EGNATIA MOTORWAY CONCRETE BRIDGES

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1.0 Introduction

The successful growth of the European Union's single market is inextricably inter-linked with the completion of the Trans-European Network for Transport, which consists of road, rail and maritime transportation infrastructure networks as they are essentially the blood lines to developing new markets. The Trans-European Network for Transport is expected to enhance the European economy by ensuring less expensive, more efficient and safer travel within the European Union and by building bridges towards the markets of Eastern Europe and the Middle East [1].

The objectives of the common transport policy of the European Union are to achieve sustainable mobility and interoperability in the Trans- European Network in order to assist in achieving the European Union's goal of economic and social cohesion. Sustainable mobility is achieved through the minimization of congestion on European networks, which allows a faster, more economical and environmentally friendly operation of transport modes. This is achieved, not only by improvement of each mode of transport with investment in infrastructure construction, but also by enhancing the interoperability between transport modes through ease of transfer and reduction of waiting time at interface sites, thus promoting the use of more than one mode of transport over a single journey [2].

It is within this aspect of interoperability between modes, which has contributed to the importance of Egnatia Motorway, the 670 km Motorway running through Northern Greece, so as to be included in the European Union's fourteen priority projects. Egnatia Motorway was completed in May 2009, thus linking the port of Igoumenitsa in the west to the Greek - Turkish borders in the east and via its vertical axes to the other Balkan countries and hence facilitating maritime and land transport links from Western Europe to the countries of South-East Europe and the Middle East. It took nearly 30 years from the conception of the project to final completion for the Greek Government to surpass all technical, socioeconomical , financial and political obstacles to final complete this much needed major infrastructure project in Northern Greece.

The idea of constructing a major motorway in Northern Greece emerged in the 1970's, when the first design contracts for reconnaissance and preliminary highway studies were awarded. The 94 km (out of a total 670 km) of the motorway, that were designed and constructed before 1994 by the Greek Ministry of Environment, Planning and Public Works (MEPPW), were financed purely by government funds, which at that time was both limited and erratic. The nearly 20 years required for only 14 percent of the axis to be completed indicated the need for upgrading the quality and efficiency of the design and construction management process for public works in Greece.

The effect of the European Union Community Support Fund on the infrastructure planning philosophy in Greece was significant because, for the first time in its history, the Greek government was allowed the agility to make long term plans for the construction of necessary infrastructure projects as funding could be secured. The €5.9 billion required to construct the remaining 576 km of the main axis was provided from the 2nd and 3rd European Union Community Support Fund, national funds, the European Investment Bank, the Trans-European Network Community Budget and the Regional Operational Programmes for Epirus, Central Macedonia and East Macedonia & Thrace. The successful management of such complicated projects as Egnatia Motorway, in order to meet funding targets, necessitated the structuring of new, flexible and modern managing units. For this reason, Egnatia Odos A.E. (EOAE) was established in September 1995 to manage the design, construction, maintenance, operation and exploitation of the Motorway, while the Greek MEPPW remained as the single shareholder of the company. In the fourteen years of its existence, the management of EOAE has succeeded in amalgamating the science of engineering and the art of management to produce a structural organization successful in realizing a state-of-the-art motorway project that has already began accelerating significantly the development of Northern Greece, linking peripheral regions to the heart of the European Union and opening Europe to the neighbouring countries [3].

The paper presents the following issues relating to the design, construction and maintenance of Egnatia Motorway Concrete Bridges:

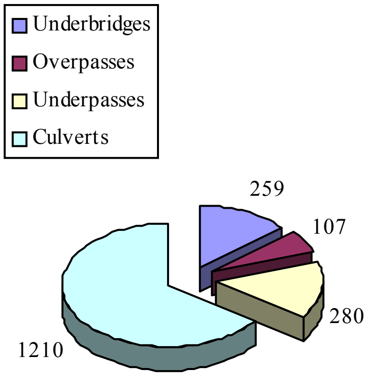
- The management systems for the design phase, including procedures for the award of design contracts, internal review and external independent checking of the procured designs.
- The project monitoring systems employed to provide immediate access to design information and facilitate effective planning of the works, as well as the Quality Assurance System used to ensure that the quality of the bridges meet state-of-the-art standards.

- A statistical analysis of the cost of construction of Egnatia Motorway bridges per construction method and deck area. The cost data analysed is from on-site actual cost information provided by surveyed quantities and unit rates from construction contracts having considered revision of prices due to inflation, contractor's overheads and profit.
- The technical characteristics and material quantities of three dual carriageway two span twin leaf balanced cantilever bridges, as well as four multispan balanced cantilever bridges constructed along Egnatia Motorway

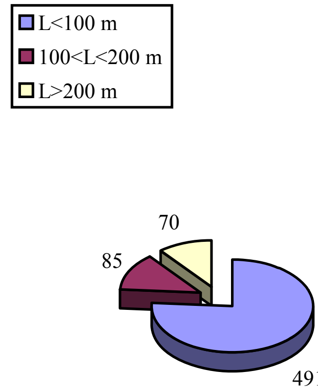
2.0 The Bridges Along Egnatia Motorway

The Motorway was designed and constructed as a 670 km long high-speed motorway of high standards consisting of a dual carriageway with hard shoulders having a combined dual carriageway width of 24.5m for most sections and 22m for difficult mountainous areas. It includes 50 grade-separated interchanges, 2 x 50 km of tunnels and 2 x 40 km of bridges.

The 40 km of bridges represent nearly 6 percent of the overall length of the Motorway. There are approximately 1856 highway structures (including 646 bridges) on the main axis with lengths varying from tens of meters to just over 1 km, which represent 20 percent of the total construction cost of the Motorway. Of these, 119 are twin bridges (2 x 119), while the remaining 408 are single bridges of either dual carriageway cross-section carrying Egnatia Motorway or varying cross-section overpasses carrying local roads. Figure1a depicts the break down of all structures between structural types, while Figure 1b focuses on the length distribution of the bridges. The Motorway runs through various mountain ranges and valleys necessitating the construction of a number of major bridges with relatively tall piers and/or long spans/lengths. Arachthos Bridge with a length of 1036m is the longest bridge on the main axis, whilst Metsovitikos and Votonosi Bridge with the main spans of approximately 235m are among the longest span balanced cantilever bridges in Europe



a. Type of structures



b. Length distribution of bridges

Figure 1 – Structures of Egnatia Motorway

2.1 Bridge Construction Methods

All bridges on this project are constructed using reinforced or prestressed concrete for a number of reasons such as low cost, excellent durability, and easy maintenance. Various bridge forms, deck types and construction methods are utilized for the procurement of the bridges. These include voided slabs, box girders, precast beams, balanced cantilever, incremental launching and travelling formwork. The maximum span and pier height per construction method is shown in Table 1.

