MATERIAL QUANTITIES FOR BALANCED CANTILEVER BRIDGES

DIMITRIOS KONSTANTINIDIS
Department of Civil Infrastructure Engineering, Alexander Technical Institute of Thessaloniki,
57400, GREECE

FANI ANTONIOU
Egnatia Odos A.E., 6th km Thessaloniki - Thermi,
57001 GREECE

ABSTRACT

The technical characteristics and material quantities of three two span balanced cantilever bridges with twin leaf piers and four significant multi-span balanced cantilever bridges constructed along Egnatia Motorway in the Region of Western Macedonia, Greece are presented. Comparisons are 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.

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.

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. 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 links 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.

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 budget 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 fifteen 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.

THE BRIDGES ALONG THE 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.

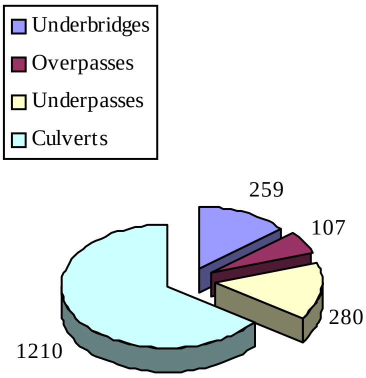

Figure-1a: Type of structures

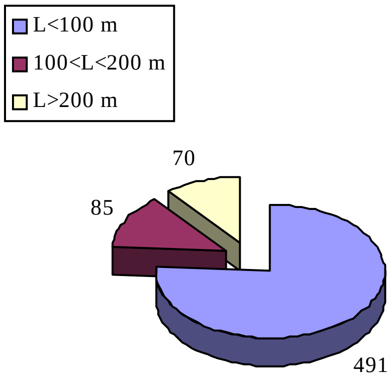

Figure-1b: Length distribution of bridges

Figure-1: Structures of Egnatia Motorway

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.

CONFIGURATION OF THE BRIDGES STUDIED

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 seven bridges is given in Table 2.

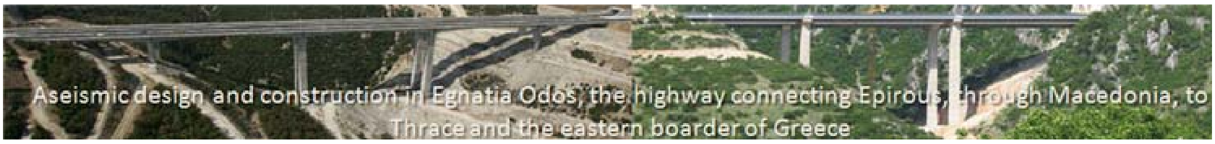

Table-2: Technical characteristics of the bridges

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

G1 bridge

G1 Bridge (Figure 2) is a two span prestressed box girder ravine bridge. It is comprised of two bridges, one for the left carriageway and one for the right. 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.

Figure-2: G1 bridge during construction

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 (Figure 3) is a two span boxed girder ravine bridge. It is comprised of two bridges, one for the left carriageway and one for the right 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.

Figure-3: G2 bridge during construction

G9 bridge

G9 Bridge (Figure 4) 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.

Figure-4: G9 bridge during construction

Greveniotikos bridge

The Greveniotikos Bridge (Figure 5) 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.

Figure-5: Greveniotikos bridge as it is seen from the city of Grevena

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.

<u>G10 and G11 bridges</u>

Bridges G10 (Figure 6) and G11 (Figure 7) 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.

Figure-6: G10 bridge during construction

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.

Figure-7: G11 bridge during construction

G12 bridge

Both branches of bridge G12 (Figure 8) 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.

Figure-8: G12 bridge during construction

MATERIAL QUANTITIES

Two span - twin leaf balanced cantilever bridges G1,G2, and G9 (Figure 9)

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, 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.

