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Assessing and benchmarking the construction cost of tunnels

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ABSTRACT

The accurate cost estimation in engineering projects and underground construction in particular, is a key parameter for the project's success. Especially in the preliminary conceptual and design stages, such cost data is crucial for the whole project development, affecting major decisions to be taken. This paper presents cost data focusing on Greek tunnel construction experience, emphasizing on the cost of the excavation process and the temporary support measures adopted with respect to the geotechnical conditions encountered. Such design options are mainly influenced by the encountered geotechnical conditions attributing to the greater portion of the tunnel's total construction cost. Furthermore, the cost estimated for the Greek tunnels under investigation is compared and benchmarked with other published data from UK and EU tunnels, as well as with other available international tunnel cost studies.

RÉSUMÉ

L'estimation précise des coûts dans les projets d'ingénierie et de construction souterraine en particulier, est un paramètre clé pour la réussite du projet. Surtout, dans les phases conceptuelles et de conception préliminaires, ces données sur les coûts sont cruciales pour l'ensemble du développement du projet, ce qui affecte les décisions importantes à prendre. Ce papier présente des données sur les coûts en mettant au point la construction de tunnels Grecs insistant pour couvrir le coût du processus d'excavation et le soutien temporaire des mesures adoptées en ce qui concerne les conditions géotechniques rencontrées. Ces options de conception sont principalement influencées par les conditions géotechniques rencontrées attribuant à la plus grande partie du coût total de la construction du tunnel. En outre, le coût estimé pour les tunnels grecques sous enquête est comparé et évalué avec d'autres données publiées du Royaume-Uni et les tunnels de l'UE, ainsi qu'avec d'autres études disponibles concernant les coûts des tunnels internationales.

1 INTRODUCTION

The construction cost is of major importance for the implementation of major infrastructure projects. This is more evident today in the light of the world financial crisis and turmoil that has started back in 2008 and it has negatively influenced the major economies in the world. Following the modern approach where private - public partnerships are the predominant practice in new project development, the whole financial security of the project (construction and operation) can be in jeopardy if construction cost, one of the main key drivers of costs, is poorly estimated from the beginning.

The development of underground infrastructure can satisfy today's increased demand for efficient, safe and environmentally friendly solutions. Nevertheless, such underground projects often find themselves in the public eye for substantial cost overruns and schedule delays in their development (Flyvbjerg et al. 2004). This is partly because they are characterized by the large scale and complexity in design and implementation, as well as the inherent uncertainty of the geologic medium. Such features and especially the latter if not managed properly could lead to problematic situations. Therefore, the accurate guidance in assessing tunnel construction cost is essential, especially in the conceptual and preliminary design stages, where limited information is available (ITA 1990, Petroutsatou et al. 2012).

One of the main objectives of the paper is to investigate tunnel cost especially focusing on Greek transportation tunnels, aiming at establishing cost categories in terms of the geotechnical conditions encountered. The data analyzed is based on as-built cost statements from a set of 9 Greek tunnels that reflect, to an extent, the influence of the encountered conditions in terms of the geotechnical environment and the logistics support of the whole construction scheme. All cost data are given in 2011 price levels to facilitate their evaluation under a common reference framework and hence they can be used as main guiding principles for estimating Greek tunneling cost, especially in the initial stages of design. Furthermore, the construction cost of the Greek tunnels under investigation is compared and benchmarked with other published data from UK and EU tunnels, as well as with other available international tunnel cost studies. This can assist in evaluating and identifying possible cost differences or even illuminating similar trends that might appear in the construction cost data.

2 TUNNEL CONSTRUCTION COST – MAIN KEY DRIVERS

The cost of setting up an underground infrastructure project is influenced by many factors. Even nowadays where management aspects (financing, procurement

strategies, logistics support, etc.) seem to have an increased impact in the final project cost, the design characteristics of the construction itself still continue to be the most significant asset in terms of the project's development cost. The matrix of the parameters involved in this is quite extensive comprising of the purpose, the geometrical characteristics and length of the project, the geological / geotechnical and hydrogeological conditions, the in-situ stress regime, the excavation process adopted, as well as the labor market and machinery characteristics, etc.

