BALTICA Vol.38, Issue.11, Part.1, Nov 2025, PP. 2-40 ISSN: 0067-3064
2025 38(11)

DOI Link: https://doi.org/10.61586/kTa4h
Received Feb 2025 Accepted Oct 2025 Published Nov 2025

A comprehensive assessments on differences in rock mass classes during tunnel investigation and excavation phases

Recep Temiz [1], Ebu Bekir Aygar [2] and Candan Gokceoglu [3,*]

1 Hacettepe University, Department of Geological Engineering, 06800, Beytepe, Ankara, Türkiye; rtemiz@hacettepe.edu.tr

2 IG Tunnel Engineering Consulting Company, 06640, Çankaya, Ankara, Türkiye; aygar@igtunnel.com

3 Cappadocia University, Faculty of Computer and Information Technologies, 50420 Mustafapasa, Urgup, Nevsehir, Türkiye; candan.gokceoglu@kapadokya.edu.tr

* Correspondence: candan.gokceoglu@kapadokya.edu.tr; Tel: +90 532 473 08 51

Abstract

The present study aims to perform statistical analyses on rock mass class differences encountered during the investigation and excavation phases of various tunnel projects and to quantitatively evaluate these differences. Using data obtained from five different tunnels constructed in Türkiye, the differences between the rock mass classes predicted during the investigation phase and the actual values encountered during excavation were analyzed with the parameter of Mean Percentage Absolute Difference (MPAD). The effects of the parameters introduced in the study, such as the drilling length ratio to tunnel length (LDn), total core recovery ratio (TCRn), rock quality designation ratio (RQDn) and uniaxial compressive strength test number ratio (UCSn) on these differ-ences were investigated with regression and random forest algorithms. The results showed that TCRn and RQDn have a strong inverse relationship on MPAD, in other words, the rock mass class differences decrease with the increase of these parameters. In addition, it was determined that the drilling length and total core recovery values are of critical importance in reducing the uncertainties in the tunnel route. This study is expected to contribute to more accurate predictions and to reduce cost and time losses by providing a quantitative approach to minimize uncertainties in tunnel engineering during excavation phase.

Keywords: geotechnical investigation, drilling, tunnel, RQD, RMR, uncertainty

1. Introduction

One of the most iconic statements for rock environments was published by Goodman [1] with the words "when the materials are natural rock, the only thing known with certainty is that this material will never be known with certainty" and although important scientific and technological advances, this statement still retains significant validity. According to Spross et al. [2], rock engineering design must be viewed as de-cision-making under uncertainty and they proposed a framework making the design process subject to general risk management principles, as risk is defined as “effect of uncertainties on objectives”. Benardos and Kaliampakos [3] stated that as demand for the development of new underground structures, regardless of the ground conditions, has increased, safety and risk considerations have become even more important. A framework proposed by Miranda et al. [4] is applied to the case of deformability mod-ulus updating in a large underground structure to quantify uncertainty while Pandit et al. [5] employed probabilistic approach to characterize rock mass using limited laboratory tests and field data for the stability analysis of rock slopes and tunnels.

Tunnel is a linear engineering structure and during its excavation and construction, environments with different geological and geotechnical properties are encountered. Before excavation works, drillings are performed to determine the geological and ge-otechnical properties of the tunnel route. In addition, surface investigation is combined with data obtained from drilling and geophysical measurements to predict the under-ground route properties. Using the data obtained from these investigations, the excavation method and the preliminary support system design are determined. In tunnel construction, construction time and costs are controlled by the excavation method and the support system. Therefore, the adequacy of the geological and geotechnical data of the tunnel route obtained during the investigation phase, in terms of quality and quan-tity, is of vital importance for a tunnel project. In some cases, tunnel routes can be hundreds of meters below the surface, and in mountainous areas, accessing the tunnel route from the surface may be impossible. This can significantly hinder surface drilling and geophysical studies. However, although important advancements over the recent years in computer methods and artificial intelligence algortihms for analyzing and synthesizing exploration and site investigation geological data for design purposes, which should have decreased project risk, unexpected failures and construction problems still occur [6]. Carter and Barnett [6] stated that part of this diminished appreciation of structural geological controls on rockmass behaviour can likely be attributed to inappropriate use of computational geostatistics, block modelling and geomechanics computer codes, without significant structural geological input. Consequently, significant structural geological input is the key for a realistic geological–geotechnical model and these inputs are obtained from sufficient drillings along tunnel runnel route.

