Construction Cost Estimation for Greek Road Tunnels in Relation to the Geotechnical Conditions

Chrysothemis Paraskevopoulou[1], Andreas Benardos[2]

[1] Mining Engineer, MSc candidate, Queens University, Canada

[2] Lecturer, School of Mining and Metallurgical Engineering, NTUA University, Greece

ABSTRACT

The accurate assessment of a tunnel construction's basic cost is of major importance of the entire financial appraisal of the overall project. Thus, efficient tools and analyses addressing this particular issue can provide significant information (even from the preliminary stages of tunnel design) and assist in the whole decision making process throughout the project's design life. The paper presents the analysis of tunnel construction cost with respect to the excavation process and the temporary support measures used. These support systems have been determined to be the most influential factors when assessing the total cost of the tunnelling project. More specifically, the analysis is based on the data gathered from the construction of 5 Greek road tunnels, where the construction cost has been estimated from respective cross-sections representative of a variety of geotechnical conditions. The assessment is made to reflect current unit prices (2011), so as to establish a common reference point for all tunnels under evaluation. Cost figures are presented in terms of cost per meter (€/m) and cost per cubic meter (€/m^3). Consequently, the findings of the analysis could be used as a preliminary construction cost estimation tooling in order to provide design engineers and project managers a rapid and representative estimation that can be in other similar underground construction projects in Greece and perhaps similar construction projects internationally.

1 INTRODUCTION

In the past 60 years, many underground works have been constructed worldwide, enabling engineers to solve complex problems and create innovating infrastructures. Underground works have become an integral part of modern engineering practice, either by contributing to the expansion of the transportation network in the form of tunnels (e.g. subway, road and train tunnels) or by enabling the utilization of subsurface space for other purposes that can be hosted in man-made underground environments such as storage facilities (e.g. oil and gas caverns, waste repositories), industrial facilities (e.g. power caverns) or even recreational activities (e.g. sport halls, swimming pools), etc.

However, the decision making process for the development of an underground project is subjected to restrictions mainly imposed by its total as-completed cost. This is something that needs to be addressed properly, especially in the conceptual and preliminary design stages, where limited information is available. Thus, the purpose of construction cost estimation is to provide information for construction decisions including areas in the procurement and pricing of construction, establishing contractual amount of payment, and controlling actual quantities (Bari, 2008).

The estimation of the project's cost is of great importance as it can shift decisions but on the same time can lead to misleading assumptions that might result to severe cost overruns. Deviations from preliminary cost data is probably the main stream in underground construction. According to data reported from the U.S. National Committee on Tunnelling Technology in 1984 (USNC/TT, 1984), almost 60% of the 84 examined tunnel cases suffered from significant cost overruns and contractor claims. The analysis revealed that the final as-completed cost including claims could differ even at 50% of the initial engineer's cost estimates, especially in cases where limited resources were allocated for exploration purposes. This issue is further acknowledged by Flyvberg et al. (2002). According to them, tunnels are engineering works that most likely tend to exceed the as-completed cost of engineers' estimation, with an excess average of 34%. Moreover, they stated that the underestimation of tunnel construction cost is a global phenomenon.

From the above, it is obvious that there is a pressing need for further analysis regarding the construction cost of underground works, where the uncertainty factor plays the leading role. The paper attempts to provide more insight regarding the construction cost of Greek road tunnels and for this purpose it analyses and evaluates data from selected cases studies. More particularly, cost data is extracted with respect to the encountered geotechnical conditions, re-evaluated at current unit prices and, finally, construction cost functions are developed and associated with widely accepted and used geotechnical classification indexes.

2 COST ESTIMATION OF CONSTRUCTION ACTIVITIES

2.1 Cost estimation methods

As it is already noted, the proper and most of importantly the accurate construction cost estimation is primarily based both on scientific methods and engineering experience; thus, the construction cost is the most decisive factor concerning the successful project completion and it should be always examined and reviewed in every stage or phase of the construction process. In general, the construction cost differs from project to project on the grounds of individual schedule time scheduling and availability of resources (capital, labor, infrastructures etc.). Especially for the case of underground construction the inherent uncertainty of the geological medium is also an important factor in having differentiations in the overall project cost. Moreover, it has been proven (Kim et al.,2004) that the choice of a cost estimation method is of paramount importance since these methods and techniques tend to approximate the construction cost by using key data at the preliminary stage of the design. Consequently, it can be easily inferred that cost estimation cannot always lead to a representative outcome at the beginning of the construction as it is not a simple process basically because of the shortage of data and information available at the first stages of the preliminary design.

