Scott, A Greek-English Lexicon)...”. It is the first tunnel known that has been built under a mountain starting to excavate it from two diametrically opposite portals using mathematics and geometry for keeping it aligned.

The Tunnel of Eupalinos is very well known in the disciplines of engineering and archaeology. Most civil and architectural engineering books refer to this monument as a unique engineering achievement. Paul Valery (see note 3) has been inspired by the architect Eupalinos, and has written the book (drama in dialogue) “EUPALINOS OU L'ARCHITECTE, L'ÂME ET LA DANSE” in 1923.

The monument is a milestone in tunnel engineering: the engineer thinks innovatively and deviates from the classical, for that period, method of tunnel construction (the qanat method) and he builds a tunnel under a mountain by starting to dig from two portals diametrically opposite; he uses mathematics and geometry not only to align the excavations but also to “manipulate” the alignment of the tunnel in order to avoid adverse geological conditions. Mutatis mutandis, the basic principle behind the method of Eupalinos, has been used again long after the Renaissance of Europe (early 18th century), and it is still in use in modern tunnelling.

Scientists have proposed probable construction methods by trying to answer the following question: how did Eupalinos keep the tunnel aligned? The first person to deal with the subject was the Greek engineer Heron (see note 4) of Alexandria (circa 70 AD). Efforts to explain the alignment method continued after the modern discovery of the monument in the 18th century. A well thought method that explains the alignment question is given in the archaeological study that is mentioned in §3.
Victor Guerin was the first person who discovered the first 400m of the aqueduct in 1853 under the auspices of the ruler of Samos Georgios Konemenos. The south and north entrances of the main tunnel have been discovered in 1882 by the monk Kyrillos Moninas (see note 5) who persuaded the ruler of Samos Kostakis Adosidis to undertake an investigation campaign. In 1992 UNESCO declared the area of Eupalinos Aqueduct a World Cultural Heritage site.

3 Architectural and archaeological study

The architectural and archaeological study (see note 6) the monument has been compiled by Dr. Hermann Kienast of the German Archaeological Institute of Greece. The initiative of this study has been of Ulf Jantzen former director of the institute. The study comprises of 213 pages of text, plus 41 pages of high quality photographs and drawings. Among others the study covers issues such as the monument's investigation and discovery, the concept of its design and construction, the subsequent interventions, design, construction and functionality of the ancient works, mathematics and geometry of the tunnel alignment, the ancient marking and aligning systems, meeting point of excavations, geometrical design assumptions, geological conditions etc. His study is the only thorough work that exploits the issue describing and explaining the aqueduct of Eupalinos to the maximum possible detail (see note 7). An extensive abstract of this study can be found in a widely available booklet (see note 8) published by the Ministry of Culture that is also available in English.

4 Brief description of the monument

The aqueduct is practically a canal 2,5 kilometres long excavated in soil and rock. Its final length however might be increased as new evidence extend it towards the nowadays Pythagoreion (the ancient city of Samos). Figure 1 is an annotated layout plan of the of wider aqueduct's area. The project starts at point 1, the spring, and ends (?) at point 9 which is the location of the ancient fountain (only its remnants are visible nowadays).

The spring water that used to flow in the aqueduct for more than 10 centuries (see note 10) collects in a remarkable manmade tank that is preserved to a percentage more than 90% (figure 2). Its stone roof is supported by 17 pillars (~60cm x 60cm) 131cm centre to centre distance, made of hewn stones while on its roof rests a small chapel of unknown date of construction. Its clear height is less than 2m and its maximum clear width is almost 8.5m. Its north-eastern wall has been hewn in the bedrock. The immediate area of the spring (point 1 of figure 1) is called Agiades.