Undoubtedly, the adequacy of the amount of data and the complexity of the geo-logical environment directly affects the accuracy of these predictions. In other words, the more data there is and the more homogeneous the environment is, the more accurate the predictions become. However, the differences between the geological and ge-otechnical conditions that are often predicted and encountered during tunnel construction continue to be a problem. This problem generally arises from reasons such as incomplete geological and geotechnical investigations performed during the investigation phase while determining rock classes, the scarcity of drillings, incomplete and incorrect definitions carried out during the preparation of drilling logs, and the lack of in-situ or laboratory tests. Such deficiencies are carried out during the investigation phase and result in problems during the excavation phase. The T1 tunnel in the Ankara– Izmir Highspeed Railway project of Turkiye is the fastest construction among the tunnel boring machines tunnels with a diameter of 13 m and larger, and Karahan and Gokceoglu [7] emphasized that the most important factor in this success is the accurate determination of geological and geotechnical conditions and taking the necessary pre-cautions in advance. On the other hand, although it is the same size as the T1 tunnel, the tunnel boring machine in the T26 tunnel, which is part of the Ankara- Istanbul High Speed Railway Project, got stuck and lost its function, as a result of which the tunnel construction period was considerably extended. Gokceoglu et al. [8] explained the main reasons for this failure as unexpected geological-geotechnical conditions and therefore the selection of an inappropriate tunnel boring machine. Seo et al. [9] examined on the factors affecting the performance of tunnel boring machine in hard rock and they stated that subjectivity in geological mapping is a substantial risk factor in the evaluation of fracturing factor. Fracturing factor has great effect on the estimation of net penetration rates used to estimate excavation times and costs for tunnel projects excavated with tunnel boring machines [9]. In addition, Isaksson and Stille [10] stated that numerous decisions have to be made regarding tender price and budget in the planning stage of tunnelling projects, and many studies presented that the predicted costs and time schedules are often exceeded in practice. However, a reliable geological model often allows providing an effective design and facing the construction phase without un-pleasant surprises in tunnel projects [11], and Perello [11] stated that a geological model can be considered reliable when it is a valid support to correctly foresee the rock mass behaviour, therefore preventing unexpected events during the excavation. In Eurocode7, reliability-based and the observational methods are suggested by Eurocode7 for managing uncertainty in tunnel design. Reliability-based methods account for uncer-tainty by acknowledging the random variation of the input parameters while the ob-servational method does this by verifying the expected behavior from an initial design during the course of construction [12]. A guidance described by Eurocode7 is not given on the selection of suitable parameters for observation [12].

As stated in the literature given above, differences between the predicted and encountered rock classes along tunnel route cause unforeseen cost increases and in-creased construction time, and it is an important research subject in tunnel engineering. Preventing such uncertainties and minimizing the differences between the predicted and encountered rock classes are one of the important goals in terms of tunnel engi-neering. In order to minimize this difference, the amount of investigation conducted and its assessment are important issues. The case studies presenting the tunnel failures in the literature is given in the subsequent section to show the importance of the study.

It is an important issue to reveal the reasons for this problem, which is frequently encountered both in scientific literature and in tunnel engineering practice and which ultimately causes serious loss of construction time and economic losses. Consequently, the purpose of the present study is to assess the differences between the rock mass classes determined during investigation and excavation phases for tunnels. The results of the present study may help for decision-makers and engineers when determining the optimum amount of drilling, and may contribute to the tunnelling literature. In addition, the original data obtained from five different tunnel cases is presented in the study. For this purpose of the study, different tunnel data were used in the present study to describe the uncertainty and the resulting differences were studied with statistical methods in terms of their relationships with various parameters introduced in this study. The obtained results were discussed and it was revealed which parameters con-trolled the rock class differences between the investigation and construction stages.

2. Previous Studies

In tunnel projects, inadequate work during the project phase and unforeseen geo-logical conditions during construction lead to both lost time and increased costs, negatively impacting project efficiency. Numerous studies exist in the literature addressing the problems encountered in tunnels due to unforeseen geological conditions. Some of these studies offer methodologies for minimizing unforeseen geological conditions and uncertainty in tunnels, while others address the problems encountered. Examples from these studies are discussed in detail below.

Fookes [13] developed a method and flow diagram by presenting suggestions on the model encountered with the predicted geological model under the title of geology for engineers. Boyd et al. [14] investigated the estimation of rock classes encountered before and during excavation for the Caldecott Tunnel using geostatistical methods and presented assessments on the sources of the differences. Dong et al. [15] proposed a procedure for a 3D geotechnical model in order to reduce geological and geotechnical uncertainties especially under shallow cover in urban tunnels in Aachen, Germany. Ertharter et al. [16] proposed a ground model with Building Information Modeling (BIM) in the Angath Tunnel in Austria. It was stated that the development of the BIM ground model was necessary and had great benefits. Fang et al. [17] investigated the uncertainties in tunnel risk estimation with seismic data. For this purpose, Fang et al. [17] developed an innovative workflow and examined the geological changes in the advancement direction of the TBM with continuous seismic data. Fellin et al. [18] pre-sented suggestions for the stability and analysis of tunnel face stability of tunnels excavated in weak soils with shallow overburden thickness using laboratory tests and finite element model. Fortsakis et al. [19] investigated the anisotropic rock behavior in tunnels excavated in bedded rock mass and concluded that this behavior was within a wide range. Gangrade et al. [20] examined the void risk and grouting volume encountered during tunnel construction with a probabilistic approach. Gangrade et al. [20] stated that there was a possibility of encountering voids especially in tunnels excavated in karstic units and estimated the injection amount to fill the voids with a probabilistic approach. Hack et al. [21] performed a study on the development of a three-dimensional model for engineering geology. Hao et al. [22, 23] conducted risk assessment of water flow in karstic tunnels with uncertainty analysis. Li et al. [24] investigated the unexpected conditions and uncertainties in rock tunnel engineering in their study. Madsen et al. [25] developed a new probabilistic approach for 3D geological modeling called ge-ology driven modeling (GDM). Mahmoodzadeh et al. [26, 27] studied to estimate tunnel geology, construction time and cost using machine learning methods. In these studies, they [26, 27] used Gaussian Process Regression (GPR), Support Vector Regression (SVR), and Decision Tree (DT) methods and found that the GPR method provided the highest performance. Panthi and Nilsen [28] investigated the squeezing mechanism in tunnels constructed in the Himalayas in Nepal using uncertainty analysis and stated that the most important and difficult part of the squeezing mechanism is the determination of the strength of the rock mass. Sarma et al. [29] studied to determine the locations of possible collapses in the tunnel using Tunnel Boring Machine (TBM) parameters and Rock Mass Rating (RMR) values with the help of Machine Learning (ML) model. Despite some deficiencies, Sarma et al. [29] suggested that the ML model could be used in on-going tunnel projects. Xiong et al. [30] studied on a 3D multi-scale geology model for risk assessment in tunnel engineering.