The optimum choice of the cost estimation methods depends on (Gitsis, 2011) the time and the information available, the engineer's experience, the estimation purpose as well as the activities to be modelled. The most commonly used cost estimation methods are the regression analysis (RA), the case based reasoning method (CBR) and the artificial neural networks (ANN) that are being shortly described below.

- **Regression Analysis Method**: the method uses every statistical technique available for the modelling and the analysis of many variables, so by using independent variables it can determine the price of a dependent variable aka the construction cost (Kim et al., 2004).
- **Case Based Reasoning Method:** the method is based on experience gained by cases, data and information of the past. In this method, it is important to find accurate and precise similarities between a new case and an older one (Aadmont and Plaza, 1994).

- **Artificial Neural Networks Method:** the method uses a mathematical model to interpreter the information that simulates the problem based on artificial intelligence. However, this process requires a high degree of specialization with the software used for the ANN development and the trial and error process used to select the most appropriate network (Adeli and Wu, 1998). Nevertheless, the ANN models developed are characterized by good generalization capabilities and may lead to fairly accurate work quantities and cost estimates of road tunnels (Petroutsatou et al., 2011).

The artificial neural networks method can provide the most representative results, according to Kim et al. (2004); yet, it could display difficulties not only in understanding the cost components, their interaction and the effect of the input parameters to the final cost assessment, but also for being tailor-made products, limiting their applicability envelope to other projects. The regression analysis is an easy and straightforward tool since there is no need for reviewing previous similar cases and it is widely used. Finally, the CBR method can provide accurate and precise cost estimates provided there is a comparable similarity between past projects and the case examined.

2.2 Construction cost estimation of underground works

Underground construction activities can be regarded as a special subset of heavy-civil construction. This can falsely lead to a miscalculation of construction costs, as tunnel construction costs cannot be estimated in the same manner as above ground structures (Romero and Stolz, 2002), as because of the linearity of the construction sequencing, small variances in production can result to large variations in construction costs.

The construction cost of tunnels and underground works is influenced by a combination of many parameters such as the purpose, the geometrical characteristics and length of the project, the geotechnical and the in-situ stress conditions, the excavation process used and the respective machine characteristics, as well as the environmental restrictions and policies, etc. Most importantly though are considered the compatibility of the adopted excavation and support methods to the geotechnical conditions, and its variations, during the tunnelling period, which govern the final outcome.

Attempts to provide cost estimates for tunnel construction are found in the literature, either focusing on capital or operational cost figures (e.g. Zhao et al., 1996; Sinfield and Einstein, 1997; Isaksson and Stille, 2005; Flyvbjerg et al., 2008). These studies cover either typical single-case studies, or are focusing on special construction areas or even dealing with the overall cost of special type of projects (e.g. metros, oil caverns, etc.). Nevertheless, even in the presence of adequate statistical data, to generalize assumptions based on them it could be tricky and should be used with caution. Main reasons for this are the heterogeneity of the encountered conditions, not due to the ones resulting from the geotechnical environment but rather from the ones influenced from the prevailing construction culture, differentiating from country to country and even from project to project, cost differentiations over time and finally cost variations influenced by different unit labour and recourse's cost.

Two notable researches do exist. The first is made in Switzerland by the Swiss Tunneling Society (2001) which analyzed the final tunnel construction cost in the country. The sample consisted of almost 1,200 tunnels with a total length of approximately 1,600 km where the construction cost was found to be from 110 €/m^3 for good rock mass quality cases to 1,077 €/m^3 for cases where poor quality rock masses was encountered. The second is made in Greece by examining the construction cost of the majority of the tunnels (approximately 100 km) built as part of the Egnatia highway. There, the construction cost ranges from 8,000 € per tunnel meter to 30,000 € per tunnel meter. Lambropoulos et al. (2005) gave data relating to the distribution of the construction cost, as shown in Fig. 1.

