TUNNELLING ON THE EGNATIA ODOS MOTORWAY: PROCEDURES ADOPTED, MANAGERIAL CHOICES MADE AND LESSONS LEARNED

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ABSTRACT

The 680 km long Egnatia Odos is the largest motorway project under construction in Greece and one of the largest in Europe. It forms part of the Trans-European Network for Transport and belongs to the priority projects of the European Union. The responsibility for the design, construction, operation and maintenance of the motorway lies with the client organisation Egnatia Odos A.E. (EOAE). A length of 50 km will be through 71 twin tunnels, i.e. an overall single bore length of nearly 100 km. 21 of the tunnels are considered long as they more than 700m in length. This paper reviews the tunnel design, tender and construction management techniques employed by EOAE. It also provides the technical solutions adopted regarding particular difficulties encountered during tunnel design and construction.

Keywords: Tunnel design, tunnel construction, squeezing ground, design management, construction management

INTRODUCTION

Egnatia Odos Motorway, one of the largest infrastructure projects currently under construction in Europe, constitutes part of the Trans-European Network for Transport (TEN-T) and belongs to the priority projects of the European Union (EU).

Figure 1: Trans-European Road Network: Egnatia Odos and its Vertical Axes

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Its main axis is 680 km long and stretches from the west coast port of Igoumenitsa, on the Ionian/Adriatic Sea opposite the southeast tip of Italy, to the Greek-Turkish borders in the east. It provides improved access to five ports and six airports and brings the major cities of Northern Greece closer together reducing the current drive time by 50 per cent. The main axis is linked to other countries in Southeast Europe via nine "Vertical Axes," five of them also belonging to the TEN-T. EOAE is responsible for three of these axes with overall length 296 km (Figure 1). The project rejuvenates the old Roman Via Egnatia, linking Italy to Byzantium. It will accelerate significantly the development of Northern Greece, remove peripheral regions from isolation and link the heart of Europe to the neighbouring eastern countries.

The Company

The client organization Egnatia Odos A.E. (EOAE) was established in September 1995 to manage the design, construction, maintenance, operation and exploitation of the Egnatia Odos Motorway. EOAE is a purpose built client organization capable of realizing a state-of-the-art motorway project.

EOAE constituted a pilot project by the Greek State in its effort to upgrade the quality of design and construction of public works in Greece, initially by making extensive use of outsourcing through international competitions for project and construction management consultants. Today the company employs three Construction Managers (Thales-OMEK for Epirus, Parsons-Salfo for West Macedonia and Scetauroutes-ADO for Central and East Macedonia) and Kellogg-Brown & Root (KBR) as Project Management Consultants. Initially, KBR's staff of 37 were integrated into EOAE's organizational structure to provide guidance in the development of working procedures and the transfer of technology within all departments in the Project Directorate while their responsibilities under their current contract as Consultant Project Manager include development and auditing of quality assurance and health and safety procedures and monitoring the approval procedures of technical designs. Today, EOAE' staff amounts to 300 and the CM's staff approximately 200.

The company EOAE along with its consultant Project and Construction Managers, through the design and construction of 100 km of tunnels, raised significantly the tunnel design and construction standards in Greece as only under 10 km of road tunnels had been constructed previously in Greece. As a result, high calibre Greek tunnel design consultancies and construction companies have developed.

The Project

The motorway consists of a dual two-lane carriageway with hard shoulders, having a combined width of 24.5m. Along its length there are 60 interchanges, 43 river crossings, 11 railway crossings, 646 twin bridges, 1210 culverts and 71 twin tunnels of an overall combined bore length of approximately 100 km of carriageway. Of these 60 are bored tunnels with lengths ranging from 100m to 4,600m and 11 are cut and cover tunnels with lengths ranging from 100m to 270m. 21 of the twin tunnels are classed as long, with lengths greater than 700 m, thus requiring cross-passages and ventilation (Appendix 1).

To date more than 90% of tunnel design has been completed while the rest is in progress; 62% of the tunnels have been constructed and 36% are under construction.

The overall completion cost of Egnatia Odos and the three Vetrical Axes is estimated at 6,770 M € incl. VAT. The project is financed by Greek and EU resources, i.e. the European Regional Development Fund, the Cohesion Fund, the European Investment Bank and the Community Budget for TEN-T. In 1994, the approved funding from the 2nd Community Support Framework was limited to 1500 M€. Under EOAE's responsibility the works accelerated rapidly to a peak of 745m €/year in 2001. This success led to consecutive increases of the project's funding by the EU and the Greek State, to the detriment of other competing projects. Today the necessary funding for the main axis and the three vertical axes has been secured. Figure 2 shows the cumulative funding absorption and the yearly absorption since the start of the project and the forecast to the end of the project.

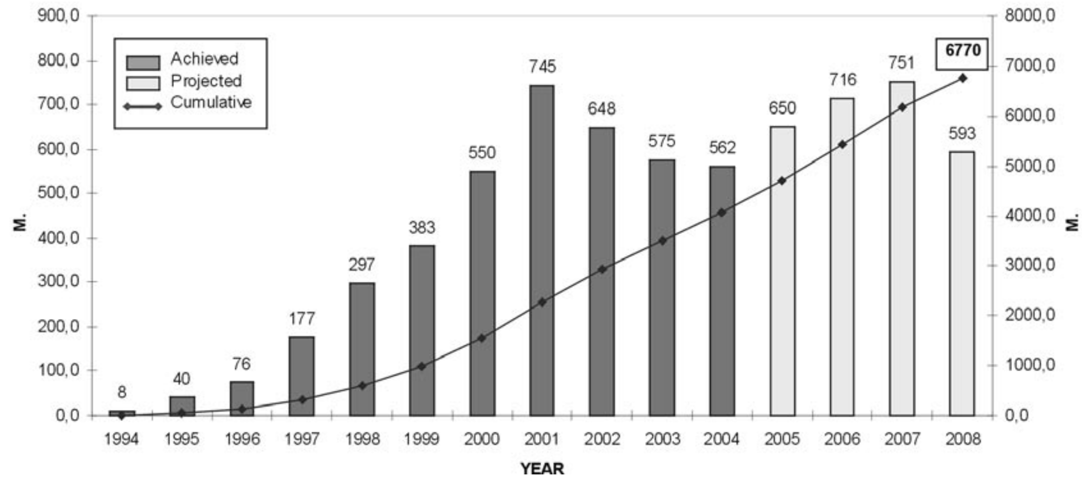


Figure 2: Yearly and cumulative funding absorption

GEOLOGY

Egnatia Odos Motorway intersects roughly perpendicularly the nine major geotectonic zones/units which represent almost the entire geological history of Greece (Figure 3). These units have overthrusted one another, travelling many kilometres from east to west and forming in some cases very complex and diverse geological structures. The resulting diversity is due to intense folding, thrusting and uplifting that occurred during the Alpine Mountain building at the boundary between oceanic and continental plates. Thus, there is an exceptional variety of geological conditions along the motorway access and each geotectonic unit displays different characteristics in terms of frequency of occurrence of weak rock masses and tectonic structure. In such conditions, it is common for the quality of the rock mass to change dramatically in a few meters, making precise prediction of the rock mass classification meter by meter almost impossible. Table 1 provides a summary of geological conditions along the motorway, which correlates with the geological map in Figure 3.