Merrie [31] presented a case from the Singapore Circle Line project, noting that a sinkhole occurred in a tunnel with complex geology, and that during the excavation phase, a sinkhole was encountered in a section identified as granite by drilling. Therefore, Merrie [31]

ISSN: 0067-3064

emphasized the importance of a geological interpretation process and an accurate geotechnical model during the investigation phase for tunnel safety. Li et al. [32] emphasized that understanding the geology of a tunnel before boring is highly advantageous for the safety and efficiency of tunnel construction. The Qiyueshan Tunnel, located on the Hurongxi Highway in China, was constructed in an area with widespread karst formations [32]. The rocks surrounding the tunnel consist of highly soluble microcrystalline limestone, and the presence of underground rivers and karst caves increases the risk of water inrush during tunnel construction. This geological situation made it difficult to predict hazards such as karst caves and groundwater in-trusion. During construction, especially during the rainy season, water intrusions occurred in the left side wall of the tunnel, causing a 500-meter section of the tunnel to be submerged [32].

Alija et al. [33] discuss the partial collapse of the Ampurdán Tunnel in Spain. The tunnel passes through a weak and weather-sensitive geological unit, the Ampurdán claystone formation. This unit is characterized by low strength and high deformation properties. While geotechnical investigations conducted prior to the project generally predicted the geotechnical properties, unexpected changes occurred during tunnel excavation [33]. In particular, the rapid weathering of the claystone material due to post-excavation weathering and water infiltration led to the partial collapse of the tunnel [33]. The Ceneri Base tunnel constructed between Bellinzona and Lugano as part of Switzerland's AlpTransit Gotthard AG project, emphasized the tunnel's complex geological conditions caused by unpredictable faults [34]. These unforeseen conditions controlled to stability issues during tunnel excavation, particularly wedge blocks falling from the ceiling and side walls [34].

Ye et al. [35] reported deformations of up to 0.8 meters around the tunnel during construction in Shanghai, China, in the Shanghai clays. They [35] determined that these deformations were much larger than expected due to false application of the backfill grouting, TBM operational issues, and frictional effects between the ground and the machine during tunnel construction. Huang et al. [36] presented that severe defor-mations occurred during construction of a metro line constructed using a TBM in the Shanghai clays of China due to extreme surface loading (surcharge). These included openings at the joints of tunnel segments, failures of segment-connecting bolts, concrete cracks, and water leaks. These deformations resulted in the tunnel losing its water-proofing function and compromising its structural integrity [36].

Since the Kop Tunnel, located on the Erzurum- Bayburt- Gümüşhane road in Türkiye, is located at the intersection of the Eastern Anatolian and Northern Anatolian fault zones, certain problems such as excessive overbreakings, water and gas intrusions along the tunnel line during construction had a adverse impact on both the excavation work and the completion time of the work [37]. Liu et al. [38] reported that serious structural problems arose during construction of a subway line in the Shanghai clays in China due to ground settlements and leaks. In particular, differential settlement occurred between tunnel segments and displacement at the circumferential joints. This resulted in cracking and spalling of the concrete lining. The main cause of the problem was identified as water and soil loss in the subgrade. These losses reduced the reaction pressure beneath the tunnel and caused the tunnel to settle [38]. The tunnels constructed in South Korea under complex geological conditions and the effects of natural hazards such as extreme rainfall, floods, and strong winds encountered adverse impacts such as collapses, landslides, and floods during tunnel construction [39]. However, strong winds and heavy rainfall, particularly those caused by typhoons, caused signif-icant financial losses during construction. These problems led to unexpected cost increases and lost time in construction projects [39].

Aygar and Gokceoglu [40] presented that a fault defined as a crushed zone and a low-strength and plastic clay unit in the Öceli Tunnel, constructed as part of the Ordu Ring Road Project in northern Türkiye, absorbed water from the surrounding lithological units, causing swelling and loss of strength. This led to severe deformations and a collapse during tunnel excavation, displacing 160 m^3 of material. In addition, Aygar and Gokceoglu [41] highlighted the significant challenges faced by the Geminbeli Tunnel, located between Zara and Suşehri in Türkiye, in terms of stability at the tunnel portal in a region with high seismicity due to its proximity to the North Anatolian Fault Zone. During construction, failure in the portal area led to deformations and collapses within the tunnel, severely impacting its stability [41].