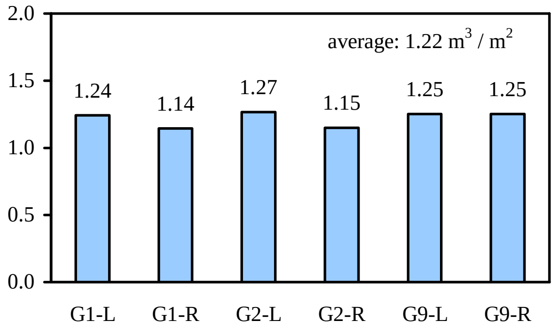

Figure-9a: Concrete per deck surface area

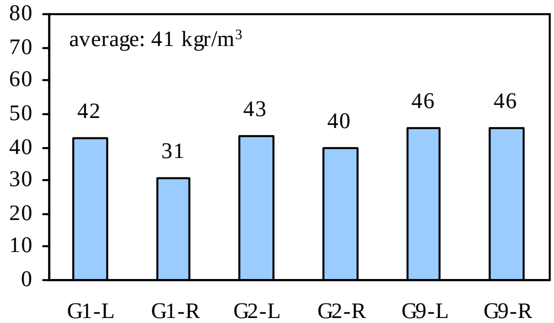

Figure-9b: Prestressing steel per m^3 of concrete in the deck

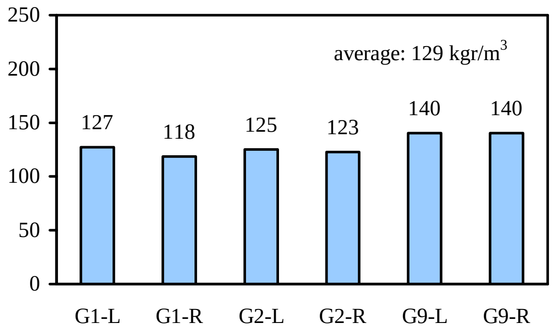

Figure-9c: Reinforcing steel per m^3 of concrete in the deck

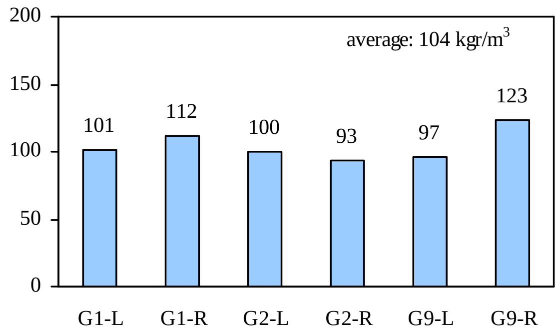

Figure-9d: Reinforcing steel per m^3 concrete in the abutments

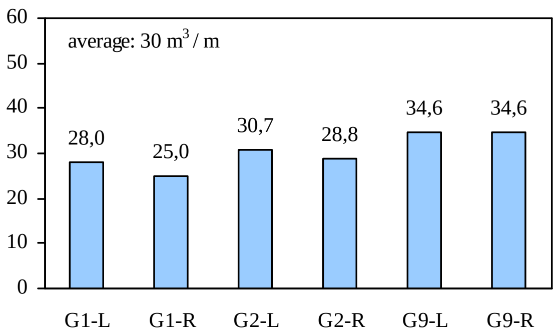

Figure-9e: Concrete volume per m of piers

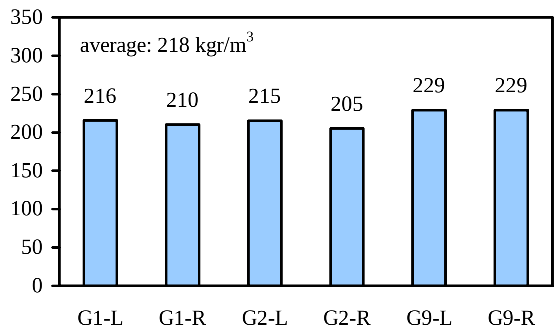

Figure-9f: Reinforcing steel per m^3 concrete in the piers

Figure-9: Concrete and steel quantities for twin leaf balanced cantilever bridges

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.

Multi- span bridges Greveniotikos, G10,G11 and G12 (Figure 10)

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.