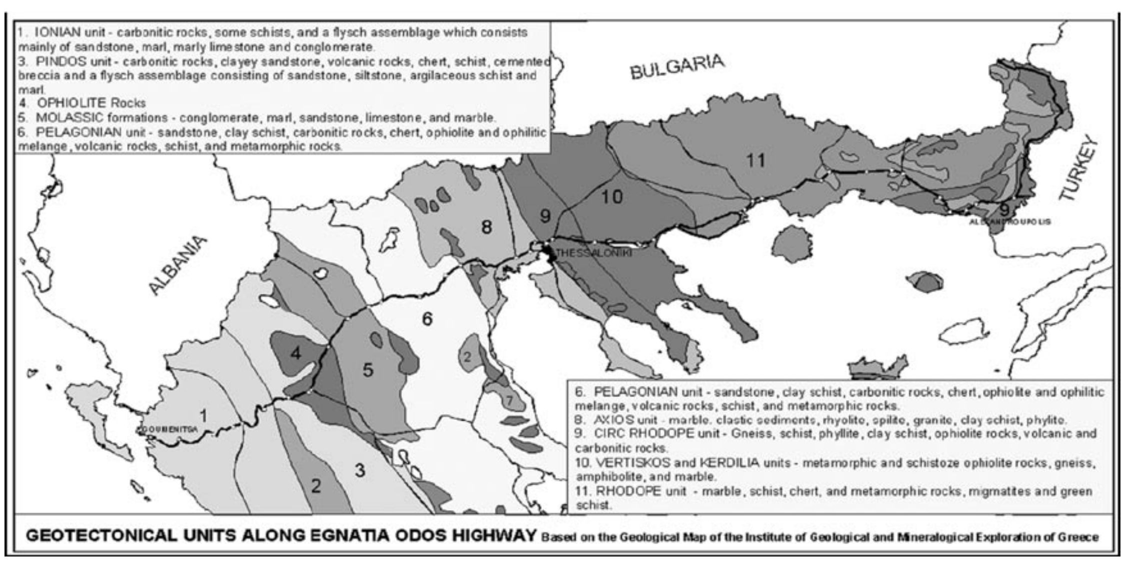


Figure 3: Geology along Egnatia Odos

Most tunnels are located in the mountainous terrain in the west and central sectors. Tunnelling works are therefore, executed in a variety of rock mass conditions, ranging from very good rock quality such as massive limestone or sandstone to very poor quality such as schist.

Table 1: Summary of geological conditions along Egnatia Odos

Geological Unit	Extent Along the Egnatia Highway Route	Rock Types	Tunnel Relevant Engineering Factors
Ionian Unit (1)	Ignoumenitsa to Arachtos River	Carbonate rocks with flysch, some shales and diapiric evaporites. Faulted and folded.	Fractured rock. Infilled karstic features in carbonate rocks create face and crown instabilities. Landslide areas.
Pindos Unit (3) (Pindos Mountains)	Arachtos River to Metsovo	Sandstone, siltstone and argillaceous flysch with some schist and carbonate rocks. All intensely folded, thrusted and faulted.	Fractured rock in fault/thrust zones. Weaker argillaceous flysch. Slope instability at portals. Rapid change in rock quality. Mixed face conditions in flysch. Landslide areas.
Ophiolite Rocks (4)	Metsovo to Grevena	Faulted ultra-basic and basic igneous rocks comprising peridotites, basalts, gabbro, dolerite, amphibolite, pyroxenite. Very heterogeneous with respect to weathering and shear strength. Some weak flysch horizons.	Rapid change in rock type and quality.
Molassic Formations (5)	Grevena to Kalamia	Molasse: conglomerate, marl, siltstone and sandstone.	Less disturbed by tectonic movements. Mixed face conditions. Local groundwater ingress.
Pelogonian Unit (6)	Kalmia to Veria	Marble, limestone, gneiss and granite with localized faulting and overthrusting. Sheared phyllite, limestone and ophiolite.	Good quality rock in some areas. Shear zones— fragmented rock—poor arching capability creating crown instabilities, poor founding strata and local water ingress. Slope instability at portals and landslide areas.
Axios Unit (8)	Veria to Thessaloniki	Clastic sediments, limestone, rhyolite, spilite, granite, clay schist, peridotite and phyllite.	Rapid change in rock quality. Mixed face conditions and deformations in weaker horizons.
Circ Rhodope Unit (9)	Thessaloniki to near Analipsi	Gneiss, schist, phyllite, ophiolite, volcanic and carbonate rocks.	Wedge instability. Infilled karstic features.
Vertiskos & Kerdilia Unit (10)	Near Analipsi to Strimonas River	Metamorphic, ophiolitic rocks, gneiss, amphibolite and marble.	Overbreak along discontinuities. Local groundwater ingress. Weaker sheared zones in competent rock.
Rhodope Unit (11)	Strmonas River to Alexandroupoli/Kipi	Marble, schist, chert, metamorphic rocks, migmatites and green schist.	Overbreak along discontinuities. Local groundwater ingress. Weaker sheared zones in competent rock.

TUNNEL DESIGN

All Egnatia tunnels have a design life of 120 years. A typical tunnel cross-section consists of two 3.75m lanes with 1.25m pedestrian sidewalks and a clearance border line of 5.0m. Egnatia Motorway tunnels are designed as twin tunnels; pedestrian cross passages are provided every 350 m and emergency vehicle cross passages and parking areas every 1000m (Figure 4).

The drainage system of the tunnel pavement includes a continuous fissured (slotted) gully which discharges every 50 m into a 400 mm diameter main collector pipe.

The waterproofing system of the tunnel structure includes a geotextile and a membrane layer placed in between the primary support and the cast concrete final lining. The run off from these layers discharges into two perforated PVC pipes of 200