Hong et al. [42] presented that during excavation of the SV Tunnel on the Dongzhi Plateau in China, water infiltration and reduced soil strength caused unexpected deformations and two sudden collapses in a geological unit known for its high water content and low strength, called a soft-plastic loess layer. This resulted in structural problems such as block falls, deformations of steel supports, and water accumulation on the tunnel surface [42].

Yu and Mooney [43], in their study on the Seattle Northgate Link Extension project, noted that due to the limited number of boreholes, data was limited, particularly at the beginning of the excavation, negatively impacting model performance. They also presented that the predicted ground condition could be completely different during excavation with a TBM. However, Yu and Mooney [43] also emphasised that the SSL (Semi-supervised learning) model they proposed, given the limited borehole data, provided a more effective measure for determining the ground condition during tunnel construction. Yousuf et al. [44] described the tunnel constructed in the geologically complex and challenging Himalayan region. The tunnel, which was excavated using the New Austrian Tunneling Method (NATM), was constructed in a young and tectonically active region. The young and tectonically active structure of the region, along with fractured rock masses, shear zones, high local stresses, and frequent seismic activity, caused groundwater intrusion, unexpected collapses, and sudden rockbursts [44].

As studies indicate, problems encountered during tunnel construction due to discrepancies between geological– geotechnical predictions during investigation phase and actual conditions during construction phase are common problem worldwide. While studies on minimizing these discrepancies and the presented methodology are wide-spread in the literature, solid and quantitative studies on these discrepancies are lack-ing. Therefore, a quantitative approach based on the rock class differences during the investigation and construction phases, the subject of this article, and the quantitative identification of the variables that influence these differences, may contribute to addressing a common and significant problem worldwide.

3. Materials and Methods

3.1. Tunnels Employed

The first stage of any tunnel project is determining the optimum tunnel route. Determining the optimum route includes important parameters such as selecting the most suitable excavation direction, shortest route, best slope, diggability and best suitability for existing transportation facilities etc. Project engineers decide on the optimum tunnel route by considering these issues. After the tunnel route is decided, more detailed field investigation studies such as the location of the portals, length of tunnel, and geological conditions are carried out and evaluated in terms of construction cost, construction period, construction and operating conditions. After this stage, detailed field studies are carried out to obtain the engineering geology map of the tunnel route and the geotechnical properties of the rock masses. For this purpose, as many boreholes as possible are performed in the field to enable modeling of the tunnel body and portals, and geophysical research is carried out. In order to obtain the necessary rock mass parameters, samples of the lithological units on the tunnel route are taken and laboratory studies are carried out. The horizontal and vertical transition of the units with each other along the tunnel route; the effects of discontinuities such as faults, shear zones, contacts etc., and the effect of water content are the primary effective features in the design of the tunnel. However, high seismicity and in-situ stresses also directly affect the design. The February 6, 2023, earthquake in Türkiye provided important information about the seismic performance of tunnels [45, 46]. Therefore, the impact of earthquakes and active faults on tunnels requires careful consideration. In the last step of the data collection phase, all the data collected are brought together to create the geological and geotechnical model of the selected tunnel route and the geological-geotechnical model of the route is created. Using this model, numerical analyses are used to estimate the displacements after tunnel excavation and the necessary supports are determined. Thus, the tunnel project is completed. However, uncertainty plays a critical role in geotechnical design projects [47].

In Türkiye, highway tunnels are generally excavated in accordance with the principles of the New Austrian Tunneling Method (NATM). During the construction phase, the geological condition of the tunnel excavation face is evaluated at each progress step and recorded with face records. This situation allows the comparison of the project predictions with the actual situation encountered during construction after the construction of the tunnel is completed.

In this study, data obtained from the project and construction phases of 5 different tunnels were used (Figure 1). All of the tunnels are double-tube tunnels constructed using NATM. Of these, Yüksekova T-1, Filyos T-4-B have 2 lanes and are 10 m in diameter, while Bahçecik, Boztepe and Gölçayır Tunnels have 3 lanes and are 12 m in diameter.