![Figure 2 (left). View in the stone-made water reservoir (Zambas, 2010). Figure 3 (right). View of the unlined tunnel part (Modified after Kienast, 1995). The trench hosting the water conveying ceramic pipeline at its bottom is visible at the left hand side of the picture](image)

The first 740 meters of the canal are excavated as an open trench (point 2 of figure 1). Its sidewalls are supported by stone walls and covered with massive hewn stones or brick arches. The width of the trench ranges from ~61cm to 25cm in areas where the trench walls have been deformed. The clear height of the trench varies from 1.5m to almost 4.3m at some locations towards the north tunnel portal. The next 150 meters of the canal is a system of successive lined vertical shafts. Their bottom ends are interconnected with underground galleries. This is the so called qanat method mainly implemented in Persia. The galleries at their bottom host the water conveying ceramic pipeline. A typical clear dimension of a vertical shaft is 80cm x 210cm. The maximum depth measured in a shaft is 19m under the apex of a hillside located after the north portal of the main tunnel. Now both the trench and the qanat portions of the aqueduct are filled with soil deposits that have been gradually accumulated through time.

![Figure 4. View of a lined tunnel part. Note the slight curvature of the roof stones (Zambas, 2010).](image)
The following 1036 meters is the most important part of the aqueduct. They have been constructed from inside the remarkable tunnel referred to by Herodotus. A simplified longitudinal section of the tunnel is given in figure 5. The tunnel bore is almost 1.8 x 1.8m wide (see note 11) and at its bottom hosts the water conveying canal (figure 3). The width of the canal is almost 60cm and its depth varies from almost 4m at the north portal up to almost 8m at the south portal. This difference in the depths builds the necessary longitudinal inclination for the ceramic pipe to convey the water. This canal however has not been excavated as an open trench at its full length. Portions of it are galleries running underneath the main tunnel (see also figure 6). Parts of the tunnel of a cumulative length ~230m have been lined with high quality faced hewn stone walls (see note 12) (figure 4).

A ~30m part though has been lined, later during the roman era, with brick walls and an arch shaped roof. Out of the 230m lined tunnel, ~18m are at the south entrance of the tunnel. The rest 210m of the lining are at the north tunnel bore towards its exit. The maximum clear height of the lined tunnel is ~170cm and its width is ~65cm.

![Figure 5. Simplified longitudinal section of the tunnel. Altitude of the walking level at north portal: +55, 22, at south portal: +55, 26, at the apex of mount Kastro: +225, 00 (modified after Tokmakidis, 2009).](image)

The most remarkable point of the tunnel is the breakthrough point of the two excavations. This was done ~170m below the apex of mount Kastro (figure 5) and as proved in the architectural study, it was selected based on a mathematical reasoning. The excavation arrangement there, took into account the possibility of a horizontal and a longitudinal mistake in the excavation directions: the last ~40m of the south bore were constructed kinked eastwards making that way a “waiting wall” for the north bore excavation end. Figure 6 is an annotated 3d sketch of the breakthrough point.

![Figure 6. Annotated sketch of the meeting point of the tunnel bores. In order to secure meeting of the excavations, the height of the excavation of north bore has been doubled (plus~2m) while the walking level of the excavation of the south bore has been lowered by 60cm.](image)

The archaeological study has identified seven marking and measuring systems used by Eupalinos to implement the alignment during construction. These systems cover the entire tunnel length and have been deciphered/proved and described in the archaeological study. Another remarkable achievement of the use of applied geometry in the tunnel construction is the triangular deviation of the excavation
(point 5 of figure 1) at the north tube; this was made for the tunnel to avoid the adverse water-bearing soft ground conditions and the subsequent need to construct the arduous lining. Eupalinos had the knowledge to deviate from the straight excavation direction and to bring it back to its straight direction when he judged it appropriate. A separate marking/alignment system was implemented for this purpose.

The final ~500 meters of the canal were channelling the water from the tunnel exit down to the central fountain in the city of Samos (see note 13) (point 8 of figure 1). This part of the aqueduct has been also constructed with the qanat method; as previously mentioned, this is a system of vertically excavated orthogonal parallelepiped shafts at 11m to 25m in between distances, that are interconnected underground. The water was conveyed through a cylindrical ceramic pipe, 24-26 cm clear diameter, resting at the bottom of the canal. Parts of this pipe are still visible from inside the main tunnel.