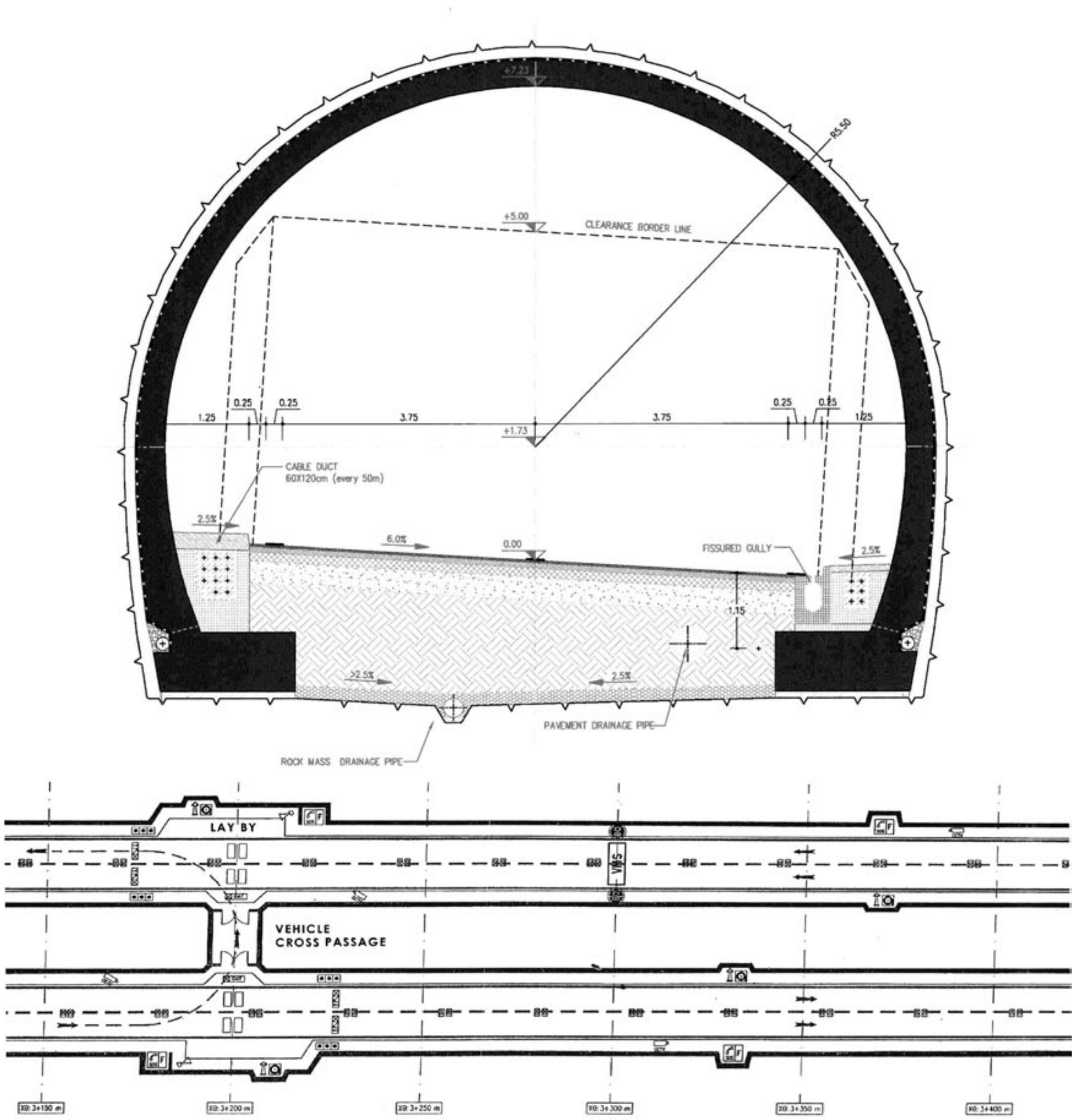


Figure 4: Typical Tunnel Cross-section and lay – by arrangement including emergency vehicle cross over

mm diameter which are located above the footings either side of the concrete lining. These pipes discharge into a main collector pipe every 75 m.

For environmental reasons the rock mass clean water is treated separately from the pavement waters. The two drainage systems are maintained separately. The natural rock mass drainage water is led to collectors located outside the tunnel and the pavement run-off discharges into pollution control units also located outside the tunnel.

EOAE developed the following documents which include tunnel design guidelines:

* EOAE Design Guidelines for Conducting Road Works Design (OSMEO): This document includes the main design principles, technical requirements and submission requirements for each design and approval stage.
* EOAE Tunnels Material and Workmanship Specification (TPS): This document deals with the quality control of both temporary and permanent works during construction. It covers excavations (underground and surface), rock mass classification, observational method (OM) - NATM procedures, primary support, ventilation requirements during construction, final lining, supply and installation of the electro-mechanical systems and specification for all associated works.
* EOAE Guidelines for Environmental Terms and Landscape Design (OSAT): This document relates to specific impacts and strategies on archaeological sites, rare fauna and flora, communities and landscapes and includes guidelines for tunnel portal designs.

Apart from the above project developed documents the design of Egnatia Odos tunnels is based on the following national and international directives and standards

* EU directives for safety in road tunnels
* DIN 1045 Subsoil, permissible loading of subsoil
* DIN 1055 Design loads for building
* DIN 4017 Parts 1 & 2 Subsoil, analysis of bearing capacity for raft foundation
* DIN 4018 Subsoil, contact pressure distribution under raft foundation
* DIN 4085 Subsoil, analysis of earth pressure
* DIN 1045-1 Reinforced concrete structures, design and construction
* DIN 1055-100 Basis of design, safety concept and design rules
* EAK 2000 Greek seismic design regulations

Design Of Primary Support Measures

Firstly, following initial geotechnical investigations, an engineering geological model/map is developed as a basis for tunnel design. This geological model, along with additional geotechnical investigations and field mapping provides the essential geotechnical and ground parameters for tunnel primary support and final lining design.

For the preliminary estimate of the ground conditions and properties, three rock mass classification systems are used on the project: namely Q-system, Bieniawski 's Rock Mass Rating (RMR) and Hoek's Geological Strength Index (GSI).

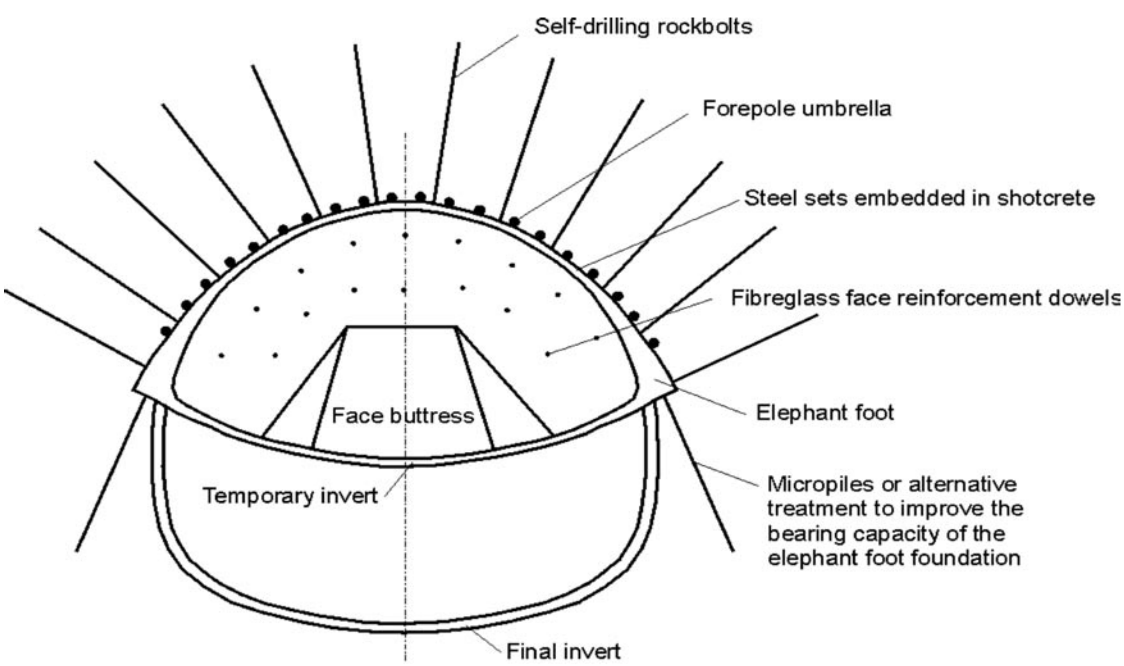
In designing the primary support measures, the anticipated response of the ground to the stresses induced by tunnel excavation is taken into account. This is governed by the ground and groundwater conditions, ground properties, deformation behaviour in relation to the in situ stresses (e.g. squeezing conditions), overburden and ground discontinuities. As all Egnatia motorway tunnels are on "green field" sites, the effects of tunnelling at the surface are a secondary consideration.