ISSN: 0067-3064

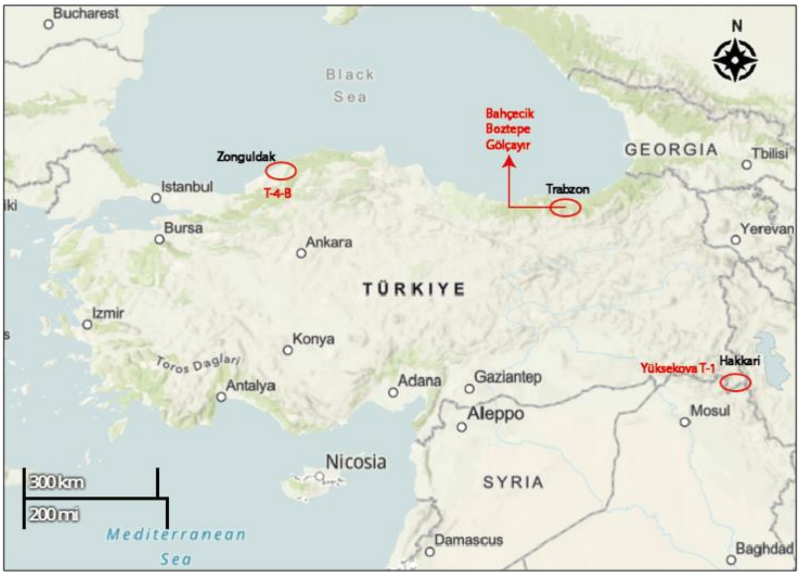

Figure 1. Location map of the tunnels employed in the study

3.1.1. Yüksekova T-1 Tunnel

Yüksekova T-1 Tunnel is approximately 4 km long, T-1 tunnel is located in Hakkari province in the south-east of Türkiye (Figure 1). Three drillings were performed in the project phase of T-1 tunnel, the lengths of which were 201 m, 212 m and 100 m respectively. 21 uniaxial compressive strength tests were carried out on the core specimens obtained from these drillings. Yüksekova Complex consisting of serpentinite, granite and limestone units is seen along the tunnel route (Figure 2). T-1 tunnel was excavated within the geological units called Yüksekova Complex. Due to the complex geological properties of Türkiye, several difficulties have been encountered when constructing tunnels in Türkiye [48- 50].

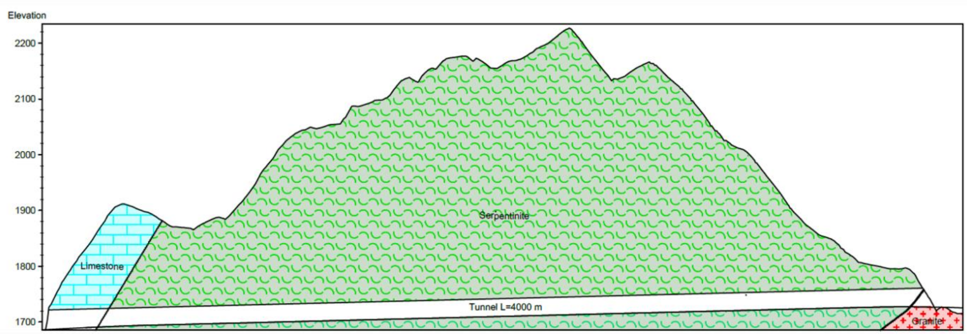

Figure 2. Longitudinal cross-section of Yüksekova T-1 tunnel

ISSN: 0067-3064

3.1.2. Boztepe Tunnel

Boztepe Tunnel, left tube is 653 m long, right tube is 727 m long. It is located in Trabzon province in northeastern Türkiye (Figure 1). During the investigation phase of Boztepe tunnel, two drillings were carried out with lengths of 92 m and 118 m, respectively. Six uniaxial compressive strength tests were applied on the specimens taken from these drillings. According to the cross-section presented in Figure 3, Boztepe Tunnel was excavated in brown-grey, slightly-moderately weathered, weak-medium strong basalt units.

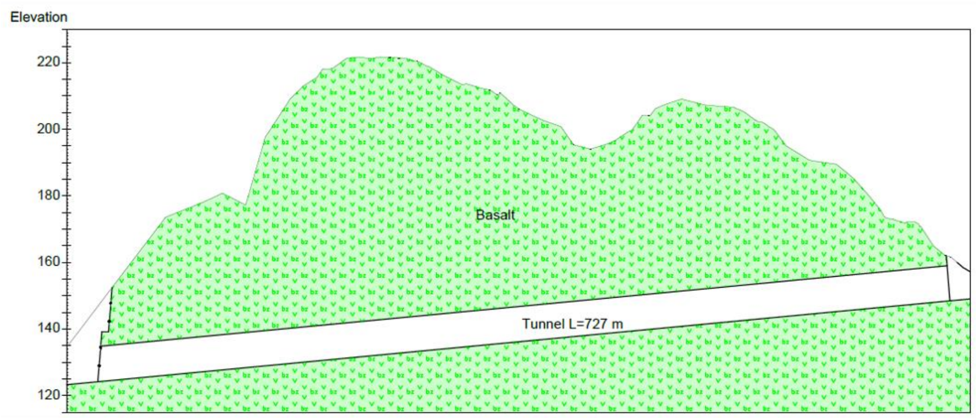

Figure 3. Longitudinal cross-section of Boztepe tunnel

3.1.3. Bahçecik Tunnel

Left tube of Bahçecik Tunnel is 529 m while its right tube is 540 m long. It is located in Trabzon province in northeastern Türkiye (Figure 1). During the investigation phase of Bahçecik Tunnel, eight drillings were performed with lengths of 115 m, 66 m, 45 m, 45 m, 35 m, 45 m, 50 m, 45 m, respectively. Total 27 uniaxial compressive strength tests were applied on the specimens obtained from these drillings. According to the cross-section presented in Figure 4, Bahçecik Tunnel was excavated in gray, slightly weathered, moderately strong agglomerate with andesite intrusions in places.