5 Outline of the restoration designs

5.1 Scope

Nowadays few parts of the monument suffer stability problems. In 2009 engineers of Egnatia Odos S.A. in cooperation with the Prefecture of Samos and the Ministry of Culture initiated a multi-discipline design study restore the monument. The scope of the restoration designs has been to rehabilitate the monument, to protect it from natural wear and to make it accessible. These designs focus in the main 1036m long tunnel and include definitive and implementation surveying, geophysical, geological, geotechnical, structural, electrical and mechanical and architectural works. The adjacent diagram shows the design stages and approvals followed. Works have been also proposed for the aqueduct parts at either side of the main tunnel. The paragraphs that follow constitute a short summarized description of the works with selected examples.

5.2 Pathology of the main tunnel

Despite the fact that the monument suffers deterioration, it is remarkably preserved. Its nowadays appearance and condition does not differ significantly from its original one. This can be mostly attributed to its underground nature that kept it protected from both the human (see note 14) and seismic actions. This chapter briefly describes a few problems associated with the stability of the underground excavation and the lining of the main 1036m long tunnel.

Two main groups of potential instability problems are identified in the tunnel. The first group includes potential instabilities at the excavation perimeter and the second includes instabilities associated with overstressing of the lining.

The tunnel is lined for a length ~230m. The archaic lining of the tunnel is made out of hewn stones. It forms vertical sidewalls and a triangular shaped roof. Its free width is almost 65cm and its maximum height from the walking level up to the apex (crown) of the triangular shaped roof is almost 170cm. It is of a remarkable construction quality and the lining’s hewn stones are so good shaped that practically attach each other leaving no gaps at all. Most impressive are the slightly curved pieces of stone that form the roof (see figure 4). This geometrical type of triangular arches can be found in temples dated back to the 10th century BC. The roman era lining (of a length ~30m) is of similar dimensions with the archaic one, and it is made out of bricks forming vertical sidewalls and a semi-circular arch shaped roof. The presence of the this type of lining that was built so many years after the archaic one indicates that roof and sidewall instabilities were happening, and that if someone wanted to keep the aqueduct in function he had to implement additional protection measures. Both linings were built to protect the tunnel and the water conveying canal in it from rock falls that could damage or block the water pipe and/or make its maintenance an extremely difficult work.

At few locations the tunnel lining suffer damages. At the south portal the archaic lining appears significantly deformed (figure 7); some stones are fractured and slightly removed from their original position. This situation can be attributed to the presence of loose soil at the tunnel portal area and around the tunnel, the shallow cover and the influence of the seismic forces (see note 15). The tunnel in this location is in scree that consists of limestone fragments “floating” in a clayey sandy matrix. The ground cover is about 2.5m to 3.0 m thick. This allowed the weathering and the subsequent loosening processes to penetrate down the level of the lining. Remnants of vegetation roots are also visible. The
lining becomes more vulnerable to the earthquake forces (that are transferred from the surrounding ground on it) when its confinement (due to the shallow cover) is limited and when the quality of the surrounding ground is poor. In fact the lining’s distortion and deviation from the verticality has a westward direction which is towards the dip of the ground surface. This is also the direction of the highest earth pressure component that acts on it.

Figure 7 (left) (Tokmakidis, 2009). Laser scanner cross section in ch.1030 showing the profile of the lining. The lining’s deviation from verticality is obvious. Figure 8 (right). Dislocated, fractured key stones at the lining’s roof (Zambas, 2010).

At ch 0+184 at the northern tunnel bore, 9 pairs of the roof key-stones suffer significant settlement, distortion and fracture (figure 8). Here, there is a possibility that the rock mass above the tunnel’s roof has exerted excessive loads on the lining. In the vicinity of this location the geophysical survey has identified a weak rock zone.

Another overstressing at the lining exists at the last tunnel part before its north exit. A significant cave-in (figure 9) has loaded the lining’s roof arch and has deformed it. At this point the roof of the lining was not in contact with the original excavation profile. It was built afterwards to protect it from rock falls. The thinly bedded limestone here is unfavorably oriented in terms of tunnel stability, having a direction almost parallel to the tunnel axis and a gently eastward dip.