Rock mass primary support categories are developed for ranges of the rock mass classification values for individual tunnels. The rock mass mechanical properties derived are used as input into numerical analyses of the ground/primary support behaviour and input into the final design. 2D plane strain continuum numerical modelling (FLAC, PHASE 2, SOFISTIK, TUNNEL) is used to simulate the ground and primary support behaviour by utilising as inputs the calculated ground parameters and the structural characteristics of rock bolts, shotcrete (both steel mesh and fibre reinforced), steel sets and/or lattice girders and pre-reinforcement elements (spiles, forepoles). In most cases a staged excavation (top heading, bench and invert) methodology is employed.

In progressively worsening ground conditions, often encountered in some of the complex geological structures common to the tunnels of Egnatia, the initial category of primary support is incrementally upgraded accordingly to include any, or indeed all, of the elements depicted in figure 5.

One of the most common additional support measures has been the use of the 'elephants foot' located either side of the top heading to improve the load distribution and hence bearing capacity and stability of the top heading ribs. An additional measure, is the face buttress, in some parts of the world colloquially known as a 'dumpling' which is left at the face of the advancing top heading to provide additional support in which stability of the face is critical. The approach of using the face buttress as a face stabilisation tool is used in the primary support design in conjunction with a forepole umbrella arching through the crown of the top heading and sacrificial fibre-glass anchors in the tunnel face.

Tunnel instrumentation and monitoring details are included in the design. These comprise 3-D monitoring, inclinometers, extensometers, strain gauges, load cells, instrumented rock bolts and standard convergence/deformation measurements. Warning and alarm levels and trends are also included in the tunnel designs for deformation and convergence monitoring during construction for the different rock support categories in accordance with OM - NATM principles; in many cases whenever required the monitoring results have been used to modify the primary support measures. In cases where interaction between the two tunnel bores is expected, constraints regarding the minimum spacing between top heading and bench excavation and between each bore are stipulated in the design.



Not to scale - final lining not shown

Figure 5: Schematic representation of all possible support measures taken on Egnatia Odos tunnels

Final Lining

The final lining takes the form of cast in-situ steel reinforced concrete, constructed using track mounted movable steel formwork and is assumed to take the ground and ground water loads, because the primary support is assumed to degrade in the long term. In most cases, a nominal water head of about 5 m above the tunnel crown is assumed. A waterproof membrane and drainage layer are incorporated in the design between the primary support and the final lining with drainage pipes located on either side of the tunnel at the footing level to ensure that there is only a minimal water head, if any, on the final lining during its design life.

In order to determine the load cases for the final lining design, the topographical, geological, geotechnical and hydrogeological information at the tunnel site is taken into consideration. This may include, earthquake, hydrostatic, self-weight, thermal, overburden, construction, surface, internal electromechanical, vehicle impact, explosion and construction sequence load cases.

The design of the final lining is undertaken by plane strain modelling using combinations of the above load cases. Both serviceability and ultimate limit state conditions are considered with regard to bending, shear and compression resistance of the final lining. The thickness of the final lining ranges from 0.35m to 0.60m and uses in most cases grade B25 (C20/25) concrete.

Tunnel Portals

The design of tunnel portals can be a particular challenge mainly because of the low amount of cover and generally the poor nature of the ground. Design, therefore, is dependent on surrounding slope stability, local topography, external drainage requirements, architectural requirements and compliance with the environmental and landscape protection requirements.

It is EOAE's aim to reduce the environmental impact of the tunnels and achieve an environmentally friendly and aesthetically acceptable result that is as unobtrusive as possible. To this end, in order to minimise the extent of open excavations, skewed portals are driven under low cover by using techniques such as forepoling.

The design of portal structures is carried out using elastic plane frame and other numerical models for the various load conditions anticipated. Seismic loading is taken into account assuming an equivalent static load from a seismic event. Particular attention is paid to construction loadings (asymmetrical loading) of the portal structures and any hydrostatic loading, both temporary and permanent.

Safety

The European Council had on several occasions underlined the urgency of taking measures to improve tunnel safety and in its White Paper of September 2001 entitled the "European transport policy for 2010", indicated that it would prepare a proposal for a European Directive on the harmonisation of minimum safety standards to offer a high level of safety for the users of tunnels, particularly those in the Trans-European Network. This Directive was finally published in April 2004 (2004/54/EC)

EOAE, in accordance with the EU Directive, ensures that all tunnels meet the following minimum safety requirements that are mandatory for all tunnels of the Trans-European Network irrespective of their length or traffic volumes.

* Crossing point of the central reserve outside each portal
* Fire resistance of equipment and structures associated with the tunnel
* Normal, Safety, and Evacuation lighting to be provided
* Water supply available at least every 250m inside the tunnel
* Road signs – particularly for all safety facilities provided for tunnel users

* Monitoring system – which includes automatic incident and fire detection systems
* Communication systems – which includes emergency radio messages for tunnel users and loudspeakers in refuge shelters and at exits.
* Emergency power supply.

In direct compliance with the EU Directive, a number of safety measures were implemented throughout the tunnels of the Egnatia Motorway. They include but are not limited to the following:

* 40m length lay-bys are provided at 1km centres for all tunnels longer than 1500m with cross passages located at every 350m leading to the second tunnel bore ensuring a direct escape route in case of emergency (e.g. fire, accident, etc.).
* Between the bores, additional, wider cross passages provide access for emergency services every 1500m.
* Mechanical ventilation is in place for tunnels greater than 700 m in length and where traffic volumes are in excess of 2000 vehicles per lane per day. These systems are built to cope both with ordinary operating conditions and with smoke extraction, e.g. in case of fire, and to automatically monitor the quality of the air in the tunnel keeping it at the desired level. All operational ventilation systems are in compliance with PIARC guidelines and consist of either natural or longitudinal ventilation.
* In the particular case of Driskos Tunnel, a 180 m tall ventilation shaft near the center of the tunnel was required.
* Other safety measures include integrated monitoring systems which feature a Supervisory Control and Data Acquisition system (SCADA) and CCTV.
* Radio Broadcast Relaying Systems are installed to facilitate communications within the tunnels for a mobile to mobile or mobile to Control Centre link for all emergency operations.

The SCADA system processes information obtained from instrumentation associated with all electrical and mechanical installations such as lighting, ventilation, drainage and security systems to determine the optimum mode of operation. A programmable logic controller ensures that the specified performance requirements and safety criteria are met, whilst avoiding unnecessary use of equipment and consequent wastage of energy.