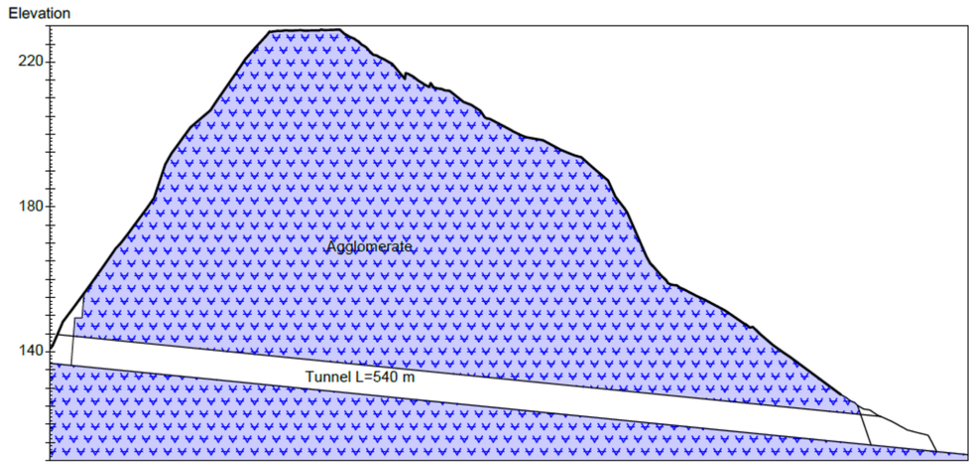

Figure 4. Longitudinal cross-section of Bahçecik tunnel

3.1.4. T-4-B Tunnel

Left tube of T-4-B Tunnel is 1227 m while its right tube is 1216.5 m long. It is located in Zonguldak province in northwestern Türkiye (Figure 1). In the investigation stage of T-4-B tunnel, two drillings with lengths of 155 and 75 m were performed. Total 11 uniaxial compressive strength tests were applied on the specimens obtained from the drillings. According to the longitudinal cross-section presented in Figure 5, it was excavated in the volcaniclastic gray, slightly-moderately weathered, medium-strong sandstone, claystone, siltstone alternation belonging to Gökçetepe Formation.

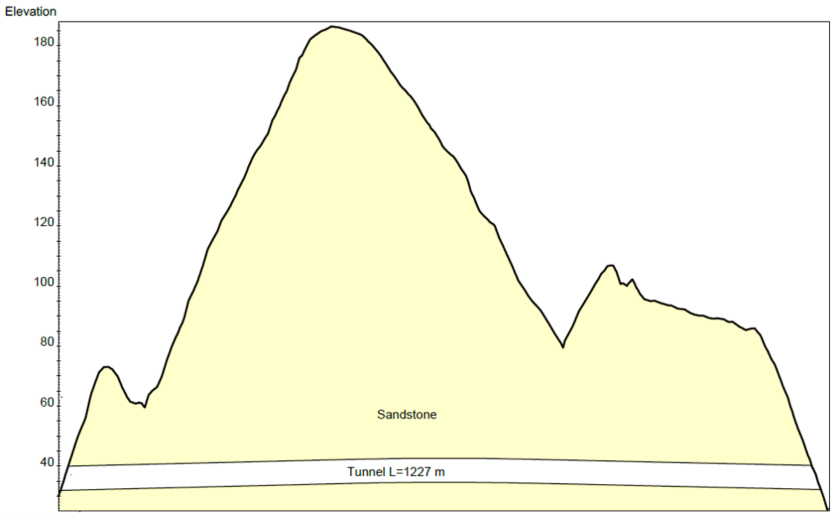

Figure 5. Longitudinal cross-section of T-4-B tunnel

3.1.5. Gölçayır Tunnel

Left tube of Gölçayır Tunnel is 444 m and its right tube is 491 m long. It is located in Trabzon province in northwestern Türkiye (Figure 1). During the investigation phase of Gölçayır Tunnel, total 6 drillings with lengths of 35, 55, 60, 75, 60 and 36 m were performed and total 19 uniaxial compressive strength tests were applied on the specimens taken from these drillings. According to the cross-section given in Figure 6, it was excavated within the dark-colored, moderately weathered, weak-medium strength, pyroclastic rocks consisting of volcanic breccia, sandstone, claystone, siltstone, tuff and tuffite alternations belonging to Kabaköy Formation.

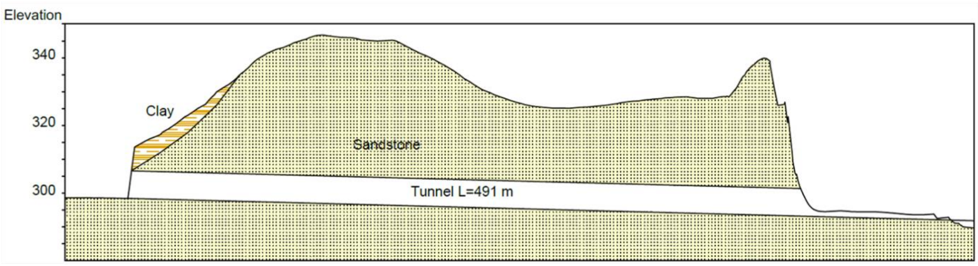

Figure 6. Longitudinal cross-section of Gölçayır tunnel

3.2. Statistical Analyses

Statistical analyses play a crucial role in assessing the impact of geological and geotechnical uncertainties encountered during tunnel design and construction, and in minimizing these uncertainties. The statistical analyses conducted in this study quantitatively demonstrate the differences between data obtained during the project phase and the actual conditions encountered during construction, allowing us to identify the parameters that influence these uncertainties. Consequently, the statistical analyses performed within the scope of this study were conducted by evaluating the differences between the predictions obtained from the studies performed during the investigation phase of five different tunnels and the actual rock conditions encountered during the construction phase.