Figure 9 (left). Cave-in above the tunnel lining. Figure 10 (right). Cave in ch 531. Part of the roof has fallen and “wedged” in the trench.
The rest of the tunnel is practically unlined. Only at very few locations ancient masonry walls support one side of the tunnel excavation only. For almost 800m the ground conditions are visible at the sidewalls and the roof of the tunnel excavation. Potential further deterioration of the rock exists at some points of the tunnel. These are mainly at cave-ins of an unknown age. Such a cave-in exists at ch 531 and it is due the collapse of a portion of loose mylonite in a fault. The collapse has affected the west sidewall and the roof (figure 10). Potential instabilities are also related with loose rock pockets in the vicinity of significant faults.

5.3 Surveying works

Surveying works covered the aqueduct at its entire 2,5klm length. Underground survey was done using both a laser scanner (figure 11) and conventional means. The purpose of the survey was to create the necessary drawings to be used in the subsequent design phases. These drawings include the unfolded projection of the tunnel excavation perimeter, cross sections (every 10m using conventional means and every ~0.5m from the laser scanner), layout plans and longitudinal sections. Initially a control network using a GPS was established. The survey was done using reflectorless total station. The main traverse through the tunnel has more than 65 stations with a total length of more than one kilometer and with a closure error of 10 cm. Survey cross sections were produced every 10 meters. The laser scanner survey was done for the ~800 meters of the underground unlined tunnel length.

![Figure 11. Laser scanner model of portion of south bore (Tokmakidis, 2009)](image)

5.4 Engineering geology

In the context of this work a thorough and detailed engineering geological design study has been compiled. Works included surface mapping in scale 1:500, underground mapping along the tunnel in scale 1:50, lab testing and reporting. Extracts of the findings of this study is given in the paragraphs that follow.

The geological sequence in the area of Eupalinos aqueduct includes the upper Quaternary formations that cover discordantly the Miocene molassic formations of Kastro hill that contain the sequence of Hora and the lower one of Pythagoreion. The first part of the aqueduct from the Agiades spring up to the north portal of the main bored tunnel has a length of ~890m. It is in the mid-upper Miocene formations of the thinly bedded (3-20cm) marly limestone for almost half of its length. The other half, towards the north portal of the main tunnel is in alternations of fissile marl, green clay shale and thinly bedded limestone. Scree, mixed with the ancient tunnel excavation products form a quaternary deposit on the top of the later formation.

The main tunnel was excavated in massive to medium bedded limestone, travertine marly limestone (RQD% 70-100, UCS 40-150MPa), thinly to medium bedded marly limestone with marl intercalations (RQD% 10-50, UCS 20-50MPa), thinly bedded to shaly marly limestone, marl and clay shale (RQD% 0-20, UCS 5-20MPa), breccia (at the south portal) and mylonite zones in faults. The north section of the tunnel has a length ~610m. Out of these 610m the ~210m are lined. Practically the tunnel lining
has been constructed in the north tunnel bore excluding the 18m of lining at the south portal. The presence of the lining is a sign of both the adverse geological conditions and the subsequent need to support the excavation. Almost all of this tunnel section has been excavated in the folded thinly bedded shaly marly limestone, marl and clay shale. These formations are water bearing (see note 16) almost all along this part of the tunnel; water is present as drops and occasional inflows.

The south section of the tunnel has been excavated mainly in the massive to medium bedded limestone. Thin-bedded marly limestone appears as intercalations at the end of this tunnel section under the apex of the mount Kastro. Except one location (see note 17) where a water flow has been observed the rest of the tunnel is wet to damp and in portions dry.

In order to quantify the hazards along the tunnel, a hazard ranking assessment along the tunnel has been done. The tunnel divided in hazard zones according to criteria such as: a) mode of the potential failure (e.g. detachment of rock along the bedding plane, minor rock slides in loose mylonite etc), b) visually estimated probability of failure and c) potential volume of failure. Figure 12 shows a section of the unfolded tunnel projection with the engineering geology mapping and the respective hazard ranking. This figure shows an ancient (?) cave-in in ch 661-552. The hazard at this location for example is further development of the cave-in by falling of rock pieces along the bedding plane from the sidewalls and the roof.