Safety during construction is also of utmost importance. EOAE has enforced all safety regulations during tunnel construction bringing about a change in attitude toward safety issues throughout the Greek construction industry and as a result has had only two fatal accidents and no other severe injuries during tunnel construction (61 km completed and 36 km under construction).

Design Management

The Design Department is the largest department of EOAE, with a staff of 60, it is the Managing Service for all design and check consultancy contracts and consists of eight disciplines: architecture, highways, hydraulics, geotechnics, structures, tunnels, electrical & mechanical and environmental engineering. The staff is called upon to play a dual role, that of technical reviewer and contract supervisor.

International competitions, according to EU Directives, are carried out in order to select tunnel designers and category III checkers. Originally a competition was held for the selection of a tunnel designer and a checker for each tunnel separately. This proved unnecessarily time consuming. Due to strict time schedules, and in order to meet targets set and funding constraints, EOAE proceeded to international competitions for a series of call up contracts for all eight disciplines. In this way, following one major competition for tunnel designers and checkers, EOAE is in the position to assign required design and checking activities to the selected consultants with relevant call up contracts via work instructions, thus saving a significant amount of time and allowing instant responses in case of emergency.

In general, tunnel designs are carried out and checked by Joint Ventures formed by Greek and international partners, e.g. Austria, Germany, Italy, Norway, Switzerland and the United Kingdom. The Designer's and the independent Checker's obligations are described in detailed design briefs (scopes of work), prepared to fit the design needs of each individual tunnel.

TUNNEL CONSTRUCTION

For management purposes the entire length of Egnatia Motorway has been split into three sectors, West, Central and East. Following international competitions three Construction Managers, one for each sector, were employed to supervise construction works on behalf of EOAE. Recently, EOAE has set up its own in-house Construction Management Teams. Tunnel construction supervision is based on the construction contract documents, which include EOAE's Technical Specifications for Tunnels.

Each detailed design for construction is reviewed by the Construction Management (CM) Team with respect to the following elements:

* constructability
* adaptation to the local conditions
* special condition of the site that shall be taken into consideration in the design
* cost and time implications of proposed design modifications
* compliance with the Technical Conditions of the Construction Contract.

Upon approval, the detailed tunnel designs are issued to the contractors for implementation.

The tunnel sections, having areas from 110 m2 to 150 m2 depending on the excavation and support category, is almost always excavated in stages (top heading – bench – invert), in line with the rockmass and overburden conditions. There was only one case where full face excavation has been adopted and this was for approximately half the length of the Dodoni Tunnel,

Egnatia Motorway tunnels have been constructed using conventional methods. Specifically, 50% have been constructed using drill and blast method, while 25% utilised hydraulic hammers and the remaining 25% mechanical excavators. There is only one case, at S1 tunnel in section 5.2, where a roadheader was used to excavate a tunnel bore. This method was selected in order to avoid disturbance to the adjacent finished tunnel, which was already in operation.

The reasons for employing these traditional methods are:

* The length of single bore for most tunnels does not exceed 1.2 Km.
* The geological - geotechnical conditions: highly tectonized rocks and continuous alternations of weak to strong unities require an easily adaptable construction method.
* The cost of equipment investment required by contractors is acceptable in comparison with construction contract values.
* The experience of the Greek contractors.

The majority of the primary support categories employed in Egnatia Odos tunnels can be divided in five main groups (Table 2).

Table 2. Primary support categories and measures

Primary Support Category	Shotcrete (1)	Rockbolts (2)	Steel Ribs (3)	Face support (4)	Pre-reinforcement (5)	Invert and foundation improvements (6)
A	✓	✓	×	×	×	×
B	✓	✓	✓	×	×	×
C	✓	✓	✓	✓	×	×
D	✓	✓	✓	✓	✓	✓
E	✓	✓	✓	✓	✓	✓

The support measures for each support category are divided into two sub-categories: C1, which includes elements that cannot be changed (shotcrete, rockbolts, steel sets), and C2, for elements that are decided upon on site by evaluating the actual rockmass conditions and the monitored data (excavation face support, pre-reinforcement elements, invert and foundation improvements). This division has been developed from past experience which showed that the latter elements carry both the greatest cost and the greatest delay to the production cycle and can only be specified on the basis of the actual conditions.

During tunnel excavations tunnel face logging is carried out by site staff to verify the ground conditions assumed in the design. EOAE employs the designers on site during difficult tunnel underground excavation periods. Since the OM-NATM is implemented for the excavation of all tunnels and its main characteristic is the adaptation of support measures according to actual site conditions, the Tunnel Support Team (TST) and the designer on site provide immediate response to possible complications encountered.

The presence of the designer's staff on site is required during excavation and application of the primary support in order to verify the design assumptions through monitoring and observation and to enable design revisions (subject to EOAE approval) to the primary support (and associated works) to be made, if necessary.

To expedite decisions on site EOAE established a small Tunnel Support Team (TST), comprising highly experienced tunnel engineers to coordinate actions between the various parties concerned with the construction and to both alert and advise the EOAE senior management as required. It is the responsibility of the site based Tunnel Support Team to:

* Verify the correct application of the final designs (in support to the CM team).
* Initiate, manage and check design modifications based on the NATM, observations and monitored data.
* Establish clear, timely and synchronous communication and information lines between the contractor and the Client's services (General Management, Technical Directorate, Project Managers and Supervision).

In addition, a panel of experts (Hoek and Marinos), is employed to make quarterly visits to the project providing assistance, advice and solutions on specific issues related to the design, construction, cost control and safety.

Finally, monitoring work is awarded to independent specialists for all critical tunnels. Lately, excavation lines and shotcrete profiles (in different construction stages) are also taken by an independent specialist in order to check quality of the work, conformance to the specifications and for record purposes measurements.

CONSTRUCTION COST

Though less than 7% of the overall length is carried through tunnels, their cost amounts to 38% of the total cost. The average construction cost for Egnatia Motorway tunnels is €21,000/m (per bore) incl. VAT, (after adjustment of results for the 1st trimester 2005 using the annual average rate of change in the harmonized indices of consumer prices reported by Eurostat). Figure 6 demonstrates the cost distribution of constructed tunnels (all works and contractor's profit included).