Table 1 shows the names and lengths of the drillings performed in 5 tunnels con-sidered within the scope of the study, the number of uniaxial compressive strength (UCS) tests performed on the core samples taken from the drillings, and the arithmetic average of the RQD and TCR values obtained from the drillings. Table 2 shows the values of the dependent and independent variables used in the statistical analyses. It should be noted that the RQDn and TCRn variables are the proportional expression of the average RQD and TCR values per tunnel unit length.

Accordingly;

LDn is the ratio of the total length of the boreholes along the tunnel line to the tunnel length. Therefore, LDn is the ratio of the borehole length per unit tunnel length.

TCRn is the ratio of the arithmetic mean of the total core yield (TCR) values obtained from boreholes drilled along the tunnel to the tunnel length.

 ISSN: 0067-3064

RQDn is the ratio of the arithmetic mean of the rock quality value (RQD) values obtained from boreholes drilled along the tunnel to the tunnel length. RQDn

UCSn is the ratio of the number of uniaxial compressive strength tests performed on core samples obtained from boreholes drilled along the tunnel to the tunnel length.

The mean absolute percentage difference (MPAD), used as the dependent variable in statistical analyses, is the absolute arithmetic mean of the percentage change between the estimated RMR (rock mass rating) scores during the investigation phase and the calculated RMR score differences encountered at the tunnel face during the construction phase. For each tunnel, the RMR values, calculated based on the geological conditions encountered at the tunnel face during the construction phase and predicted during the investigation phase, were calculated at 20-meter intervals. For example, for the Yüksekova T-1 tunnel, when the RMR values from the investigation and construction phases were compared at 20-meter intervals, approximately 200 absolute percentage difference values were obtained for each tunnel tube. The arithmetic average of these values was then calculated for the right and left tubes of each tunnel (Table 3). This calculation was also performed at 20-meter intervals for the other tunnels. Therefore, a precise difference analysis was performed for each tunnel, increasing the number and precision of data. Whole dataset employed during the study is given in Appendix.

Table 1. Data obtained from the tunnels considered

Name of Tunnel	Name of Drilling	Drilling Length (m)	Uniaxial Compressive Strength, (number of test)	Mean RQD, (%)	Mean TCR, (%)
Yüksekova T-1	SK-0+872	201	5	40.36	74.57
	SK-0+980	212	9	50.85	89.43
	SK-3+860	100	7	20.23	64.78
Bahçecik	SK-7+014	115	2	46.59	80.83
	SK-7+150	66	3	61.21	96.97
	SK-7+300 Left	45	0	13.31	73.08
	SK-7+300 Right	45	0	17.33	76.53
	TSK-21	50	6	68.73	92.31
	TSK-22	45	8	60.08	88.67
	TSK-23	35	0	67.33	100
	TSK-24	45	8	61.38	94.38
Boztepe	SK-3+860	100	7	20.23	64.78
	SK-9+695	118	3	89.71	98.46
	SK-9+890	92	3	68.16	98.86
Gölçayir	TSK-19	36	3	23.78	56.27
	TSK-20	35	0	36.00	72.17
	TSK-30	55	3	24.81	56.44
	TSK-33	60	4	61.43	92.03
	TSK-35	75	5	69.96	100
	TSK-36	60	4	65.54	100
T-4-B	SK-9+900	155	6	64.87	80.58
	SK-10+400	75	5	72.50	85.39

Table 2. Data on tunnels

Name of Tunnel		LDn* (ratio)	TCRn* (ratio)	RQDn* (ratio)	UCSn* (ratio)	MPAD* (%)
Yüksekova T-1	Left tube	0.13	1.92	0.94	0.005	73.05
	Right tube	0.13	1.93	0.94	0.005	38.95
Bahçecik	Left tube	0.58	16.62	9.40	0.025	17.74
	Right tube	0.26	16.23	9.09	0.026	15.62
Boztepe	Left tube	0.14	15.14	10.44	0.005	6.47
	Right tube	0.16	13.54	12.34	0.004	6.68
T-4-B	Left tube	0.19	6.76	5.60	0.009	9.48
	Right tube	0.19	6.82	5.65	0.009	8.23
Gölçayır	Left tube	0.60	17.79	10.90	0.034	2.31
	Right tube	0.46	17.31	10.97	0.032	0.17

*LDn: The ratio of drilling length to tunnel length, TCRn: The ratio of the arithmetic mean of the TCR (total core recovery) values to tunnel length, RQDn: The ratio of the arithmetic mean of the RQD (rock quality designation) values to tunnel length, UCSn: The ratio of the arithmetic mean of the number of UCS (uniaxial compressive strength) test to tunnel length, MPAD: Mean percent absolute difference

Table 3. MPAD sample calculation for Yüksekova T-1 tunnel

No	RMR		Difference,%
	Project	Construction	
1	37	39	5.13
2	37	39	5.13
3	45	39	-15.4
4	45	42	-7.14
5	45	42	-7.14
6	45	42	-7.14
7	45	42	-7.14
-	-	-	-
-	-	-	-
-	-	-	-
191	41	39	-5.13
192	41	39	-5.13
193	41	39	-5.13
194	41	15	-173.33
195	41	15	-173.33
196	48	15	-220
197	48	15	-220
198	45	15	-200
199	45	39	-15.39
Mean Percent Absolute Difference, MPAD, %			73.05

Two different methods were used in statistical analyses. One of them is regression analysis while the other is feature importance analysis. First of all, the relationship between dependent and independent variables was investigated with regression anal-ysis. The effect of independent variables on the dependent variable was examined using feature importance analysis and random forest algorithm.