Figure 12. Example of engineering geological mapping of the tunnel excavation perimeter on its unfolded projection (Evrikos Lymberis in Edafos S.A. 2010) Translation of annotations: 1: Over-excavation at the roof along the axis of an anticline and fault. Falls along bedding plane and discontinuities. 2: Limit of over-excavation 3: Trace of man-made ground that has been removed. Follows a trace of calcite deposited on the deposits. 4: Thin horizons of weathered and damp clayey siltstone that caused slippage of the rock plates. 5: Travertine with horizons of green clayey siltstone. 6: Main fold associated with fault zone. 7: Portion of the sidewall is formed along joint planes. T1-I-B is a hazard class.

Another ancient (?) cave-in has happened in ch 537-528. Figure 13 is a cross section in ch 531 showing the trace of the original excavation geometry. The rock fall has happened along a system of subparallel faults that brecciated the rock (figure 14) at the tunnel roof and sidewall. The hazard at this location is also the gradual further development of the cave-in. Minor rock pieces have fallen from the tunnel wall damaging the girders that cover the aqueduct canal. The rest of the aqueduct (~500m) from the south portal to the city has been excavated from vertical shafts that are interconnected by
underground excavation (18 shafts). Only the top of the shafts are easily accessible. It is in clay sandy scree that includes limestone fragments and boulders.

Figure 13 (left). Geometry profile of the cave-in in ch 531 (Evrikos Lymberis in Edafos S.A. 2010). Figure 14 (right). Brecciated clayey siltstone layer in the limestone (Edafos S.A., 2010).

5.5 Geophysical investigation
A geophysical survey was carried out at the main tunnel. The purpose of it was to investigate the thickness of the lining and to provide some evidence about the geological conditions between the tunnel and the ground surface. The following methods have been applied: a) electrical tomography at the ground surface, b) ground penetration radar, d) seismic refraction at the ground surface, e) electrical tomography using sensors inside the tunnel and along its projection at the ground surface, f) seismic tomography using geophones in side the tunnel and producing elastic waves at ground surface, g) VLF and SP.

Figure 15. Interpretation of the evaluated of the geophysical results along the lined part of the tunnel at the north tunnel bore (Tsokas, 2009).

Figure 15 shows elements of the geological structure between the lined section of the tunnel and the ground surface, which identified from the geophysical survey. Also noted that the geophysical survey
has identified zones of poor ground at the two locations where the lining is damaged. Therefore the restoration measures at these locations aimed not only to restore the curved stones of the roof but to strengthen the surrounding ground also.

The thickness of the lining along the tunnel was investigated by both the ground penetration radar and the electrical tomography methods, along two lines at either sidewall. Figure 16 shows a portion of the GPR evaluated results. Here the thickness of the lining varies from 20cm to 50cm.

![Figure 16. Evaluated results of the ground penetration radar. The red line represents the outer limit of the tunnel’s lining. The yellow line most probably depicts a geological discontinuity (Tsokas, 2009).](image)

5.6 Restoration, protection measures at the main tunnel

In order to strengthen and reinforce the rock mass at the tunnel’s excavation perimeter, a rock reinforcing system that combines stainless steel rock bolts with flexible netting has been selected and dimensioned. These measures allow also viewing of the geological conditions along the tunnel, which can be considered as a “geological museum” also. Rock bolting capacity, length and installation pattern have been adjusted to the rock mass conditions along the tunnel. The same holds for the stainless-steel netting as far as the net’s diameter and net’s cable spacing is concerned (figure 17).

At locations of significant cave-ins the tunnel has been also protected by a stainless steel canopy made out of steel sets and girders (figure 18). At the cave-in behind the lining at the north exit portal, the netting was replaced by a drained reinforced concrete layer. At this location, the tunnel’s lining protection measures also include careful removal of the failed rock material that accumulated behind the lining’s arch, strengthening the arch with neutral grouts and filling the space between the arch and the cave-in’s perimeter with bags filled with lightweight material.