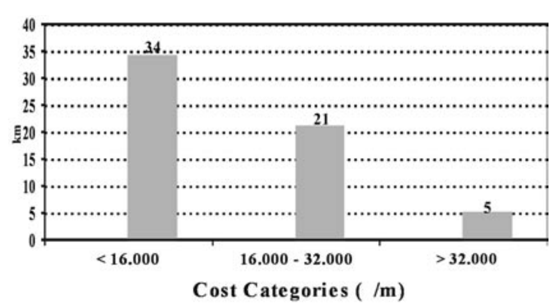


Figure 6 – Cost distribution of bored tunnels

The most significant component to tunnelling costs is the cost of underground excavation and support, which depends on the geological-geotechnical and geomechanical conditions of the rock mass; it ranges from 62 % to 73% of the total tunnel construction cost. The cost of the final concrete lining is on average around 17% of the total cost, while 14% of the cost is allocated to the electro-mechanical and telematics installation required for the safe tunnel operation. The cost of construction of the tunnel portals, cross-passages, ventilation shafts and pavement account for the remaining 7% (Figure 7)

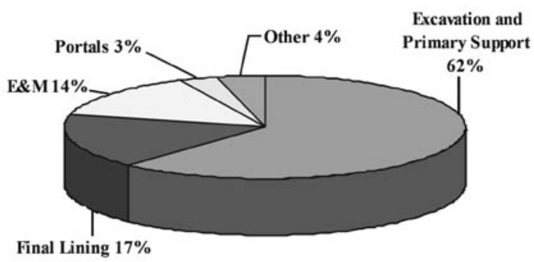


Figure 7 – Total cost breakdown

The cost of underground excavation and primary support installation varies significantly according to the corresponding rock mass and the degree of excavation difficulty. It has been found that the cost is inversely proportional to the rate of excavation, as the poorer rock class requires the installation of forepoles and more rock bolts, shotcrete and steels sets (Table 3).

Figure 8 shows how the cost of the excavation and primary support of Egnatia Odos tunnels varies according to GSI values of the corresponding rock mass. This curve is a result of a statistical analysis of the cost of tunnel excavation and support for 23 completed twin tunnels. For weak ground with low GSI values where heavy forepoles (Φ114) are generally employed, the cost might reach 300 €/m³. This cost greatly diminishes with higher values of GSI that require lighter support measures.

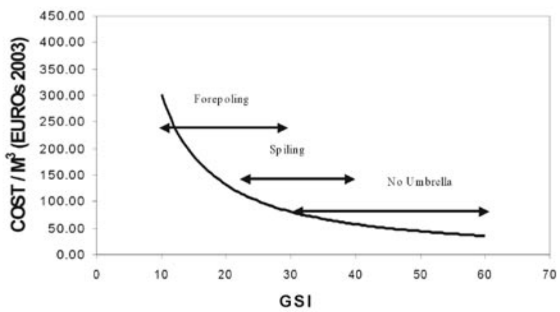


Figure 8: Tunnel excavation and primary support cost versus GSI

CONTRACTUAL ISSUES

In the mid '90's, design and build was the general tendering strategy for the Greek Ministry of Public Works. EOAE's early contracts inherited this method for the tunnelling works, as a part of larger motorway contracts. Lump sum prices for the underground excavation and primary support were given with very high price discounts. This, together with some poor final designs and a general low level of experience, led to contractual difficulties, delays

Table 3 – Indicative Production Rate and Cost for the Excavation and Support of a Tunnel

Rock Mass Class	Rate of excavation (m/day)	Cost (excl. VAT) (€ /m)
A	7-9	3200-4000
B	5-7	4100-4600
C	3-5	4400-5000
D	2,5-3	5200-7000
E	1,6-3	8000-17000

and additional costs.

EOAE then decided to return to the traditional method of procurement and to complete the detailed design before tender and award 'construct only' contracts. Public Works contracts in Greece are usually tendered on discounts against a pre-determined detailed works price list. They incorporated payment per linear meter of tunnel excavation per category of primary support together with unit prices for all other works carried out. The existing rates for the 'heavier' support category favoured the contractor's profit margins and therefore led to extensive disagreements on site with disputes over who would take the underground risk. Claims for overbreak, highly variable/unforeseen ground conditions, new rates, squeezing ground, steel-fibre reinforced shotcrete, contractor's proposals for methods to suit their equipment etc. also arose. Although results and progress was much better, it was clear that there was room for further improvement.

Recently, a series of contracts has been awarded for the 35km mountainous section from Panagia to Grevena (West Macedonia), with an overall tender budget of €500 M. With 13 twin tube tunnels, ranging from 300m to 2,600 m in length and with a total length of bore of 22,160 m, the tunnels proportion of the cost amounted to approximately €300 m and therefore comprised the major element of the contracts. Once again, due to changes in procurement law, Greece is experiencing a period of high tender discounts, which is indicative of tight margins for the contractors; the lowest bids for this section ranged between 26% and 32%.

It was essential, therefore, to ensure that the pricing strategy for the tunnels was realistic and controlled. In preparing the tenders, a new price list was produced, based on a detailed critical value management analysis of the tunnels already completed. After study of the geotechnical conditions, the height of overburden, the excavation step, the thickness of shotcrete and the steel sets, five standard support categories were selected. The underground excavation and primary support elements were broken down into primary functions of materials, labour and plant, the effects of cycle times was factored in, and the combined results used in the creation of new rates. With a tendency towards lighter, faster methods attracting profit through more efficient production rates, the intention has been to encourage greater productivity and improve the clarity of procedures and ease of communications between the contractors, the designers and the site supervision team.

Based on the above, a new Price List for tunnel tendering was developed which included both prices per tunnel linear meter T_i for each excavation and primary support category and Unit prices Ei for all construction elements used.

Specifically, $T_i = C_i + P$

where: C_i is the "core" cost per linear meter for each excavation and primary support category. It refers to the basic geometrical features, i.e. it corresponds to the maximum excavation volume, the maximum volume of shotcrete applied and all defined elements of the primary support (steel sets and anchors – rockbolts). In a few cases only ("high risk" conditions) it refers also to the pre-reinforcement elements above and ahead of the excavation face (forepoles, spiles, face anchors, face shotcrete) as well as to the works for foundation improvement of the primary support shell (e.g. micropiles). C_i is the "inelastic " part of every excavation and primary support category cost.

P is the Contractor's profit for all excavation and primary support categories. The Client accepts the Contractor to profit a reasonable percentage of the total "core" cost (ΣC_i) of every tunnel. P is the quotient of the division of this total profit for each tunnel by its length. Therefore, the Contractor is not disadvantaged in terms of direct profit regarding the excavation and primary support category, whereas the total cost for the Owner is minimized.

Furthermore, when "lighter" excavation and primary support categories from those of the design are used, the time schedule of the project is shortened, resulting in increased indirect profit for both parties involved. Additional "potential" profit for the Contractor can also be derived from the accuracy achieved regarding the excavation lines, since Ti includes a certain accepted "over excavation" and respective shotcrete quantity

E_i includes activities for:

* Prereinforcing above and ahead of the excavation face (forepoles, spiles, face anchors, face shotcrete),
* Improving the foundation of the primary support shell (micropiles),
* Dewatering (drainage holes).

The real need (number, arrangement) for these elements can be specified only on site by evaluating the real geological – geotechnical conditions of the exposed excavation face in relation to the monitored behaviour of the underground rock mass. Their use delays production and results in cost and time increases. Therefore, they have been strategically characterized as "not attractive" with the scope to use only the "necessary" quantities and no profit was assigned to them.

Further to reducing the cost of tunnel excavation, the aim of this new pricing strategy is also to minimize the number and magnitude of claims.

TECHNICAL CHALLENGES

In the design and construction of Egnatia tunnels a number of technical challenges were met. Difficult ground conditions were overcome by using advanced tunnelling techniques.