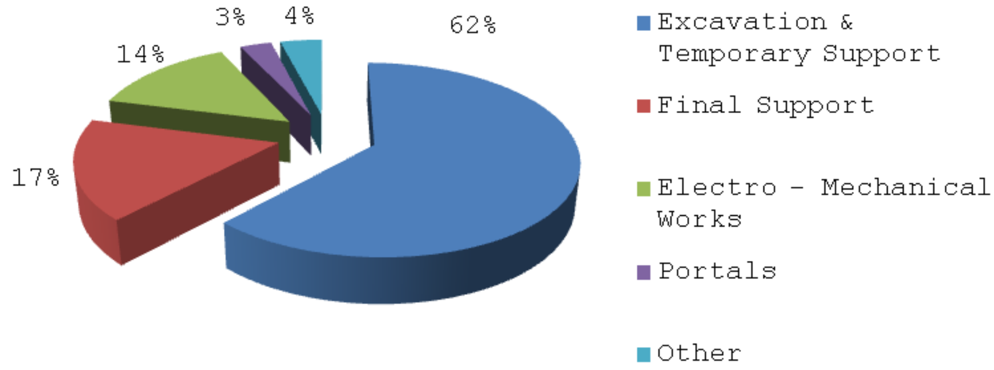

Figure 1 Distribution of Tunnel Construction Cost (Lambropoulos et al., 2005)

According to the findings, the excavation and temporary support cost consists the major cost component attributing almost the 65% of the total cost, whereas, in some cases relating to very poor quality rock masses, its share can even raise to 75% of the cost. Petroutsatou (2008), also for the tunnels of the Egnatia highway, related the excavation cost with the rock mass quality, reaching to the following conclusions:

- for GSI = 10 – 30 the excavation cost is 100-300 €/m^3
- for GSI = 25 – 40 the excavation cost is 50-100 €/m^3
- for GSI = 40 – 60 the excavation cost is 30-50 €/m^3.

3 COST ANALYSIS OF GREEK ROAD TUNNELS

In the paper, the cost analysis performed is based on the principles of the CBR, taking into account the experience gained from a selected set of tunneling projects in Greece. The CBR selection is made following the recommendation of Wagner (2006) which states that in order to reduce the risk of unrealistic cost estimates it is recommended to investigate both the overall cost of comparable projects and to examine the cost composition of data. Likewise, the data is gathered and evaluated with the aim to breakdown the tunneling activities and quantitatively estimate their cost components, under a common reference framework. Finally, the cost data is related to the geotechnical conditions encountered and it is presented using a regression analysis (RA) that reveals the relation between construction cost and basic geotechnical indicators.

Taking into account data from previous cases can be risky and sometimes can be lead to false conclusions; unless an in depth analysis takes place. For instance, in Table 1 cost data from 21 Greek road tunnels are presented. In the data presented, an extremely wide range of construction cost can be seen, ranging from 2,500 €/m (Paliou tunnel) to 25,000 €/m (Egnatia Road Tunnel S4-Lefkopetra). Even in the case where an average construction cost for all tunnels' is calculated at 9,700 €/m, this particular value is something that cannot be taken as a reliable estimator applicable to subsequent cost analyses.

In order to come up with a more realistic analysis regarding the construction cost of Greek road tunnels, a selection of 5 tunnels is made (Rapsommati Tunnel, Agios Elias Tunnel, Agia Kyriaki Tunnel, Tunnel AS1 - Kakia Skala and Knimida Tunnel). The set of these five tunnels is chosen as they cover a wide spectrum of geological conditions in Greece, they have all been constructed during the last decade according to the latest standards and regulations and all of their data are taken either from as-built or final design studies. Consequently, the analysis can be considered as representative of the contemporary Greek road tunnel construction practice. It should be noted that the analysis takes into account costs relating to the excavation and temporary support, which as it is already stated cover the largest portion of the total construction cost and furthermore can be directly linked to the encountered geotechnical conditions. Also, all portal areas and cut-and-cover construction lengths are excluded.

Table 1 Excavation and temporary support cost of Greek tunnels (before VAT)

#	Tunnel Name	Excavation and Temporary Support Cost (€/m)
1	Rapsomatti	3,901.25
2	Agios Elias	15,484.20
3	Dodoni	4,819.57
4	Kastro	3,680.95
5	Vasilikos	4,743.11
6	Egnatia Road S1 (right tunnel)	6,065.05
7	Driskos	6,764.36
8	Kalamon	4,305.87
9	Egnatia Road S1 (left tunnel)	8,957.53
10	Egnatia Road S2 (left tunnel)	16,180.42
11	Egnatia Road S2, part 5.2.	17,778.55
12	Egnatia Road S4, part 5.2.	25,358.35
13	Egnatia Road S5, part 5.2.	6,483.24
14	Paliou	2,512.05
15	Timfristos	20,488.15
16	Pathe tunnels K1 - K4 (Patra's detour)	8,191.38
17	Pathe tunnels K1 - K4 (Patra's Wide detour)	8,900.44
18	Pathe tunnels ("Ghrokomeio")	6,770.19
19	Agia Kyriaki	8,557.42
20	Kakia Skala	17,123.30
21	Knimida	7,209.75
Cost Deviation		2,512 - 25,358
Average Cost		9,727.39