![Figure 17 (left). Annotated tunnel excavation cross section with support measures. Figure 18 (right). Proposed stainless steel canopy (George Dounias, 2010 in Edafos S.A., Zambas, 2010).](image)
As previously mentioned in the §5.2 which describes the pathology of the main tunnel, the archaic lining suffers serious damages at certain points along the tunnel. In particular, the key stones of the roof suffer significant settlement, distortion and fracture. In another case the sidewall of the tunnel is significantly deformed due to horizontal earth pressures. At these locations the results of the geophysical survey identified weak fault zones in the vicinity of the lining. The protection/restoration measures that were dimensioned include: a) staged dismantling of the lining stone by stone, b) supporting the ground behind the lining using rock bolts, steel sets and a concrete mantle, c) rebuilding the lining at its original position before the failure. The measures previously described are the most significant ones. Other minor measures include spot bolting, minor nailing and local grouting.

5.7 Other facilities

The design also includes electrical and mechanical facilities such as lighting and communication systems. The canal in the tunnel that hosts the water conveying pipe is proposed to be covered with a grid, a few cm below the walking level of the tunnel, and lightened. Other facilities that are proposed at the tunnel portal areas including rest areas, information booths and screens. Two parking areas have been designed in suitable locations at either tunnel portal. Finally a paved walking path is included in the proposed works. This path will start at the spring in Agiades and following the route of the aqueduct will approach the north tunnel portal. Afterwards, circa the mount Kastro, it will pass at the toe of the hill that hosts the ancient quarries (figure 20). These quarries exploited by ancient Samians in order to construct most of their monumental works. These include the fortress around the ancient city (point 15 in figure 1), the aqueduct and the temple of Iraion. Nowadays these quarries is a monument both in the science of archaeology as well as in mining/geological engineering. After all is a proof that the ancient Samians possessed a well developed underground exploitation technology well before starting to dig the Eupalinos tunnel. The “room and pillar” method seen at the low left corner of figure 20 is often used in modern mining exploitation. The path, after passing the south portal of the main tunnel, will follow again the route of the aqueduct up the location of the ancient fountain (see note 18) that has been identified in the archaeological study.

Figure 20. View of the ancient quarries from the top of mount Kastro. Almost 48 underground exploitation chambers exist. The “room and pillar” method used by the ancient Samians at the left corner (at the floor of the cave are visible orthogonal traces of the ancient exploitation works)
6 Closing information

Design work in aqueduct started 2009 following approval by the Ministry of Culture. The design work has been financed by the Ministry of Public Works. The architectural design was done by Dr.Ing. Kostas Zambas & Associates (see note 19). The restoration designs were jointly done by Dr.Ing. Kostas Zambas and the geotechnical firm EDAFOS S.A. (see note 20). On behalf of EDAFOS S.A. Dr.Ing. George Dounias coordinated the geotechnical designs. The surveying works were done by Ing. Panagiotis Tokmakidis (see note 21) in cooperation with Prof. Kostas Tokmakidis (see note 22) of Aristotle University of Thessaloniki.

The geophysical investigation was done by the geophysical laboratory of Aristotle University of Thessaloniki under the coordination of Prof. Grigorios Tsokas (see note 23). The electrical and mechanical design was done by the design firm Vassilios Konstandinidis & Associates (see note 24). Works lasted almost 1½ years; in total about 40 engineers worked in the different disciplines of the project. All works were done in close cooperation and with the help of the chief archaeologist of Samos Mrs. Maria Viglaki and the prefect of Samos Dr. Med. Manolis Karlas.

7 Notes

Note 1. Egnatia Odos S.A. is a state-owned company, responsible for the design and construction of the Egnatia Odos Motorway, a 680km project (and its vertical axes leading to the Balkan Peninsula), in northern Greece. The authors have been the supervising engineers of the subject’s designs on behalf of Egnatia Odos S.A. The members of the design team are presented in the last chapter. Works also presented in Samos Summerschool 2013 of the Geology Department, University of Athens.

Note 2. Herodotus (in Greek pron.: Hēródotos) was an ancient Greek historian who was born in Halicarnassus, Caria (modern day Bodrum, Turkey) and lived in the fifth century BC (c. 484 – 425 BC). He has been called the "Father of History", and was the first historian known to collect his materials systematically, test their accuracy to a certain extent and arrange them in a well-constructed and vivid narrative (New Oxford American Dictionary).