Tunnels in Karst Ground

"Dodoni" tunnel is a 3.6 km-long twin tunnel with cross passages located every 350 m and parking areas every 1000 m. It is located in the province of Epirus near the ancient Dodoni Theatre.

The tunnel was driven in the limestone series of the Ionian Zone as a full-face excavation with the support being adjusted to suit the rock mass categories encountered. The main technical problem during the excavation of this tunnel related to the karstic voids found along its length. Significant collapses occurred, one of which holed through to the surface 80 m above the tunnel and created a crater of almost 8m diameter.

To deal with the situation, a systematic program of probe drilling 25 m ahead of the face was put in place. The support measures designed to confront these geological conditions incorporated heavy duty forepoles, to pre-reinforce the tunnel excavation front with diameters ranging from 51mm up to 154mm. The selection of the support type was based on the evaluation of the probe drilling results in terms of the geometry of the void and the infilling material.

The tunnel is currently open to traffic after 4 years of construction.

Tunnels In Running Ground

Tunnel "S1", in Epirus, was excavated in a limestone formation with different degrees of brecciation. This carbonate formation suffered extreme tectonic events such as large scale overthrusts and faulting. Occasionally, during the excavation of the tunnel this formation was found as a powder-like material leading to unstable ground conditions. To deal with this extreme variation of the rock mass conditions the primary support measures incorporated pre-reinforcement of the ground ahead of the tunnel face, using forepoles in conjunction with grouting.

Tunnels In Squeezing Ground.

"Driskos" Tunnel, the longest Egnatia Odos tunnel

(4.6 km) located in Epirus, experienced squeezing ground conditions during the excavation of the top heading in an area of a faulted siltstone under an overburden of 220 m.

The support measures that were implemented aimed at preventing the ground movements anticipated during the bench excavation in the difficult area. Initially, 18 m long prestressed anchors were placed in the top heading. Other measures included: installation of an additional 80 mm layer of reinforced shotcrete; removal of temporary filling material below the temporary invert of the top heading; removal of the temporary invert of the top heading and bench excavation in short lengths of 1 m; immediate installation of HEB 160 steel set and 250 mm of shotcrete in the bench invert and 200 mm (8 inch) in the side walls; installation of 9m (9.84 yd) long rock bolts every 4 m of bench excavation in the pillar side walls and 6m long rock bolts in the other side walls; the installation (once ground deformations has ceased) of the final lining. The meter by meter excavation and the immediate closure of the permanent invert led to the successful completion of the tunnel construction.

“Anthochori” Tunnel is also located in Epirus. It is almost 700 m long under an overburden of 70 m. The majority of the Anthochori Tunnel was excavated in a tectonic melange comprised of sheared and folded siltstones in a chaotic structure. No specific orientation can be determined in the tectonic melange and a significant proportion of the siltstone has been transformed to a plastic material, particularly along the shear zones. Sandstone boulders of various sizes and different proportions are found within the melange. Intact sandstone boulders from 1 m to 2 m across were encountered as well as boulder masses covering the whole tunnel excavation face.

The geomaterial was soft and in some cases it could be moulded by hand. In this area the tunnel suffered severe deformations in the order of 300 mm, that led to damage of the shotcrete support, buckling of the steel sets and overstressing of the installed rock bolts. To tackle the most extreme conditions the tunnel design adopted a stiff support system comprising of 400 mm thick shotcrete shell, reinforced with steel fibres and heavy steel sets (HEA 240) with forepoles. The whole construction sequence was carefully designed so that the distance between the top heading excavation face and the closing of the permanent invert (including the final concrete) would never surpass 24 m. Again the principle that was followed during construction was the immediate closure of the permanent invert constructed by cast steel reinforced concrete.

Shallow Slope Tunneling

Tunnel “Kastania 3” belongs to a mountainous 26Km section of the motorway which has been open to traffic since December 2004. It is categorized as a “shallow slope tunnel” as it is relatively short (the left bore has a length of 202 m and the right bore 260m), the overburden is limited to 30 m and it traverses a narrow segment of a hill.

The anticipated rock formations were thin to medium bedded limestones with phyllite intercalations and characterized by an extremely blocky to crushed structure with medium to heavy weathering.

Underground works started in the autumn of 2000. However, following excavation of the first 40m of the top heading problems occurred which were made evident by the formation of cracks in the ground surface above the top heading excavation area and in the primary support shotcrete shell.

It was first thought that the cracks were related to the shallow overburden and it was decided to continue the excavation of the top bench in a series of straight lines supported by cast in-situ concrete using temporary shutters followed by normal excavation to the final invert. Breakthrough of the complete section of the left bore was achieved in the autumn of 2001. At this stage 70m of bench and final invert excavation remained in the right bore. However, at that time, heave and crack failure occurred in the final invert of the first 70m of both bores accompanied by further cracks in the upper shell.

Work stopped and after further geotechnical and geological studies, including a study of the stability of the hillside, the failure was considered to be the result of a very old landslide. The material properties were reassessed, and using a decreased value of the elasticity modulus of the rockmass of E ' = 300Mpa a design solution for the strengthening, repair and completion of the tunnel was prepared. This was as follows:

Surface works

* Construction of a pilewall uphill from the tunnel.
* Construction of a pilecap to link the piles and ensure they act monolithically

* Installation of prestressed (to 60t) anchors in the pilecap.

Underground works

* Strengthening the tunnel's surrounding rockmass using the tube-à-manchette grouting technique.
* Installation of prestressed (to 60t) anchors in the uphill face of each tunnel tube.
* Remining the whole tunnel section of the first 70m of both bores to achieve the required tunnel profile.
* Excavation of the remaining part of the bench and invert in the right bore.
* Construction of the final lining.

The cost estimation for this solution was €9 million and the time duration 18 to 20 months.

In view of the cost and time anticipated for the work, EOAE decided to proceed to a gradual application of these measures with continuous reappraisal of both the stability situation and the design solution. The strategy established was as follows:

* A limited ground investigation programme was approved.
* The worst affected area of the right bore was selected as an experimental field to test the application of the proposed grouting technique.
* An independent specialist (GEODATA GmbH) was selected to set up a comprehensive precision monitoring programme.

This strategy was successful and led to the following conclusions and savings:

* The average estimated value of the elasticity modulus of the rockmass was 600 MPa.
* The application of the tube-à-manchette technique was not appropriate and open hole grouting technique should be applied.
* The continuous evaluation of the precision monitoring results allowed decisions to be made that in turn resulted in a significant reduction of the strengthening works, including, elimination of almost half of the original proposed prestressed anchors from within the tunnel bores, aborting the remining works in the sidewalls and the crown of the tunnel bores and minimization of the support measures for the part (bench and invert) remaining to be excavated in the right bore.

As a result, the cost of all the strengthening works was reduced from €9 million to €5 million and the construction time from 18 months to 11 months.

CONCLUSIONS

In its short existence as a project specific client organization, EOAE, along with its project and construction management consultants, has developed management techniques, design standards, construction specifications and supervision expertise for the design and construction of tunnels. Its unique experience has been shared with Greek design firms and construction companies, thus elevating the national tunnel construction experience to international standards.