The influence of the encountered conditions in the whole project's success has been noted by the majority of the researchers (USNC/TT 1984, UTRC 2007). This is not only because of unforeseen conditions imposing greater strain in the construction activities, but mainly due to the increased recourses required for the excavation through difficult conditions while leaving behind a robust engineering structure.

The geotechnical characteristics affect tunneling performance, with the following rule of thumb: the more complex and difficult the characteristics, the more affected the capacity of the tunneling method. The latter is due to the adoption of a more careful and less aggressive advance rate, the subdivision of cross-section to multiple parts and the installation of more complex and heavier support elements.

According to Isaksson and Stille (2005) the normal construction cost (C_{Ni}) for a geotechnical zone, i.e. without accounting the occurrence of any undesirable events, can be expressed as a function of the production effort and cost variable, according to Eq. 1:

$$C_{Ni} = \int_L z \cdot g(x(i)) dl \quad [1]$$

where i is the zone, L is the length of the zone, $x(i)$ is the geotechnical characteristics, $g(x(i))$ is the construction effort and finally z is the cost variable.

The relationship between the geotechnical characteristics and the production effort is established first, and then the product of the effort and cost variables is integrated along the given tunnel length. Equation (1) can mathematically model the influence of the conditions where greater construction effort and resources are required, with an increased unit cost, to the overall cost of the construction.

This is in line with a questionnaire survey, conducted by Efron and Read (2012), to tunneling experts / stakeholders (clients, consultants, contractors and cost estimators) with respect to key cost drivers relating to tunneling projects. The answers from all stakeholders coincided in identifying geology as the major cost contributor, while the adopted type of excavation is found in second place, while the least influential cost drivers were found to be depth, contract type and the project's end use (Figure 1). It is also notable that, according to the survey's findings, the geological conditions can yield the most prominent results in terms of cost reduction, if a more aggressive site investigation campaign could be enforced.

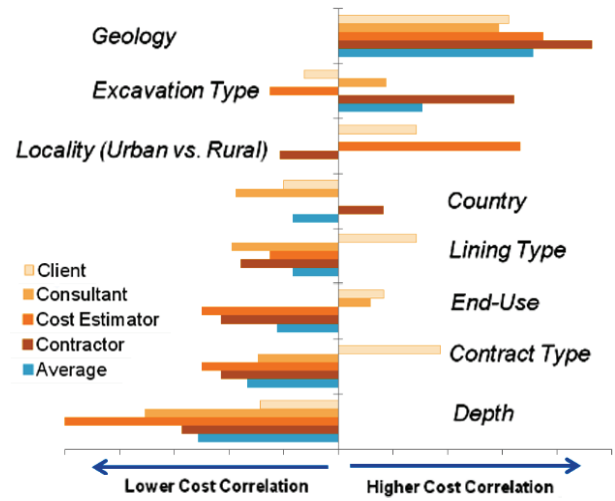


Figure 1. Final cost contributors in tunnelling projects (Efron and Read 2012).

3 ANALYZING THE CONSTRUCTION COST OF GREEK TUNNELS

The purpose of construction cost estimation is to provide information for construction decisions including areas in the procurement and pricing of construction, establishing contractual amounts of payment, and controlling actual quantities (Bari et al. 2008). Paraskevopoulou and Benardos (2012) presented an analysis for the assessment of Greek tunnels following two cost estimation methods, the Case Based Reasoning (CBR) and the Regression Analysis (RA) methods.

CBR was used by taking into account the engineering practice and experience gained from tunneling projects constructed in Greece. This is in accordance with Wagner's (2006) recommendation, in order to eliminate the risk of unrealistic cost estimates by both investigating the overall cost of comparable projects, and examining the cost composition breakdown of the selected data. RA was adopted so as to reveal the interconnection between the encountered conditions and the tunnel construction cost, explicitly expressing their relationship by mathematical formulas in order to be used for future reference. The analysis examined the excavation and temporary support cost, that governs the total construction cost, attributing to almost 65% of the total cost; whereas, in some cases relating to very poor quality rock masses, its share can even be raised to 75% of the total construction cost (Petroutsatou and Lambropoulos 2005).