The assessment is made by establishing five major geotechnical categories (namely ground classes A, B, C, D and E) as presented in Table 2, in terms of RMR and GSI classifications. These categories cover all ground classes, from very good to very poor quality rock masses, respectively. The categorisation, allocation and grouping of each encountered condition during the construction period, for each one of the examined tunnels, is made accordingly. More particularly though, emphasis is given on lower quality rockmass conditions, in order to enhance the analysis resolution in those particular cases, where the application of heavier and complex support measures is required. Consequently, this contributes to better and more precise interpretation of the results in areas characterised by high construction cost.

Table 2 Rock mass categories as established for the analysis

Rock Mass Categories	GSI	Rock Mass Quality (RMR - Bieniawski)
A	GSI=55-100	Good to very good - RMR=60-100
B	GSI=35-55	Fair - RMR=40-60
C	GSI=15-35	Poor - RMR=20-40
D	GSI<15	Very Poor - RMR<20
E	Soil	Soil Behaviour

The analysis is made for each individual type of tunnel cross section, where the excavation and the applied support measures are assessed and their corresponding cost figures are assigned. All cost data is revised into the latest available pricing units (July 2011), eliminating biases resulting from different construction periods (inflation impacts, etc.). This means that the analysis results reflect the tunnel cost at today's construction prices.

The cost is expressed at cost per cubic meter (€/m^3) and at cost per tunnel meter (€/m). However, the cost as expressed per cubic meter appears to be a more representative indicator of the construction cost as it is independent of the tunnel geometry, comparing to the cost per meter that depends both on tunnel geometry and length. The results of the analysis are presented in detail in Table 3. In there, the construction length of each tunnel with respect to the 5 rock mass categories (A, B, C, D, E) is presented, along with their cost.

Table 3 Excavation and temporary support cost per cubic meter (€/m^3) per rock mass category regarding the five road tunnels

Rock Mass Category	Tunnel name and total length (m)	Application Length (m)	Cost per m^3 (before VAT)	Cost per m^3 (with VAT=23%)
A (GSI=55-100)	Knimida (5,000)	676.00	27.02	33.23
Average Cost			*27.02*	*33.23*
B (GSI=35-55)	Rapsomatti (1,405.5)	570.00	34.04	34.04
	Agia Kyriaki (1,030)	61.00	90.90	111.81
	Knimida (5,000)	309.64	36.49	44.89
		1,606.45	38.12	46.89
		1,715.91	39.91	49.09
Average Cost			*47.89*	*57.34*
C (GSI=15-35)	Rapsomatti (1,405.5)	300.00	61.14	73.06
		300.00	63.22	75.54
	Agia Kyriaki (1,030)	741.00	93.46	114.96
		237.00	82.98	102.06
	Kakia Skala - AS1 (843.5)	8.740	66.37	79.31
		475.60	98.95	118.24
	Knimida (5,000)	401.80	46.11	56.71
		65.36	47.96	58.99
		511.95	53.23	65.47
Average Cost			*68.16*	*82.70*
D (GSI=<15)	Rapsomatti (1,405.5)	34.00	82.41	98.47
	Agios Elias (644)	153.00	112.81	134.80
	Kakia Skala - AS1 (843.5)	150.58	135.06	161.39
	Knimida (5,000)	72.00	83.74	103.00
Average Cost			*103.51*	*124.42*
E (GSI<15 - soil behaviour)	Agios Elias (644)	140.00	146.91	175.55
		153.00	224.19	267.88
			203.30	242.92
Average Cost			*191.47*	*228.78*

It can be seen that a pattern in cost data, in relation to the geotechnical conditions, does exist, even though cost spikes are experienced. This particular table is of high information value as besides the construction cost, it can also reveal the accuracy degree of the conclusions. For the case of the “B” and “C” rock mass categories the estimated construction costs are based on data resulting from 4.3 km and 3.0 km of tunnel length, respectively. Furthermore, their data is obtained from 3 or 4 independent tunnels. As a result, it can be stated that the conclusions drawn regarding the construction cost, for those particular categories can be characterised as highly representative. The data for rock mass category “A” (GSI ranging from 55 to 100) cover only 676 m of tunnel length, thus, additional data from other tunnels is required to increase the assessment’s accuracy. Similarly, for the case of rock mass categories “D” and “E” having an application length up to 400 m and 300 m, respectively, further data is needed to enhance their precision degree.