Table 1 *– Maximum spans and pier heights of Egnatia Motorway concrete bridges*

Construction Method	**Max. Span (m)**	**Max. Pier Height (m)**
Traditional scaffolding	65.0	17.0
Precast prestressed beams with continuity slab	43.0	61.0
Incremental launching	45.5	27.0
Travelling formwork	55.0	30.0
Balanced cantilever	235.0	105.0

Precast beams are the most widely used method for deck construction for medium spans of up to 45m, as they have been proven to be both fast and cost effective. Traditionally, bridge decks consisting of precast beams have been built in Greece without the continuity of the in-situ top slab over the piers. However, the existence of numerous expansion joints has resulted in maintenance problems and has adversely affected ride-ability. In order to avoid such shortcomings, precast beams in combination with continuous in-situ top slabs are used for Egnatia bridges. Egnatia Motorway contractors construct the precast beams, whether post-tensioned, pre-tensioned or reinforced concrete, on site rather than in the factory and for bridges with relatively tall piers the precast beams are placed by means of mobile cranes.

For bridges of spans up to 55m, where access for mobile cranes is limited, other types of construction, e.g. incremental launching and travelling formwork, have been chosen as alternatives to the precast beam method. For ravine bridges the method of in-situ balanced cantilever construction has been employed where necessary, due to topography or geotechnical reasons, to reduce the number of piers by increasing the span length significantly, typically in the order of 100m. The method of precast segmental balanced cantilever construction, despite its speed of construction, is not utilized on this project, due to the fact that this method is not yet permitted by the German DIN Standards.

Where decks are constructed using precast beams, the beams are supported by the piers via crossheads and bearings, while in in-situ concrete deck construction, the piers are usually built into the deck. Piers of overpasses and the shorter piers of underbridges have been designed as solid rectangular or circular cross sections. Rectangular hollow sections are used for the construction of most tall piers on this project, as a result of their economy and the fact that they maximize the structural efficiency in terms of stiffness/mass and strength/mass ratios. In a few cases, double leaf piers, which provide greater flexibility than hollow sections, have also been utilized for construction of tall piers.

2.2 Bridge Design Consideration

The minimum specified design life for the structural elements of all bridges is 120 years. Meeting this target in Greece, the highest seismic area in Europe, where approximately half of the annual seismic energy of the continent is released, requires conservatism in the design and more stringent quality control measures during construction. Earthquakes in Greece are typically shallow with focal depths of less than 18 km and magnitudes up to 7.5 on the Richter scale. Egnatia Motorway traverses through zones I, II, III of the Greek seismic map with corresponding peak ground acceleration of 0.12g, 0.16g and 0.24g. In accordance with the current Greek legislation, bridges are designed based on the German DIN Standards, except for seismic loading where the Greek standards are utilized and which refer to the European Standards (i.e. Eurocodes). The majority of Egnatia Motorway bridges are designed to behave elastically during an earthquake, but in the case of major bridges this leads to exorbitant expenses and/or impractical detailing. As a result, major bridges are designed with inherent ductility in order to dissipate the imparted seismic energy[4].

In carrying out feasibility studies to assess the viability of the construction of transport infrastructure projects, apart from initial design and construction costs, whole life costs and environmental impact are also considered. Whole life costs encompass inspection and maintenance costs, repair costs, possible required strengthening operations costs due to increased loading, as well as possible bridge modification or even replacement costs due to required widening to accommodate future increases in traffic loads. In Greece, as in other earthquake prone areas, the cost of damage inflicted on the bridges by earthquakes and additional costs related to resulting traffic disruption are also considered in the calculation of the whole life costs leading to conservative structural systems.

The engineering awareness in improving bridge appearance, hence minimising the adverse impact to the surrounding environment, is increasing at least in developed countries. Within the boundaries of this project, which crosses 250 sites of historic importance, 17 areas of the Natura 2000 European Network, 4 Ramsar International Convention Wetlands and about 70 areas protected by the Forest services for the development of wild Fauna, the special attention given to the visual appearance of the bridges and the selection of the construction method is well justified. Standardisation of the designs, construction of decks with variable depth, increase in bridge slenderness, reduction in the number of piers and expansion joints, as well as the use of high strength materials endeavours to enhance the aesthetics of Egnatia Motorway concrete bridges.

3.0 Design Management Techniques

3.1 EOAE Design Management Process

The general alignment of Egnatia Motorway had been laid out by the MEPPW prior to hand over to EOAE in February 1997. Numerous sections, especially in the East Region had been completely designed and construction was underway before EOAE took over, while 94 km had been completed. While keeping to the general alignment and following detailed reviews of the designs handed over by the Ministry, EOAE completed the definitive designs for many sections, but in quite a few cases the designs had to be revisited due to lack of geotechnical designs and/or availability of new information. In the region of Epirus, nearly 60 km of the original MEPPW designed motorway were realigned to cater for dual instead of single carriageway construction. Other sections have been realigned in order to achieve more cost effective solutions. Throughout its life, EOAE's design department’s engineering staff was responsible for managing over 1000 design contracts and carrying out nearly 15000 technical reviews. These figures alone demonstrate the necessity for developing acceleration methods for the award, design and checking procedure and building a flexible organizational structure.