Furthermore, Paraskevopoulou and Benardos (2013) introduced a more realistic estimator for tunnel construction cost by analyzing data, taken from as-built or final design reports, from 9 Greek tunnels (Rapsommati Tunnel, Agios Elias Tunnel, Agia Kyriaki Tunnel, Tunnel AS1 - Kakia Skala, Knimida Tunnel, Klisoura Tunnel, Platanos Tunnel, Domokos Tunnel and Kiato Tunnel). The assessment was made for each tunnel, for every available type of design cross-sections, which corresponds to the

rock mass categories that were identified, namely ground classes A, B, C, D and E, ranging from very good to very poor quality rock masses.

According to the authors, the selection of these 9 tunnels serve as an attempt to cover all possible cases of the geotechnical conditions encountered. Additionally, this set of tunnels is representative of the types of construction method adopted characterizing contemporary tunnel construction practice in Greece. Hence, they cover a wide spectrum of the geological conditions found in Greece since they were all constructed during the last decade according to the recent regulations, and finally, their cost data was derived by the same pricing method. In order to assign a common reference point for all the examined projects eliminating bias merged from inflation etc., the authors calculated the total construction cost for each and every one of the design cross-sections through unit price estimation according to the latest available pricing data (October 2011).

The results of the analysis are presented in Table 1, where the cost per cubic meter of excavation ($\text{€}/\text{m}^3$) is presented with respect to the ground classes identified (A, B, C, D and E).

Table 1. Rock mass categories as established for the analysis and construction cost of Greek tunnels (Paraskevopoulou and Benardos, 2013)

Rock Mass Categories	GSI	Cost per m^3 (before VAT)
A	GSI = 55 - 100	30.5
B	GSI = 35 - 55	68.5
C	GSI = 15 - 35	89.3
D	GSI < 15	94.2
E	Soil behaviour	145.6

This average cost is estimated taking into consideration the application length of the different rock mass categories for each tunnel; thus the average cost is not the mean of the calculated prices but rather the weighted average allowing more reliable conclusions to be drawn. Furthermore, the cost is expressed and presented in terms of cubic meters of excavation ($\text{€}/\text{m}^3$) in order to be more representative for the construction practice and independent of the tunnel geometry, in comparison to cost expressed in meters of tunnel ($\text{€}/\text{m}$), which can be more influenced by both tunnel geometry and length.

Figure 2 illustrates the construction cost ($\text{€}/\text{m}^3$), with respect to the geological conditions encountered in terms of the GSI (Geological Strength Index) rock mass classification system (Paraskevopoulou and Benardos, 2013). This chart can be either used to directly provide estimates regarding the construction cost according to GSI in a straightforward approach, or it can be further processed, through which the influence of geotechnical conditions on tunnel cost will be explicitly decoded and quantified through regression analysis. In Figure 2, the best fit equation is plotted, along with the curves denoting the 99% confidence intervals, marking the upper and lower boundaries of the construction cost estimates.

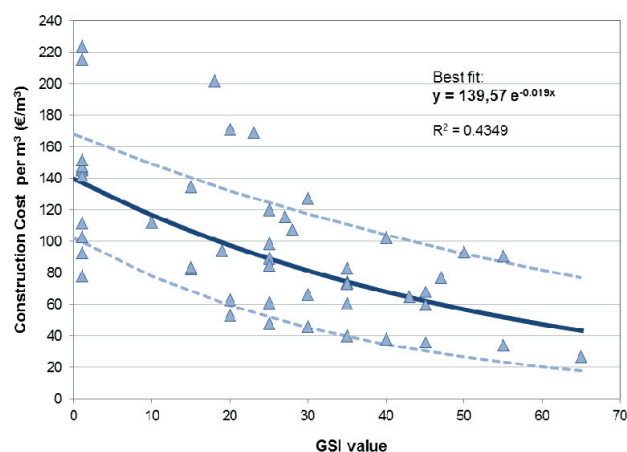


Figure 2. Tunnel construction cost (excavation and temporary support) vs GSI index values (Paraskevopoulou and Benardos, 2013)