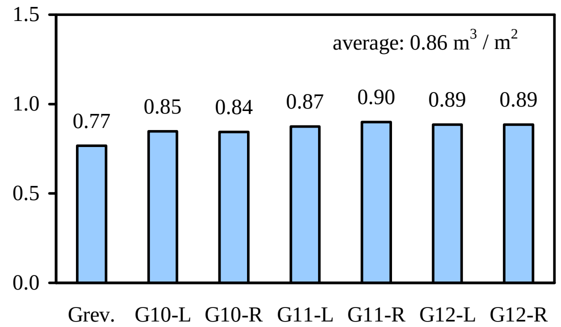

Figure-10a: Concrete per deck surface area

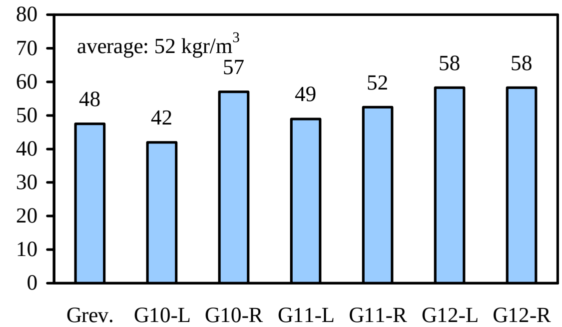

Figure-10b: Prestressing steel per m^3 of concrete in the deck

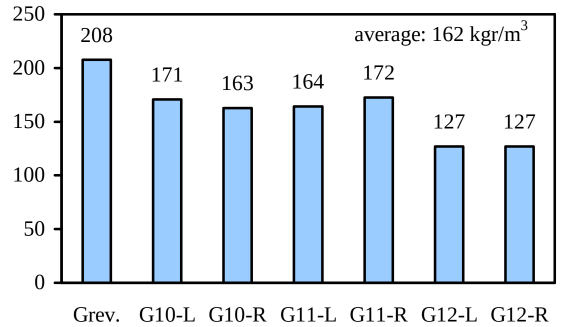

Figure-10c: Reinforcing steel per m^3 of concrete in the deck

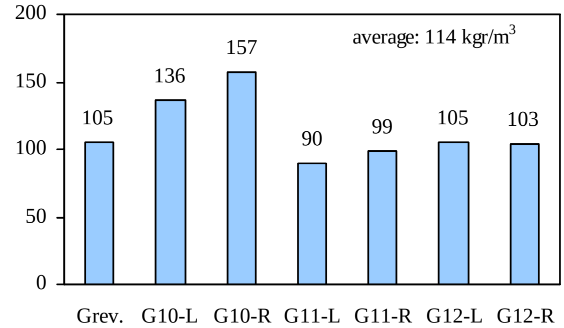

Figure-10d: Reinforcing steel per m^3 concrete in the abutments

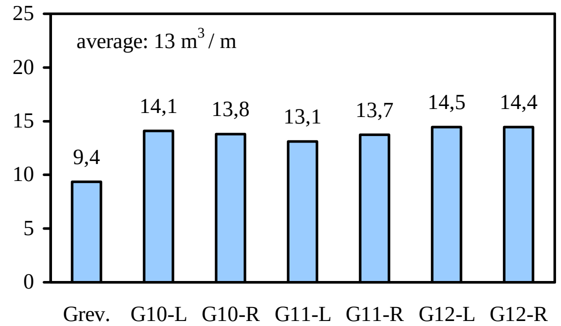

Figure-10e: Concrete volume per m of piers

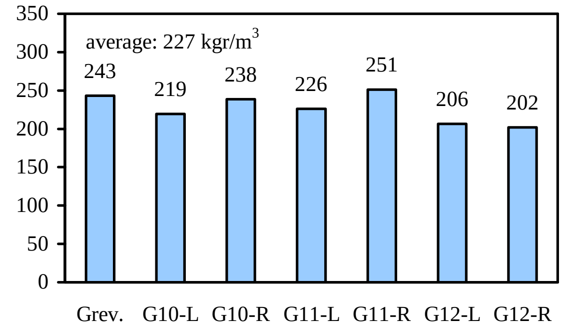

Figure-10f: Reinforcing steel per m^3 concrete in the piers

Figure-10: Concrete and steel quantities for multi - span bridges

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, 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.

CONCLUSIONS

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.