3.2 Fast Tracking Design procedures

(a) Design Guidelines and Standardization

An early requirement for the design department was the production of a design standards manual incorporating the latest standard details and design specifications. To this end, standardised Design Guidelines, the OSMEO were created. This two-volume document contains among others information on criteria, specifications, design stages, deliverables per stage for all types of designs relevant to construction of the project. The OSMEO is a standardised and controlled document under constant review. The application of OSMEO permits maintenance of uniform standards throughout all designs, as compliance of designs with OSMEO is obligatory and any deviation there from must be justified and approved. In addition to OSMEO, another standardised document, the OSAT was developed, which contains the design and construction requirements for environmental protection and restoration. This document is the first of its kind nationwide and was developed in order to set guidelines for all environmental issues at the time when the first environmental protection laws came in to force.

Throughout the entire length of Egnatia Motorway, 1100 culverts of less than 6 m spans and numerous retaining walls are being constructed. Even though these structures do not present significant technical difficulty, they are key to maintaining good progress during construction as their completion is always at the top of the overall construction schedules. In order to accelerate the design procedure of such structures, standard culvert designs and retaining wall designs were created. These standard designs have greatly reduced the required design and review time, as the adaptation of the standard design to local conditions is the only requirement and checking of this adaptation is carried out by the Construction Manager on-site, allowing the approval procedure to be completed quickly and detailed drawings for construction to be readily available.

The OSMEO and OSAT design guidelines and the standard designs for culverts and retaining walls permitted a systematic approach to defining detailed Scopes of Works for designers, which simplified the approval procedures, as all engineering staff were trained to review submissions based on the requirements defined in the Scopes of Work and the guidelines. The success of these documents has been acknowledged by the Greek Ministry of Public Works and they are now national design guidelines.

(b) Award procedures

Due to the strict time schedules in order to meet targets set and funding constraints, international competitions were held for a series of call up contracts for all eight disciplines to minimize the time required for contract award for both the above procedures. In this way, following one major competition for each discipline, required design activities are assigned to those designers with relevant call up contracts via work instructions, thus saving a significant amount of time and allowing instant responses in case of emergency.

(c) Accelerating Geotechnical Investigation Procedures

The initial stage of the design of a section of the motorway includes the execution of complete geotechnical investigations and evaluations of the results for the determination of the required ground parameters for the design of the foundations of structures, the definition of gradients for cut and fill slopes, the determination of the quality of pavement foundations and the definition of the attributes of any required borrow materials. Therefore, an essential part of the design procedure is the planning, execution, supervision and evaluation of geotechnical investigations carried out by geotechnical contractors. This stage of the design process had proven to be significantly time consuming in the early years due to delays in the availability of drilling rigs as a result of lengthy contractual procedures, bad weather conditions or lack of proper supervision. To improve on this situation, a system was developed by which the drilling of boreholes and lab testing is carried out by geotechnical contractors based on programmes designed and supervised by geotechnical designers.

3.2. Design approval procedure

The reviews of submitted designs carried out by the Design Department's staff or external design managers (EDM) ensure that the OSMEO Guidelines are adhered to, the relevant codes of practice are employed and sound engineering principles are implemented with durability, future maintenance and whole life cost in mind.

EOAE employed national and international design firms with sufficient experience commensurate with the work to be checked, to carry out detailed checking of bridge, non-standard culvert and tunnel designs i.e., to evaluate design assumptions, calculations, computer model simulations and detailed construction drawings.

Each detailed design to be implemented for construction was also reviewed by the Construction Manager with respect to constructability, actual site conditions, cost and time implications and compliance with the technical conditions of the construction contract. In all cases, final approval of construction drawings was given by the Design Department and relevant Regional Project Managers.

As the scope of work for EOAE expanded from the management of the main axis to include the design management of its vertical axes and in order not to overburden the design department, it became necessary to temporarily outsource the technical and contractual management of the vertical axes designs. As a result, External Design Managers (EDM) were employed for the necessary management, technical reviews and preparation of tender documents.

Finally, a number of complex engineering difficulties due in most cases to geological – geotechnical situations have been overcome by seeking the advice of European and International experts, who have provided their expertise and technical know-how both in terms of design and construction, thus supporting technological transfer to domestic engineers.

3.3 Project Information System – Document Management

Among project management requirements is the implementation of methodologies for planning, scheduling and control. Though computers cannot replace attributes such as leadership abilities, communication skills and motivation, they can support many aspects of project management due to their capability to store, retrieve and process large quantities of data [5]. The Project Services department has developed a project information system as a tool for strategic management of the project, by which time schedules and budgets of design and construction contracts are monitored. In terms of design management, time schedules for every design contract are set up using Primavera Project Planner based on milestones delivery dates defined in the contract. All design schedules are linked together in the Master Schedule and are updated on a regular basis. This system provides clear, reliable and justified information to all management levels within the company, while allowing departures from the schedule to be spotted and remedied quickly.

Another significant information management system that has been developed to support resource management in the Design Department is the design submissions management system that is carried out by the Document Control Department. An electronic Document Management System has been developed to monitor the daily approval process. The software employed in this process is Expedition developed by Primavera Systems Inc. Every design submitted is logged on to the system via a unique box number in Expedition and then each stage is monitored until final approval. The document control system has achieved a paperless environment as all relevant documents (transmittal letter, review letter and decision letters) are attached to the unique box number allowing all engineers access to this information.

The Project Managers, the Design Manager and Discipline Heads are informed of every submission allowing planning of the work to be efficiently achieved. On a weekly basis, the Project Managers and the Design Manager are informed by Document Control of those submissions for which the review is outstanding. At any time the review/approval status of each study is controlled and delays in approval are avoided.

3.4 Design Quality Assurance

As part of the overall Quality Assurance System implemented, a series of 9 Operational Procedures and 5 Work Instructions govern the design management process within the Project Division. Both internal and external audits are carried out in order to verify the effectiveness of the Quality Assurance System. On a regular basis, internal auditors carry out audits within the Project Division while technical audits of the Design Department have been carried out by an independent International Consultancy firm.

All designers, advisors or consultants employed on work associated with design are required to use procedures in line with basic ‘good practice’ procedures and at intervals, consultants are audited by examining submissions and/or visiting the offices of the consultant to examine work in progress.