In Table 4 the average excavation and temporary support cost for each geotechnical category is given, expressed in cubic meters (€/m^3), whereas in Table 5 the average cost is expressed in meters per tunnel length (€/m). In these tables, the cost is given in 2 modes. The first is referring to the cost data obtained for the actual construction year, while the second, the “revised” one, reflects current cost data and takes into account changes in resources and their pricing as for 2011 values.

It is shown that the average cost for category “A” (good geotechnical conditions) is 27 €/m^3, while, as the rock mass is deteriorating and more complex excavation and heavier support measures are required, the cost increases, reaching 190€/m^3 for category “E”. Likewise, for category “A” the cost is approximately 4,600 €/m, while it reaches almost 20,300 €/m for category “E”.

Table 4 Average excavation and temporary support cost per cubic meter (€/m^3) per rock mass category regarding the five road tunnels (before VAT)

Rock mass category	Average excavation and temporary support cost per cubic meter (€/m^3)	Revised average excavation and temporary support cost per cubic meter (€/m^3)
Category A	21	27
Category B	39	48
Category C	51	68
Category D	82	104
Category E	127	191

Table 5 Average excavation and temporary support cost per tunnel meter (€/m) per rock mass category regarding the five road tunnels (before VAT)

Rock mass category	Average excavation and temporary support cost per tunnel meter (€/m)	Revised average excavation and temporary support cost per tunnel meter (€/m)
Category A	3,638	4,579
Category B	5,100	6,800
Category C	6,980	9,220
Category D	12,467	14,404
Category E	13,662	20,363

4 CONSTRUCTION COST vs GEOTECHNICAL INDEXES GSI & RMR

The above data show that a clear association between construction cost and the encountered tunneling conditions, as expressed by the use of rock mass categories, exists. In this context, it could be most useful to reveal and quantify the significance of this influence by illustrating a more direct relation between these parameters. That could assist in developing a straightforward and accurate assessment of the construction cost from the initial design stages of the project.

In order to produce such relations, cost data is presented against their corresponding GSI and RMR values existing at the tunnel face. In Figs. 2 and 3 the construction cost per cubic meter (€/m^3) is presented as a relation of GSI and RMR classifications, respectively.

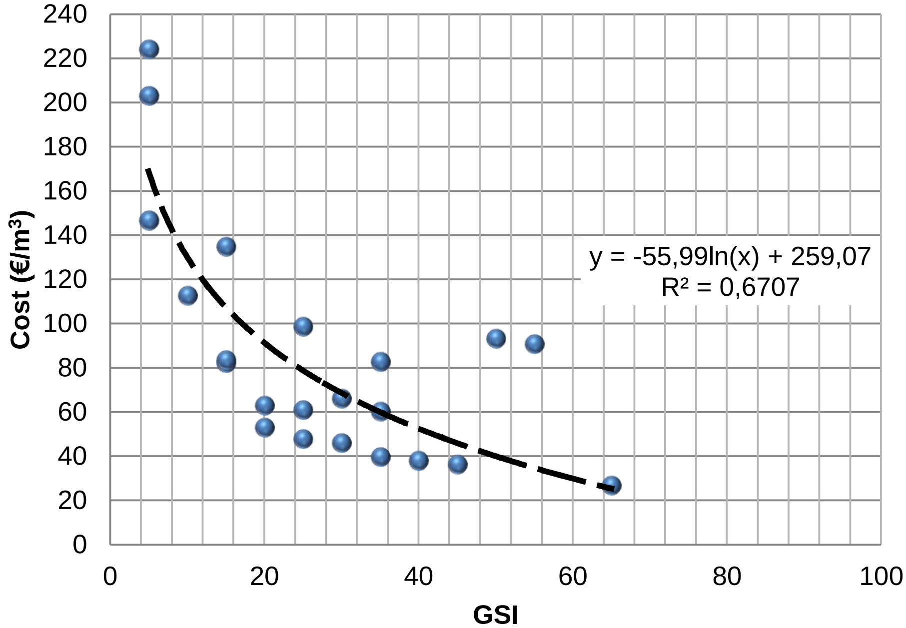

Figure 2 Construction cost (excavation and temporary support cost) vs GSI index values