The advance construction management techniques provided successful solutions to the technical challenges encountered, kept the cost of tunnel construction within acceptable limits according to international standards and raised safety standards significantly.

The success of EOAE has been recognized by both the Greek Government and the European Union, co-financiers of the project. The Ministry of Public Works has adopted EOAE's design standards and construction specifications and tender documents. The Greek State and the EU have now provided full funding for the completion of Egnatia Odos motorway as cost savings and on schedule absorption of previous funding have proved that EOAE is capable of completing major infrastructure projects within time and budget.

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Appendix 1: Egnatia Motorway Twin Tunnels

Section	Tunnel	Average Length (m)	Construction Method	Status	Ground Conditions
West Region					
1.1.3	Vassiliko 1	505	Bored	Open to traffic	Limestone
1.1.3	Vassiliko 2	250	Cut-and-cover	Open to traffic	Limestone
1.1.4	Mesovouni	450	Bored	Open to traffic	Flysch/Limestone
1.1.4	Grika	685	Bored	Open to traffic	Dolomitic limestone

1.1.5	Neochori	530	Bored	Constructed	Limestone
1.1.6	S1	430	Bored	Under construction	Brecciated limestone /Flysch/ Evaporite
1.1.6	S2	1000	Bored	Under construction	Brecciated limestone /Flysch/ evaporite
1.1.6	S13	150	Cut-and-cover	Open to traffic	Brecciated limestone
1.2.2	SN1	580	Bored	Open to traffic	Sandstone flysch
1.2.3	S2	800	Bored	Under construction	Colluvium sandstone/ Siltstone flysch
1.2.3	S3	400	Bored	Constructed	Limestone
1.3.2	Dodoni	3600	Bored	Open to traffic	Limestone
2.3	T1	210	Cut-and-cover	Under construction	Flysch
2.3	Driskos	4570	Bored	Constructed	Sandstone/Siltstone flysch
2.3	T6	100	Cut-and-cover	Under construction	Flysch
2.4	T6	290	Bored	Constructed	Flysch
2.4	T8	2600	Bored	Under construction	Flysch
3.1	S1	270	Cut-and-cover	Constructed	Flysch
3.1	S2	145	Cut-and-cover	Constructed	Flysch
3.2	Anthohori	690	Bored	Constructed	Siltstone flysch/Thrust zone—chaotic
3.2	Votonossi	510	Bored	Constructed	Sandstone flysch
3.2	Dio Korifon	735	Bored	Constructed	Sandstone flysch
3.2	Kriminou	1080	Bored	Constructed	Sandstone/Siltstone flysch
3.2	Kalamion	790	Bored	Constructed	Sandstone flysch
3.2	Agiou Nikolaou	365	Bored	Constructed	Sandstone/Siltstone flysch
3.3	Anilio	2135	Bored	Under construction	Flysch—sheared thrust zone, red shale
3.3	Metsovo link	450	Bored	Constructed	Flysch
3.4	Metsovon	3550	Bored	1st Bore Constructed 2nd Bore Under Design	Ophiolite/Flysch thrust zone
3.5.1	Malakasi A	245	Bored	Constructed	Ophiolite
3.5.1	Malakasi B	300	Bored	Constructed	Ophiolite
3.5.1	Kostarakos	685	Bored	Constructed	Ophiolite
3.5.2	Malakasi C	165	Bored	Constructed	Ophiolite
Total No of twin tunnels: 26 bored and 6 cut-and-cover Total length of twin tunnels: 28.14 km bored and 1.12 km cut-and-cover					

Central Region					
4.1.1	Panagia	2615	Bored	Under construction	Ophiolite
4.1.1	Sirtou	1485	Bored	Under construction	Ophiolite/Limestone
4.1.1	Agiou Triados	270	Bored	Under construction	Ophiolite
4.1.2	Agiou Paraskevi	440	Bored	Under construction	Ophiolite/Molasses/ Sandstone/Marl
4.1.2	Agnanterou	670	Bored	Under construction	Molasse
4.1.2	Prionia	745	Bored	Under construction	Molasse
4.1.2	Velanidion	600	Bored	Under construction	Molasse
4.1.2	Nika	420	Bored	Under construction	Molasse
4.1.2	Lagadia	375	Bored	Under construction	Molasse
4.1.2	Zigra	340	Bored	Under construction	Molasse
4.1.2	Kilomatos	990	Bored	Under construction	Molasse
4.1.2	Karatza	675	Bored	Under construction	Molasse
4.1.3	Venetikou	655	Bored	Under construction	Molasse
4.2.2	Taksiarches	260	Bored	Open to traffic	Molasse
5.1	S10	2250	Bored	Open to traffic	Gneiss/Granite
5.1	S11	460	Bored	Open to traffic	Gneiss/Granite schists
5.1	S12	500	Bored	Open to traffic	Gneiss/Granite schists
5.1	S13	780	Bored	Open to traffic	Gneiss/Granite schists
5.1	S6	160	Bored	Open to traffic	Gneiss/Granite schists
5.1	S7	335	Bored	Open to traffic	Gneiss/Granite schists
5.1	S8	100	Cut-and-cover	Open to traffic	Gneiss/Granite schists
5.1	S9	180	Cut-and-cover	Open to traffic	Gneiss/Granite schists
5.1	S14/S15	170	Cut-and-cover	Open to traffic	Gneiss/Granite schists
5.2	S1	830	Bored	Open to traffic	Limestone/Sandstone / Siltstone/Phyllite
5.2	S2	365	Bored	Open to traffic	Limestone/Phyllite
5.2	S2.1	200	Bored	Open to traffic	Limestone/Phyllite
5.2	S3	210	Bored	Open to traffic	Limestone/Phyllite
5.2	S4	200	Bored	Open to traffic	Old debris flow material gneiss phyllite
5.2	S5	170	Bored	Open to traffic	Gneiss/marble/Limestone
11.1	Vrasna	160	Bored	Constructed	Gneiss/marble/ Limestone
Total No of twin tunnels: 27 bored and 3 cut-and-cover Total length of twin tunnels: 17.16 km and 0.45 km cut-and-cover					

East Region					
11.3	Asprovalta 1	240	Bored	Open to traffic	Gneiss
11.3	Asprovalta 2	185	Bored	Open to traffic	Gneiss
11.3	Asprovalta 3	200	Bored	Open to traffic	Gneiss
12	Paggaion	1100	Bored	Design	Gneiss/Granite marble
13.2	Palio	235	Bored	Open to traffic	Gneiss/Granite
13.2	C & C 7	180	Cut-and-cover	Open to traffic	Gneiss/Granite
13.3	C & C 9	230	Cut-and-cover	Open to traffic	Gneiss/Granite
14.1.1	Kastro	200	Bored	Constructed	Limestone/Marble
14.2.1	Nestos	300	Bored	Under construction	Marble/Limestone /Gneiss
Total No of twin tunnels: 7 bored and 2 cut-and-cover Total length of twin tunnels: 2.46 km and 0.41 km cut-and-cover					

Total No of twin tunnels along the axis:	60 bored and 11 cut-and-cover
Axis total length of bored twin tunnels:	47.76 km and 2 km of cut-and-cover