4.0 Project monitoring systems – Quality Assurance

4.1 Construction Management Systems

For management purposes the motorway was split into geographical regions. The Project Manager (PM) of each region, who signs all relevant construction contracts on behalf of EOAE, has the main responsibility to achieve time, cost and quality targets, and reports directly to the Project Director and General Manager. To manage and supervise works, the provisions of Law 1418/84 were adopted, as effective after the issuance of Law 3263/04, as well as the executive PD 609/85 and other similar decrees, and relevant provisions were incorporated with minor amendments in the Regulation for the Execution of Works of EOAE. Subsequently, using a tool adapted to the Community Directives and the Greek industry of public works, the implementation of works of the Egnatia mainline and vertical axes proceeded with no substantial administrative and legal problems.

The management of the construction contracts and supervision of construction was carried out by Regional Services based in Ioannina, Metsovo, Kipourio, Kozani, Thessaloniki, Kavala, Komotini and Komotini, who refered to one of the Regional PM’s. Between 1996 and 2004, day to day construction supervision on behalf of EOAE was carried out by Construction Management Consultants who were employed following international competition. In 2004, EOAE set up its own in-house Construction Management Teams (CMT) who gradually took over supervision of all works by January 2006, as a result of successful transfer of technology from experienced international Construction Managers to the developing industry in Greece.

The CMTs ensure that required construction quality standards are met by applying a specially designed Quality Assurance System for construction management and supervision which is included in the company’s Total Quality Management system and consists of a series of 34 Operational Procedures, evaluating, approving and auditing the Quality Management Systems implemented by the contractors, evaluating the Contractors’ laboratories and carrying out tests at independent laboratories at each stage of construction (soil tests, concrete cube strength etc.), checking the management of suppliers by the contractors,ensuring that all plant and equipment are properly maintained, checking and accepting “As Built” drawings, and keeping electronic data bases for all testing and auditing results. Both internal and external audits were carried out in order to assure quality standards are met. In cases where defective work is noted, these are not accepted and remedial works are ordered.

Bridge construction supervision was carried out by using Checking Guidelines which include check lists that allow systematic checking by the supervision and include critical check points at various construction stages. For bridge construction, guidelines for foundation excavation, pile construction, concreting, prestressing, tension grouting and backfilling are implemented. The described checks are carried out prior to accepting the completed work and signing of the relevant work acceptance forms which allow the contractor to proceed to the next construction phase. These guidelines all define the minimum checking frequency.

Finally, cost control and schedule monitoring are carried out by implementing the EOAE’s Project Management System. The activities for each project are broken down into a predefined work breakdown structure to which a duration and a contractual cost are attached. A schedule is set up using Primavera Project Planner at the onset and is updated periodically. A member of the CMT is responsible for updating the schedule on a monthly basis and preparing progress reports. Each project schedule is being linked to a Master Schedule which when completed will allow monitoring and reporting for the entire project.

4.2 Maintenance Procedures

Due to the lack of relative specifications in Greece, EOAE has developed its own guidelines for maintenance and operation of the motorway based on modern international specifications taking into consideration the particular characteristics and particularities of work. Those guidelines relating to the maintenance of bridges and structures are the guidelines for routine maintenance of the motorway, winter maintenance and operation of the motorway, The Guidelines for Motorway Routine Maintenance describe the requirements for maintenance of the road and its structures, the inspection techniques as well as the use of a Routine Maintenance Management System (RMMS), which is a computerised database that records all highway assets, inspection and maintenance data. The road elements that are subject to routine maintenance are a) pavements, b) central reserves, curbs and sidewalks, c) drainage system d) cuts and embankments e) landscape, f) safety barriers, g) signage, h) M&E installations and i) general road cleanliness. The manual describes the various types of structural inspections which will be required to identify any deterioration or visible signs of distress in structures or their elements.

Technical patrolling is carried out routinely on the motorway in order to determine the defects that require repair. Regarding the bridges, the key scheduled inspections are general inspections (every two years and generally made on foot without special means of access, but “invisible” areas such as bearings inspected every 6 years) and benchmark inspections (much less frequent, not less than 6 years and up to 20 years apart, which will involve close contact with the structure or selected elements).Individual planned programmes of maintenance work would normally arise as a re-sult of re-commendations made within reports from these inspections – both routine (each year) and capital (as required, e.g. bearings and expansion joints).

Winter maintenance refers to the required actions for dealing with ice and removing snow for the road surface. The organizational structure for winter maintenance on Egnatia Motorway relies on the snow plough depots which will operate at each Road Management Centres and salt refilling depots. The main winter maintenance actions are α) preventive maintenance b) snow ploughing and c) ice melting. The EOAE Winter Maintenance Guidelines provide detailed instructions for the required work, salt quantities, method of application to the road surface etc. Winter patrols and inspections are carried out in order to determine those sections of the road that require attention. Patrols are carried out whenever required while the inspections can be emergency or scheduled. Emergency inspections are carried out after emergency events while scheduled inspections are carried out once a year before the start of the winter season when the required machines and equipment are checked and personnel are evaluated.

It must be noted that EOAE outsources all operations and maintenance work by employing operations and maintenance contractors following international competitions. It is the responsibility of the maintenance contractors to apply the Maintenance Guidelines which in conjunction with EOAE’s Operational Procedures provide the framework for the optimum maintenance and operation of Egnatia Motorway.

4.3 Seismic Hazard Risk Assessment

Egnatia Motorway will be an important link in the European road network and will play a vital role in the socio-economy of the broader Balkan region. In severe natural disasters the motor-way will also act as a lifeline for supply of food, medicine and shelter for the communities in the region. In the event of major natural disasters the value of direct and indirect losses caused by the interruption in the transportation system in monetary terms could run into billions of Euros. It is therefore crucial to preserve, as far as possible, the continuity of the transportation service provided by this link in the aftermath of such events. Recognition of the potential loss of human life and the damage to the local and national economy has led EOAE to adopting the philosophy of preparedness for events such as earthquakes.