4 COMPARING GREEK TUNNEL COST DATA WITH INTERNATIONAL EXAMPLES

The benchmarking and comparison of tunnel cost worldwide is something that has raised interest in recent years throughout the engineering community and stakeholders (Flyvbjerg et al. 2008). Thus, there is a need to for comparable cost data to assess the feasibility and the appraisal of tunnel projects. Likewise in this section the comparison between the construction cost of Greek tunnels and published data coming from worldwide experience are presented. Although, there are differences in the characteristics of the cost data provided emerging from time differences, project individuality and locality, an attempt is made to gather all the compared information under a common reference framework, in order to facilitate assessments.

There are many approaches that provide cost data for underground projects available in literature, such as, Zhao et al. (1999), Sinfield and Einstein (1997), Hoek (2001), Flyvbjerg et al. (2004), (2008), Isaksson and Stille (2005), Petroutsatou and Lambropoulos (2005), HM Treasury (2010), Efron and Read (2012), and lately Rostami et al. (2013). Although, most of these researches refer to case specific studies, (geological conditions, cost-pricing methods, regulations, etc), they can still provide valuable data, not to explicitly address exact cost figures but rather for enabling identify general trends and drawing general conclusions.

Hoek (2001) cited that the costs associated with tunnel excavation and support methods can be high. Figure 3 summarizes typical tunnel costs for large tunnels in different ground conditions. These costs refer to excavation and temporary support only and do not include the cost of final concrete lining or the tunnel fittings (ventilation, lighting, rails, roadway etc.). Also, these costs were incurred in major projects under construction in various parts of the world and great consideration was taken to ensure that the information is as accurate as possible.

The cost values of the original chart were in US\$ for 1999 price levels, but the chart given hereinafter (Figure 3) represents Euro (€) prices for 2011 levels by making the necessary conversions to cater for inflation biases through the time as well as for exchange rates. Coincidentally, these price levels are almost the same (1€ in 2011 = US\$ 0.997 in 1999). The cost data from the Greek tunnel cases under examination are shown in the chart (Figure 3), with reference to their identified ground class. It is shown that they follow the general pattern of the zones identified by Hoek (2001). The cost of the ground class categories A and B are in the lower cost zones, while D and E classes are found in the upper cost zones. However, the data relating with ground class C display a more complex behavior. These findings can indicate the great sensitivity of the excavation and support measures adopted, and their respective costs, within the GSI's range (15-35) of this particular ground class.

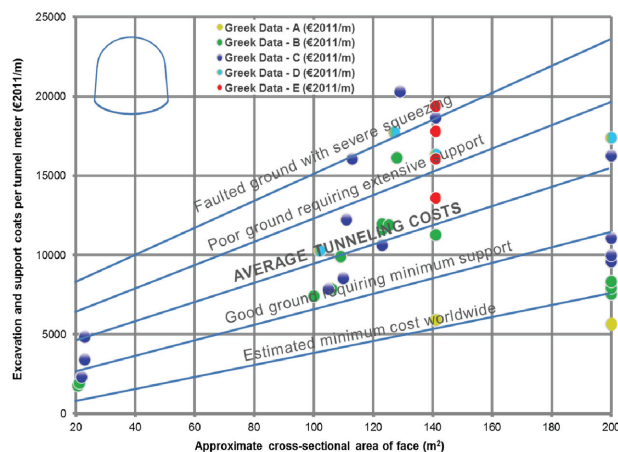


Figure 3. Approximate costs for tunnel excavation and support per tunnel meter according to ground conditions compared with Greek data (adapted from Hoek, 2001)

Zhao et al. (1999) estimated the cost for underground excavation and support with respect to the rock mass quality, using the Q system. The researchers found that the construction cost can vary from 36 €/m³ to 85 €/m³, from good to poor quality ground conditions. This pricing was based on the construction of underground caverns in the Jurong sedimentary rocks in Singapore.