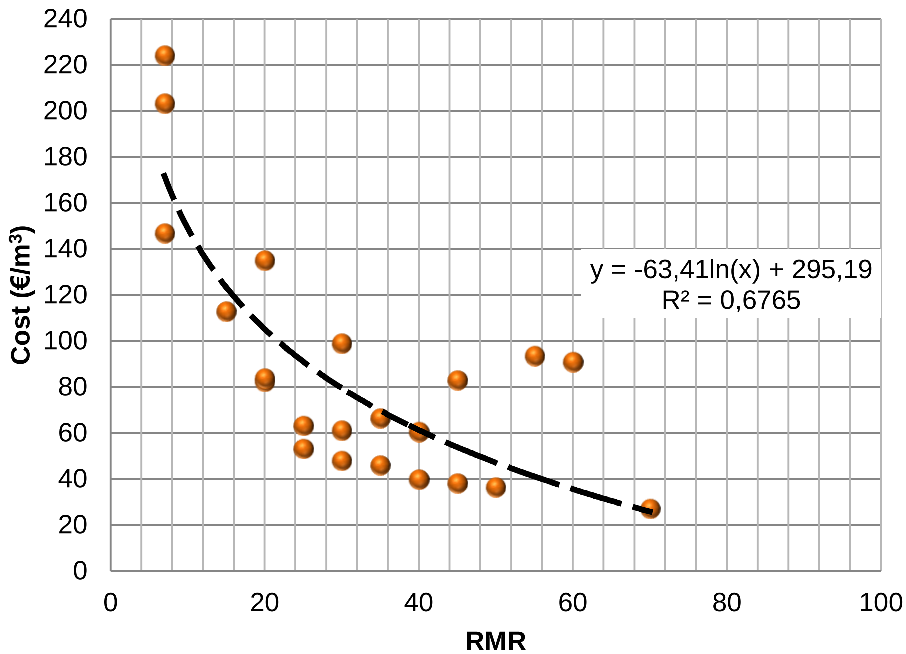

Figure 3 Construction cost (excavation and temporary support cost) vs RMR index values

These graphs can be either directly used to assess construction cost against data relating to those principal geotechnical classification indexes or can be further processed for the development of cost function equations. Two cost functions, one for each classification index (GSI and RMR), can be indicatively drawn:

$$\text{Cost } (€/m^3) = -55.91 \times \ln(\text{GSI}) + 259{,}1 \quad (1)$$

$$\text{Cost } (€/m^3) = -63.41 \times \ln(\text{RMR}) + 295{,}2 \quad (2)$$

5 CONCLUSIONS

The analysis presented on this paper aims at analyzing the cost of Greek road tunnels and to provide key data which would allow for a rapid and accurate assessment of construction cost estimation, even from the preliminary stages of tunnel design. The analysis re-evaluated and assessed cost data coming from the excavation and temporary support of a selected set of 5 Greek road tunnels. The significance of the geotechnical conditions to the construction cost is proved and it is concluded that:

- Construction cost for category “A” (GSI = 55-100): 27 €/m^3
- Construction cost for category “B” (GSI = 35-55): 48 €/m^3 (31-91 €/m^3)
- Construction cost for category “C” (GSI = 15-35): 68 €/m^3 (46-93 €/m^3)
- Construction cost for category “D” (GSI < 15): 104 €/m^3 (82-135 €/m^3)
- Construction cost for category “E” (soil behaviour): 191 €/m^3 (147-224 €/m^3)

Furthermore, the relation (cost functions) between the cost and the geological indexes (RMR and GSI) can be calculated from the following equations:

$$\text{Cost } (€/m^3) = -55.91 \times \ln(\text{GSI}) + 259{,}1$$

$$\text{Cost } (€/m^3) = -63.41 \times \ln(\text{RMR}) + 295{,}2$$

Finally, the analysis described above, can be used as a first step in developing a database to include cost data for all Greek tunnels. In this manner, the analysis requires further examination and data inputs from additional underground projects and applications in order to improve its precision and reliability, so as to be used as a preliminary cost estimation tool in underground projects in Greece and internationally.

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