Note 3. Ambroise-Paul-Toussaint-Jules Valéry (October 1871 – 20 July 1945) was a French poet, essayist, and philosopher. His interests were sufficiently broad that he can be classified as a polymath. In addition to his poetry and fiction (drama and dialogues), his interests included aphorisms on art, history, letters, music, and current events (wikipedia). He scheduled to be Nobel prize laureate for 1945; he died in July of the same year. „Eupalinos or the Architect” is the name of a Platonic dialogue about architecture between Socrates and Phaedrus, as regards Eupalinos, who according to Phaedrus, had the great ability to put things in order. By connecting the regular and the irregular Eupalinos clears and organizes forms and immersive space. Inside this quasi-total work, humans could move around and feel their presence in the world either in silence or with a pleasant murmur (Eupalinos oder der Architect, tran. Rainer Maria Rilke, Frankfurt: M. Suhrkamp, 1973)

Note 4. Hero (or Heron) of Alexandria (c. 10–70 AD) was an ancient Greek mathematician and engineer who was active in his native city of Alexandria, Egypt. He is considered the greatest experimenter of antiquity and his work is representative of the Hellenistic scientific tradition. Most of his writings appear as lecture notes for courses in mathematics, mechanics, physics and pneumatics. Although the field was not formalized until the 20th century, it is thought that the work of Hero, his automated devices in particular, represents some of the first formal research into cybernetics (wikipedia). For some he is the spiritual father of Leonardo Da Vinci.

Note 5. The ruler of Samos Kostakis Adosidis formed a committee responsible for the organization and supervision of the investigation works. The monks Theofanis Arelis and Kyrillos Moninas from the monastery of the „Holy Cross” have been the persons responsible for the supervision of the works.


Note 7. The archaeological information included herewith, originate from the study of Dr. Herman Kienast.

Note 9. The Hellenistic period or Hellenistic civilization is the period of ancient Greek history starting with King Alexander the Great in 323BC of the Macedonian Kingdom of Greece, up to the dominance of ancient Rome.

Note 10. The aqueduct operated until the 7th century AD, when it was eventually abandoned and its entrances blocked.

Note 11. Dimensions given throughout the text are indicative, aim to give the magnitude of the works only.

Note 12. The bigger stones that form the roof have hewn letters on them that denote their location at the lining.

Note 13. Why the Samians built the aqueduct underground? All the monument's works are underground: the spring water collecting tank (outside the fortress of the ancient city) in Agiades is completely hidden; the same holds for the rest of the monument up the fountain inside the fortress. The most possible answer is that the water supply system of the city should have been completely hidden from its enemies who besieging it over long periods of time (in the order of several months).

Note 14. According to the archaeological study the tunnel has been inhabited for a long periods of time especially during the byzantine era. It offered unique protection of the people against the Arabic pirate invasions. Fortressing walls have been built inside the tunnel just after its south entrance portal.

Note 15. The first historic reference about a strong earthquake in 110 AD in the wider area of Samos is that of the byzantine chronographer Ioannis Valalas and it concerns the city of Ephesus. He reports that Ephesus and Smyrna and other cities of Minor Asia suffered a disaster and that the emperor Claudius helped the people to rebuild them. Next reference is coming from the byzantine historian Agathias and concerns the island of Kos in 554 AD. The historian mentions that many cities of Ionia and Aeolia suffered extensive damages from the shock and the subsequent seismic sea wave (a tsunami?!). Subsequent references (11 reports) concerning earthquake shocks having their epicentres in Samos Island are from 1800 AD till today. They caused significant damages such as building collapses and landslides (The earthquakes of Greece. Vasilios Papazahos, Edition C', ZITI, Thessaloniki 2003, in Greek: ISBN: 960-431-847-0, ISBN 13: 978-960-431-847-6)

Note 16. In the water bearing formations (~270m from N. Port) Eupalinos shifted the alignment upwards for some cm for the water to flow backwards towards the portal and not to stagnate at the excavation front. He put the alignment back to the horizontal level when the excavation front moved away from the water bearing formations.

Note 17. In ch 680 there exists significant water inflow and the remnants of a man-made water-collecting tank made out of small marble columns and hewn orthogonal plates with the early-Christian symbol of the holy Cross.


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