Figure 4 shows the comparison between the construction costs from both the Greek's and Singapore's cases expressed in cubic meter (€/m³), with respect to the ground category. All values are in Euro (€) prices of 2011. It is shown that the cost distribution for both countries is comparable, especially in ground classes A, B and D. However, for ground class C the lower bound of cost is also in proportion to the ones found in Singapore, nevertheless the maximum cost data recorder for this category exhibits far greater values.

HM Treasury (2010) conducted a noteworthy analysis regarding the infrastructure costs in UK, in a part of which, UK tunnel development costs are compared with costs from other European tunnel projects, in an attempt to assess the cost efficiency of UK tunnel construction with other European countries.

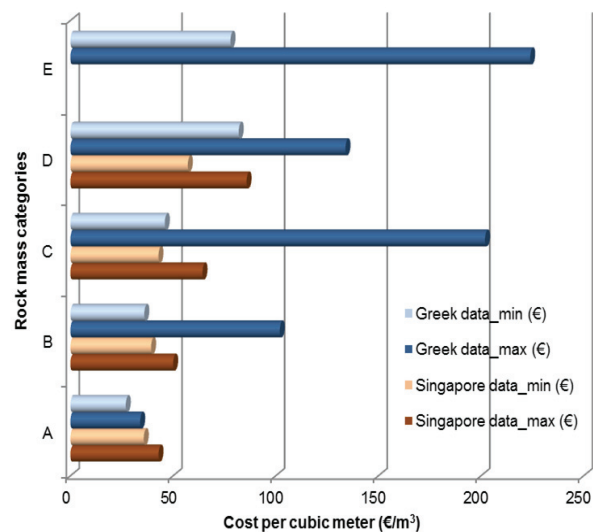


Figure 4. Construction cost data from Greece and Singapore according to rock mass categories

More particularly, the comparison consisted of a selected sample of 14 tunnels constructed in the UK and 21 tunnels developed in other EU countries. The study noted that the planning and pre-construction phases of the project were main source of costs increase. Lesser factors influencing construction cost include overall length, ground conditions, tunneling method and lining type. In the HM Treasury's study a number of analyses are made and charts are drawn illustrating the construction cost with respect to the examined tunnel's diameter and length.

These two charts are included in the paper, enriched with the respective data coming from the Greek tunnel cases under examination, taking into account their total construction cost. This can facilitate the benchmarking of the Greek tunnel cost data with respect to the EU's leading countries in term of construction activities and performance. The Euro/GBP conversion for the Greek cost data are taken from the average exchange rate at the 1st quarter of 2011.

First, in Figure 5 the cost of tunnels (£m/km) is presented with respect to their outer diameter (OD). The larger diameters recorded for the Greek tunnels derives from the fact that all Greek cases are involving transportation projects with typical cross-section of more than 100 m², while the other cases cover a great variety of tunnel types (rail, highway, water and power projects) having significant differences in their design diameter.

It can be seen that for all data there is a positive correlation between construction cost and the span of tunnel. This seems to be most influential after an initial threshold value of diameter. In the HM treasury study this threshold is identified as the diameter of 3 m. Perhaps for the Greek tunnels case this value is somewhat larger, but apparently, based on the available data this cannot be definitely stated. From the chart however, it can be deduced that the cost recorded in the Greek tunnels is lower – in the order of 10 £m/km to 20 £m/km – compared to all other UK and EU projects, which are ranging

approximately from 15 £m/km to 40 £m/km. Of course, having larger tunnel cross-sections, especially when encountering competent rocks, can have a positive result in the construction cost.