The damage to the road pavement can be readily repaired in such events and the disruption to the service would be minimal. This is not, however, so for bridges where a significant damage to, or collapse of a bridge will interrupt the traffic for a considerable time. Even with the best practice in design and construction severe damage to, or failure of, bridges in a major earthquake cannot be totally ruled out. This is evident from the recent earthquakes in North-ridge (USA, 1994), Kobe (Japan, 1995), Duzce (Turkey, 1999) and Chichi (Taiwan, 1999), where many bridges have suffered from significant damage and have even collapsed. A plausible prediction of the most likely extent of damage to the bridges of the motorway can lead to the determination of the weak sections of the link, and can help in planning alternative arrangements such as detours. To achieve this objective, EOAE has commissioned EQE International to develop a seismic hazard risk assessment software tool in order to:

- assess the vulnerabilities of bridges along the motorway,
- identify sections of the motorway most at risk from seismic events,
- assess the likely damage resulting from an earthquake scenario,
- assist in making emergency plans for the aftermath of an earthquake.

The software is compatible with EOAE GIS database and uses the standard GeoMedia tool-set. It utilizes various data including a seismic hazard model developed by ITSAK (Institute of Engineering Seismology and Earthquake Engineering) based in Thessaloniki, and a vulnerability function developed by Imperial College, University of London. The seismic hazard model provides frequencies of earthquakes of different magnitudes on a grid points around the broader Motorway area together with an attenuation relationship for northern Greece. The vulnerability function has been developed analytically for a typical three span bridge on the project with additional functions planned for development to represent other bridge types on the project.

5.0 Egnatia Motorway Bridge Construction Costs

The cost of construction of bridges varies depending on the bridge type, construction method used and site conditions (topography, foundation conditions, seismic risk, importance of the bridge itself). To demonstrate the variation between construction costs of bridges with different characteristics, information referring to 141 bridges stored in the Egnatia Motorway Structure's database was utilised. The database apart from technical characteristics of each structure included on-site input such as, surveyed material quantities, the contractual unit rates and final cost per work item. The cost records were re-valued to prices of the first quarter of 2009 using the annual average rate of change in the harmonized indices of consumer prices reported by Eurostat. The total construction cost of each bridge comprised of the cost of foundations, substructure, superstructure and accessories.

Foundation costs include the construction of the foundations of abutments and piers, temporary works including slope stabilisation/protection and soil improvement works, as well as earthworks and all works necessary to provide safe access to the construction site. Substructure costs include the construction of abutments and piers whereas superstructure costs refer to the cost of construction of the deck. Finally, under the term accessories, the cost of bearings, expansion joints, drainage system, guardrails, bridge waterproofing and asphalt layer, is considered. Analysis of the resulting data reveals (Figure 2) that for all construction methods, the cost of construction of the deck represented the highest proportion of the total cost ranging from 35 percent for precast beam bridges to 53 percent for balanced cantilever bridges. This variation in deck costs is justified by the fact that both longer construction periods and greater cross-section sizes are required for balanced cantilever bridges due to the significant increase in span lengths, while precast beams benefit from economies of scale due to repetition of beam elements. The next significant cost category was foundation costs, which ranged from 24 percent to 34 percent of the total cost of construction. Similar proportions (31 to 34 percent) were observed for all methods except for the balanced cantilever method, which is attributed to the reduction in the number of piers. Substructure costs ranged from 10 percent for bridges constructed using travelling formwork to 17 percent for bridges with precast prestressed beam decks, which can be attributed to the construction of six twin ravine bridges with relatively high piers [6]. The use of numerous bearings in the precast prestressed beam bridges resulted in the accessories representing 17 percent of the total construction cost, while on the other hand they represented only 7 percent for balanced cantilever bridges as bearings are used only at the abutments.

The results of the analysis of the available data showed (Figure 3) that the most expensive per square meter bridges on Egnatia Motorway are balanced cantilever bridges (1550 €/m2), while the least expensive are bridges built using traditional scaffolding (990 €/m2), as expected. Balanced cantilever bridges are justifiably the most expensive bridges as they are adopted to overcome the most difficult terrain constraints when large spans are unavoidable and hence require significantly greater section depths and pier heights. As a result, the deck cost of balanced cantilever bridges is directly proportional to the maximum span length. The most economical bridges carrying Egnatia Motorway over local roads, streams, rivers and valleys are bridges built using traditional scaffolding methods since the average height of the piers is approximately 10m. The bridges in this category include both reinforced and prestressed concrete bridges of various cross-sections, including solid slab, voided slab and box girders, all cast in-situ.

The remaining three construction methods are of similar average costs. Specifically, precast beam bridges have an average cost of 1030 €/m2 and those built using the travelling formwork technique cost 1050 €/m2, while the cost of construction of incrementally launched bridges is 1160 €/m2 on average. All three of these methods have been used on Egnatia bridges in order to cross deep valleys and ravines with maximum pier height of 61m. Specifically, precast beams have been implemented not only in situations where tall piers have been required but also in situations where speed of construction was an important factor. In investigating the difference between the average costs of incrementally launched bridges and bridges built using travelling formwork, it can be concluded that although the use of travelling formwork yielded greater deck costs, the overall cost per square meter can be significantly reduced when using this method for the construction of longer bridges with numerous repetitive span lengths.

The average overall cost resulting from the analysis of the available data on the cost of construction of Egnatia Motorway bridges is 1160 €/m2. From information presented in the literature [7,8] on the cost of construction of similar concrete bridges in Europe re-valued to current prices for a sample of 19 bridges, it can be found that the average cost per square meter of these bridges is 1430 €/m2. More specifically, from the analysis of the data available, the mean construction costs per construction method are 1540 €/m2 for precast concrete bridges, 1200 €/m2 for incrementally launched bridges, 1250 €/m2 for bridges built using travelling formwork and finally 1850 €/m2 for balanced cantilever bridges. It is interesting to note that even though nearly all the bridges in the sample obtained belonged to zones of very low seismicity, except for the Petra Tou Romiou Viaduct in Cyprus, the resulting costs were still significantly greater than Egnatia Motorway bridges which were all more conservatively designed to sustain significant seismic forces.

However, a straightforward comparison of bridge construction costs cannot be made, as costs are a result of several factors both internally and externally related to the bridge construction industry. Low labour costs are a significant factor that influence contractors' to precede to construction of precast beams on site rather than in the factory. Higher labour costs in other countries partly explains the tendency to industrialise the bridge production process as much as possible which requires less labour, but leads to greater overhead costs. To overcome these significant overhead costs there must be adequate demand for precast units, something that has not been significantly promoted in Greece. For these reasons and the fact that concrete industry is well established, Greek contractors prefer in-situ concrete construction methods.