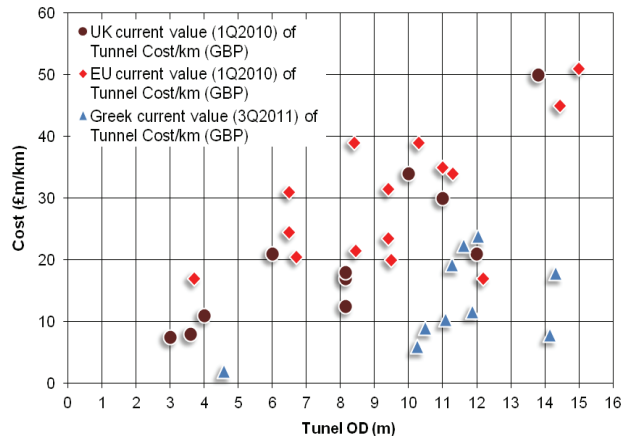


Figure 5. Cost of tunnels with respect to their diameter for UK, EU and Greek projects (adapted from HM Treasury, 2010)

In Figure 6 the influence of tunnel length in the tunnel cost (£m/km) is presented. As the initially findings of the HM Treasury's study (2010) indicate, a slight trend of reducing unit costs with the increase of tunnel length can be seen, especially for the case of UK tunnels.

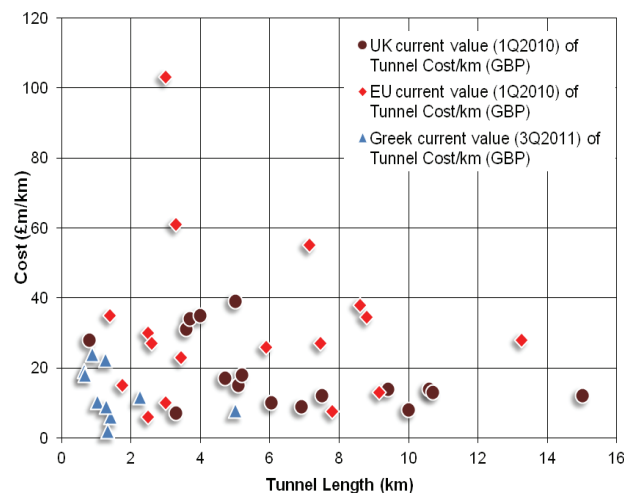


Figure 6. Cost of tunnels with respect to their total length for UK, EU and Greek projects (adapted from HM Treasury, 2010)

This can be thought as a general trend; nevertheless in order to specifically adopt such a notion for the case of Greek tunnels more data are required especially in longer tunnels over 4 km in length. Currently in the Greek database, the majority of tunnels are having lengths in the order of 1 to 2 km and only one (Knimida twin tunnel) has a combined length of 5 km. The average unit rates for tunneling construction contracts in the UK (20£m/km) are

not significantly different from those in Europe. For the Greek cases under investigation the average unit cost (£m/km) lies approximately between 10 and 15 £m/km.

From Figures 5 and 6 it can be noted that, in general, construction cost for tunnel projects in Greece follows the same trends as indicated in the UK benchmarking study. More particularly though based on the examined dataset it can be inferred that the cost of contemporary Greek tunnel construction is slightly lower compared to European data. Nevertheless, this needs to be further assessed and validated with the inclusion of additional data coming from other types of underground projects besides road tunnel applications.

5 CONCLUDING REMARKS

The cost of tunneling projects is greatly influenced by a number of parameters, with the most influential being the geological and geotechnical conditions encountered. The design requirements to provide solutions compatible with the ground conditions, especially relating to the excavation process and the installation of the temporary support determine the construction effort and govern the tunneling cost.

The case analyzed from Greek tunnel projects emphasized on the above issue, presenting the costs with relation to the encountered conditions in terms of the GSI, as well as to five identified ground class categories (A, B, C, D and E). Also, the benchmarking and comparison between Greek tunnels and international data, indicate that contemporary tunnel construction in Greece can attain cost-effective results.

Even though tunnel and underground project construction in general is characterized by a number of individual characteristics, making each project a unique endeavor, the assessment of its costs can provide insight to all stakeholders in order to make adjustments or adopt new features in future projects that would help in reaching a cost-effective construction. The benchmarking and comparison of projects, as the ones presented, act towards this particular pursuit. This is why comprehensive and accurate data relating to tunnel construction cost should be made publicly available to the engineering community in an attempt to form a worldwide project database which could be used as a basis for sound project costing and appraisal even from the preliminary stages of design.

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