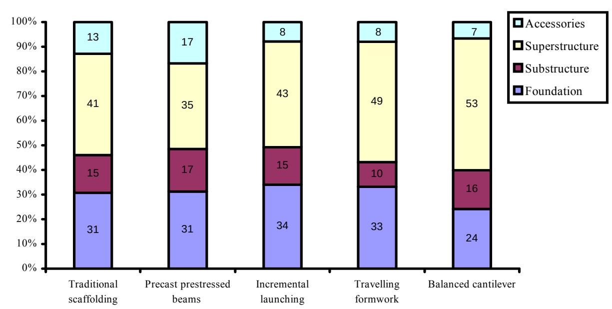


Figure 2 – Cost distribution of Egnatia Motorway bridges

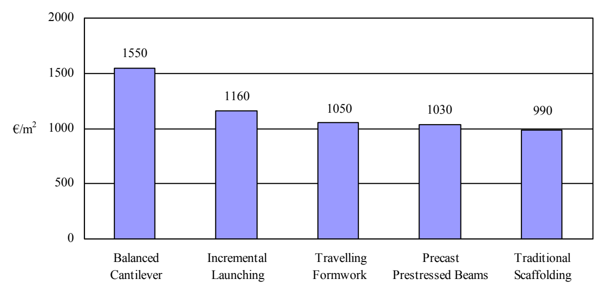


Figure 3 –Cost of Egnatia Motorway Bridges

Finally, the size of construction companies, the current competition, the tendering system and the size of contract are additional aspects affecting the cost of construction. The most economical method for construction of bridges, as anticipated, is using traditional scaffolding methods and the least is the balanced cantilever method, which is utilized for the construction of long span bridges. In situations where the use of traditional scaffolding methods is not physically possible, it appears that precast beams is the next most economical solution followed by travelling formwork and incremental launching methods, which offer potential financial benefits only for long bridges. The results of this analysis could be used in the calculation of cost pre-estimates during the feasibility studies of similar infrastructure projects in Greece.

6.0 Case studies

The technical characteristics and material quantities of three dual carriageway two span dual carriageway balanced cantilever bridges constructed along Egnatia Motorway in the Region of Western Macedonia, Greece are presented. Comparisons are made, in terms of material consumption and conclusions are drawn that may provoke further statistical elaboration for all bridges on Egnatia Motorway that will allow accurate cost estimations to be made for bridges to be tendered in the future.

6.1 Configuration of the Bridges

The bridges presented have a number of characteristics in common. They are all post- tensioned concrete box girder bridges constructed as in situ balanced cantilever structures and consisting of two independent 14 m wide structures, one for each carriageway. The distance between the two structures depends on highway alignment characteristics and seismic design requirements, but in any case there is a minimum of 1.0 m. The bridge sites are all in a medium seismicity zone with peak ground acceleration of 0.16g .The minimum specified design life for the structural elements of all bridges is 120 years. Factors that were considered during the conceptual design phase were the structural effectiveness, the impact to the surrounding environment, aesthetics, and the cost. In order to achieve a better aesthetical result and to minimise the disruption to the local environment, it was decided that the piers between the left and right branches of each bridge would be in parallel rather than staggered. Balanced cantilever was chosen as the most appropriate construction method. A summary of the technical characteristics of the three bridges is given in Table 2.

Table 2 – Technical characteristics of the bridges

Bridge Name	Length (m)	Span arrangement (m)	Pier height (m)
G1-L	155.00	75.00 + 80.00	38.4
G1-R	119.00	62.00 + 57.00	39.4
G2-L	166.00	80.00 + 86.00	46.0
G2-R	150.00	82.00 + 68.00	35.8
G9-L	170.00	85.00 + 85.00	32.5
G9-R	170.00	85.00 + 85.00	32.5
Greveniotikos-L	920.00	60.00 + 8 x 100.00 + 60.00	23.6-23.5-32.6-3 x 38.2-32.6-29.6-21.6
Greveniotikos-R	920.00	60.00 + 8 x 100.00 + 60.00	23.6-23.5-32.6-3 x 38.2-32.6-29.6-21.6
G10-L	265.18	60.05 + 110.05 + 60.08 + 35.00	41.8 - 46.6 - 15.5
G10-R	234.20	61.05 + 112.10 + 61.05	45.2 - 41.3
G11-L	299.45	26.90+33.60+62.16+114.63+62.16	20.7 - 19.5 - 39.6 - 46.1
G11-R	247.20	64.30 + 118.60 + 64.30	36.0 - 45.0
G12-L	457.00	61.00 + 3 x 107.00 + 75.00	32.8 - 86.2 - 82.6 - 34.9
G12-R	457.00	61.00 + 3 x 107.00 + 75.00	29.1 - 82.5 - 87.8 - 40.2

L : left branch; R : right branch

G1 Bridge

G1 Bridge is a two span prestressed box girder ravine bridge. The central piers for both bridges are hollow 7.0 x 9.0 m box sections with 1.00 m thick walls along the axis of the bridge and 1.40 m thick walls in the transverse direction, up to a height of 18.16 m from the top of the foundation shaft. From that point to the pier head the cross-section of the central piers become twin leaf with 1.40 m thick walls. The bridge loads are transferred to the bedrock through 12 m diameter bearing shafts of 22.0 m depth. Both abutments A1 and A2 for both bridges are founded on pile groups of consisting of 1.5 m and 1.0 m diameter piles of varying arrangements. The central piers are monolithically connected to the superstructure, while at the abutments the superstructure is supported on pot bearings allowing longitudinal movements only. The superstructures consist of a single cell box girder with height varying between 8.60 m at the pier cap to 3.60 m at the abutments for the left branch and 7.30 m to 3.0 m for the right branch.

G2 Bridge

G2 Bridge is a two span boxed girder ravine bridge. The central piers for both bridges are hollow 7.0 x 9.0 m box sections with 1.00 m thick walls along the axis of the bridge and 1.80 m thick walls in the transverse direction, up to a height of 22.89 m and 11.38 m from the top of the foundation shaft for the left and right bridge respectively. From that point to the pier head the cross-section of the central piers become twin leaf with 1.80 m thick walls. The bridge loads are transferred to the bedrock through 12 m diameter bearing shafts of 20.0 m depth for the left bridge and 17.0 m for the right bridge. Both abutments A1 and A2 for both bridges are founded on pile groups of consisting of 1.5 m diameter piles of varying arrangements. The central piers are monolithically connected to the superstructure, while at the abutments the superstructure is supported on pot bearings allowing longitudinal movements only. The superstructures consist of a single cell box girder with height varying between 9.00 m at the pier cap to 4.00 m at the abutments for the left branch and 8.00 m to 3.60 m for the right branch at abutment A1 and 3.40 m at abutment A2.

G9 Bridge

G9 Bridge is a two span boxed girder ravine bridge. It is comprised of two identical bridges, one for the left carriageway and one for the right. The height of the central pier for both branches is 32.5 m. The central piers for both bridges are for the most part twin leaf with 2.00 m thick walls, while the first 6.19 m at the base of the piers are solid 7.0 m x 9.0 m blocks. The bridge loads are transferred to the bedrock through one common 23.00x9.00 m bearing shaft of 14.0 m depth. Both abutments A1 and A2 for both bridges have spread foundations at varying levels in order to reduce the required excavations. The central piers are monolithically connected to the superstructure, while at the abutments the superstructure is supported on pot bearings allowing longitudinal movements only. The superstructures consist of a single cell box girder with height varying between 9.00 m at the pier cap to 4.00 m at the abutments.

Greveniotikos Bridge

The Greveniotikos Bridge one of the longest bridges of the Egnatia Motorway with 920 m length, is a valley bridge near the city of Grevena. Since it is visible from the city and there many historical stone arched bridges in the Grevena area, aesthetics was an important factor. On the other hand, a landmark structure with special features would increase construction costs. In order to avoid high embankments with an average height of 25 m, the overall length of the bridge was increased by 190 m. Therefore a balanced cantilever bridge consisting of eight 100 m middle spans and two 60 m end spans was preferred.

For architectural reasons all bridge piers have hexagonal hollow sections with external dimensions 6.0 x 3.8 m and wall thickness of 0.5 m. The foundations of both abutments and piers consist of 1.50 m diameter piles and pile caps. The number and the length of each group of piles at each pier ranged between 8 to 11 and 12.0 m to 27.0 m, correspondingly. The three central piers (M4, M5 and M6) are monolithically connected to the superstructure. At the remaining piers and abutments the superstructure is supported on sliding bearings allowing longitudinal movements, while shear keys block movement in the transverse direction. Additionally, at the next two piers, on either side of the central piers (M3 and M7), lockup devices were provided to prevent any longitudinal dynamic displacement. The superstructure consists of a single cell box girder with height varying between 6 m at the pier caps to 3 m at mid span.

Bridges G10, G11 and G12

Bridges G10 and G11 are ravine bridges, each consisting, of two bridges one for each carriageway. Both bridges are located between tunnels. The height of piers for both bridges range from 15 m to 47 m. Piers M1 and M2 for both bridges are hollow 3.50 x 7.30 m box sections with 0.74 m thick walls, while M3-L is solid 1.50 x 7.3 m. The bridge loads are transferred to the bedrock through 9 m diameter bearing shafts of depths varying from 10 to 12 m, apart from pier M3, which like the abutments sit on spread foundations. The central piers M1 and M2 are monolithically connected to the superstructure, while at the remaining pier and abutments the superstructure is supported on sliding bearings allowing longitudinal movements only at the abutments and both longitudinal and transverse movement at pier M3. The superstructures consist of a single cell box girder with height varying between 6.5 m at the pier caps to 3.0 m at mid span. The right carriageway bridge G11-R is of 247 m overall length with a 119 m long central span and two 64 m long end spans, while the left carriageway bridge G11-L is a 5 span bridge of 299 m overall length. The first two spans were built using traditional scaffolding while the three longer spans were designed and built using balanced cantilever bridge construction technology. The height of deck varies from 7.0 m at the position of piers to 3.0 at the middle of the span. The height of piers for both bridges range from 19 m to 46 m. Piers M1-R, M2-R, M3-L and M4-L are hollow 3.50 x 7.30 m box sections with 0.74 m thick walls, while M1-L and M2-L are solid 1.50 x 7.8 m.

Bridge G11-R's articulation system consists of monolithic connections between the superstructure and piers and simple supports through pot bearings at the abutments. Similarly, bridge G11-L's superstructure is monolithically connected to piers M3 and M4, while being simply supported at the remaining piers and abutments. Both the main pier and superstructure sections were of similar dimensions to bridge G10 in order to facilitate construction and keep construction costs to a minimum through repetition as both were built under the same construction contract.

Both branches of bridge G12 are 457 m long and consist of 5 spans, i.e. three identical central 107 m spans and two end spans 61 m and 75 m long. The bridge superstructures are of a single cell box cross-section, which is connected monolithically at all four piers and is simply supported at the abutments through sliding bearings. The height of deck varies from 6.5 m at the position of piers to 3.0 at the middle of the span. The significant characteristic of this bridge is that it is the bridge with the tallest piers, up to 88 m high, constructed thus far on Egnatia Motorway. The cross section of these piers is hollow 5.50 x 6.80 m box sections with 0.70 m thick walls and are all founded on 9 m diameter shafts of depths varying from 14m to 18m depth, while the abutments have spread foundations.

6.2Material Quantities

(a) Two Span Bridges G1,G2, and G9

The material consumption results for the two span bridges G1,G2 andG9 were presented by Liolios et. Al.[9] In short, the total quantity of concrete consumed in the construction of the foundations, piers and superstructures for the two span bridges ranges from 6500 to 8160 m^3 of concrete, while that of steel ranges from 750 to 1150 tonnes. In terms of total steel quantities per m^3 of concrete in the superstructure the differences observed are of the order of 18 per cent and are due to the varying value of the behaviour factor taken into consideration during the design. Specifically, for reinforcing steel the average index is 129 kgr/m^3, while for prestressing steel this index is 41 kgr/m^3. Finally, as expected, Liolios et. Al [9] prove that the greatest concentration of reinforcing steel (up to 229 Kgr/m^3 in bridge G9) occurs in the piers, due to stringent requirements by the Greek code for confinement reinforcement. In addition , it was deduced that two span bridge G1-R is more economical in terms of concrete and steel consumption in the superstructure. This is due to the shorter length of the cantilevers and therefore, the dead load of the deck is smaller leading to reduction of required concrete cross-sections, prestressing and reinforcement. Bridge G9 has a higher steel consumption due to the fact that it was designed for ductility factors q_x=1.9, while the other bridges were designed for higher ductility factors ranging from 2.38 to 2.88. As a result, regardless of the fact that all three bridges are situated in the same seismic zone, bridge G9 was designed for greater seismic forces and therefore required greater steel quantities. Finally, bridge G9 consumes a greater amount of concrete per m height of piers due to both the 7.0 m x 9.0 m x 6.19 m solid reinforced concrete section at the base and the larger twin leaf cross section as compared to the other two span bridges include in the comparison.

(b) Multi- span bridges Greveniotikos, G10,G11 and G12

The material consumption results for the Multi- span bridges Greveniotikos, G10, G11 and G12 were presented by Lambropoulos et. Al.[10]. In these cases, the total quantity of concrete consumed in the construction of the foundations, piers and superstructures for each multi-span bridge ranges from 6000 to 22000 m3 of concrete, while that of steel ranges from 1000 to 5000 tonnes. Obviously, these differences are attributed to the varying overall and maximum span lengths, as well as pier heights. In terms of total steel quantities per m3 of concrete in the superstructure, all bridges gave similar results. Specifically, for reinforcing steel the average index is 162 kgr/m3, while for prestressing steel this index is 52 kgr/m3. Finally, as expected, Lampropoulos et. al [10] prove that the greatest concentration of reinforcing steel (up to 251 Kgr/m3 in bridge G11-L) occurs in the piers, due to stringent requirements by the Greek code for confinement reinforcement. In addition it was deduced that Greveniotikos Bridge is the most economical multi-span bridge in terms of concrete consumption in the superstructure and piers, as well as in terms of steel consumption in the piers. On the other hand, bridge G10-R has proven to be less economical in terms of concrete and steel consumption in the piers while Bridge G11-R requires more concrete, reinforcing and prestressing steel in the deck. Finally, bridges G12 and G11-L proved to be more economical in terms of reinforcing and prestressing steel consumption in the superstructure. The average values of the concrete and steel quantities in the superstructure and in the piers may prove to be useful for calculating initial construction cost estimates of balanced cantilever bridges for the same seismic hazard area.

7.0 Conclusions

Egnatia Motorway is a project that has been successful in meeting current state-of-the-art standards while achieving a balance between financial costs and benefit to society in terms of providing a significant life line between cities and villages in Northern Greece and concurrently showing due respect to the environment.

The management and project monitoring systems developed for the design, construction and maintenance of structures in a mega project, within a limited time schedule are presented in this paper. The efficiency of these procedures, some of which are introduced in public works in Greece for the first time, have proven to be very satisfactory. The benefits resulting from their application can be summarized as follows:

1. Uniform design performance is achieved by the implementation of the EOAE's design guidelines, the OSMEO and the OSAT.
2. Significant design and checking time is saved due to the standardization of culverts and retaining walls, which allows the immediate start of work on site as well as the implementation of fast track principles.
3. Call up contracts for all disciplines have significantly reduced the time required to assign design work to competent designers.
4. The employment of external consultants by EOAE to carry out technical reviews, independent checking and management of designs resulted in optimised productivity of human re-sources.

5. The Project Information System in combination with Primavera Project Planner and the electronic Document Management System provide immediate access to design and construction in-formation and facilitates effective planning and monitoring of the progress of the works.
6. The Quality Assurance System implemented by EOAE central offices, Construction Management Teams, designers and contractors ensures that the quality of the designs and completed works meet state-of-the-art standards.
7. Acceleration of decision making is achieved by reducing lines of communication and by authorizing the Managing Committee to make most design and construction decisions.
8. The development of the Egnatia Motorway Operation and Maintenance Guidelines was necessary as no similar codes or guidelines existed in Greece for the operation of major motor-ways. The application of these by O&M contractors is new, therefore revisions to these documents are expected to be made in the future.
9. The seismic hazard risk assessment software tool being developed is expected to allow the prediction of the most likely extent of damage to the bridges of the motorway in the case of a serious earthquake, thus permitting the planning of alternative routes around predetermined weak links.

The second objective of this paper was to present and analyze actual cost data of a portion of Egnatia Motorway bridges in order to develop a clear picture regarding the average costs per square meter per bridge construction method. The results showed that the most economical method for construction of bridges, as anticipated, is using traditional scaffolding methods and the least is the balanced cantilever method, which is utilized for the construction of long span bridges. In situations where the use of traditional scaffolding methods is not physically possible, it appears that precast beams is the next most economical solution followed by travelling formwork and incremental launching methods, which offer potential financial benefits only for long bridges. The results of this analysis could be used in the calculation of cost pre-estimates during the feasibility studies of similar infrastructure projects in Greece. In any case, spending the allocated budgets wisely will be rewarded many times over in the form of safe, reliable and sustainable transportation

Finally, this paper presented seven case studies including the technical characteristics of three two span balanced cantilever bridges with twin leaf piers and four significant multi-span balanced cantilever bridges located in one of the most remarkable mountainous terrain along the alignment of Egnatia Motorway. A comparison was made between the bridges in terms of concrete and steel quantities consumed per unit area of deck or linear meter of pier, but it is the average values that may prove beneficial for the calculation of cost pre-estimates during the feasibility studies of similar bridges in areas of analogous seismicity.

It was shown that it is the span arrangement, height of piers and foundation conditions that directly affect the section dimensions and therefore the required material quantities. Determining factors for the span arrangement are geological foundation conditions and aesthetics which may impose restrictions on the number and position of allowable piers, such as unacceptable foundation conditions or the requirement to keep piers in line with one another to prevent a staggered appearance. It is therefore essential that a balance is achieved between cost and aesthetics in the design of balanced cantilever bridges.

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