3.2.1. Regression Analysis

In the first stage, the relationship between independent variables LDn, TCRn, RQDn and UCSn and dependent variable MPAD was examined in regression analyses. Accordingly, regression analysis results obtained from the relationship between MPAD and each independent variable are summarized in Table 4. The equations obtained from the regression analysis results are given in Table 5.

Relationship graphs of the equations having the highest coefficient of correlations (R^2) values achieved are given in Figure 7. When the results given in Table 4 are assessed, the highest R^2 values between dependent variable MPAD and independent variables were found as 0.36 for LDn as exponential function, 0.80 for TCRn, 0.82 for RQDn; and 0.17 for UCSn as linear function.

Table 4. Regression analysis results (R^2) for the dependent variable of mean percent absolute difference (MPAD)

	Linear	**Logarithmic**	**Exponential**	**Power**
LDn	0.16	0.23	0.23	0.36
TCRn	0.52	0.69	0.70	0.80
RQDn	0.65	0.79	0.79	0.82
UCSn	0.17	0.16	0.16	0.13

Table 5. Equalities According to Regression Results

	MPAD
LDn	$y = 0.9087x^{-1.511}$
TCRn	$y = 116.36x^{-1.229}$
RQDn	$y = 54.795x^{-1.105}$
UCSn	$y = -755.86x + 29.468$

ISSN: 0067-3064

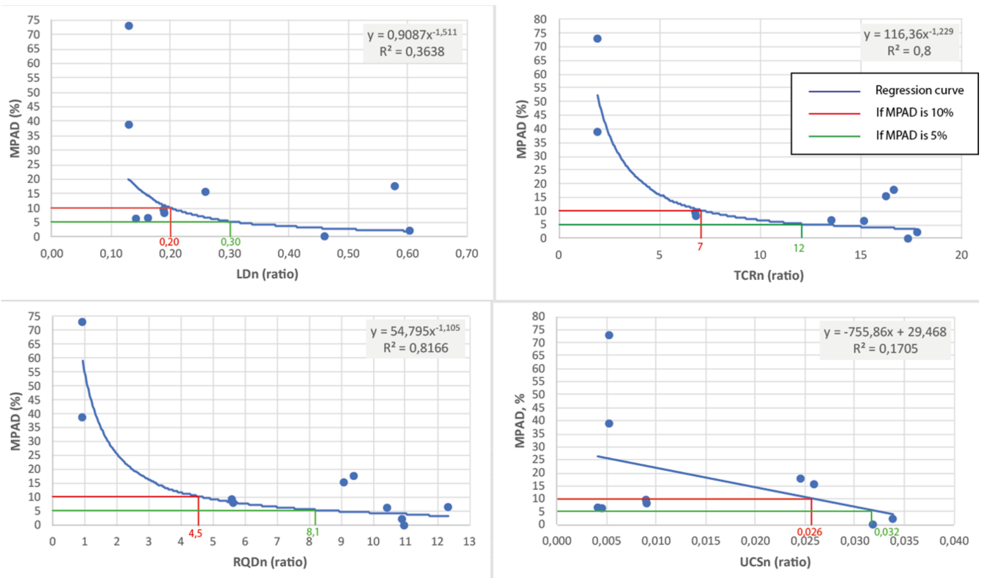

Figure 7. Regression analysis graphs according to the dependent variable of MPAD

According to these results, the heat map and grouped bar charts showing the dis-tribution of the regression analysis results of MPAD with independent variables are given in Figures 8 and 9. Accordingly, the highest R^2 value on MPAD was obtained from the RQD independent variable with the exponential function relationship, while the lowest R^2 value was created by the UCS independent variable with the linear function relationship.

In Figure 7, the relationship between the Mean Percentage Absolute Difference (MPAD) variable, which is based on the geological conditions in the project and construction phases of the tunnels used in this study, in other words, the rock classification differences made in the project and excavation phases, and the independent variables is also expressed numerically. Accordingly, if the MPAD is 10%, it corresponds to the values LDn=0.20, TCRn=7, RQDn=4.5, UCSn=0.026. In case the MPAD increases, these values decrease depending on the relationship (Figure 7). Similarly, if the MPAD de-creases, for example, if it is 5%, the values of the independent variables increase and become LDn=0.30, TCRn=12, RQDn=8.1, UCSn=0.032, respectively. Therefore, these values were determined according to the geological conditions of the ophiolitic mélange, volcanic, volcano-sedimentary units belonging to the tunnels used within the scope of the study. The MPAD and the decrease in the absolute difference numerically express that the current situation encountered during the construction phase is ap-proached with the studies carried out during the investigation phase. This situation is also related to the homogeneity or complexity of the geological conditions in which the tunnel will be constructed. More homogeneous geological conditions, better drilling quality during the tunnel design phase and high TCR values will reduce the MPAD, together with better presentation of the geological conditions. The relationships presented in this study need to be further developed by increasing the data sets and conducting studies according to different geological conditions, and this should be considered as a limitation of the study.

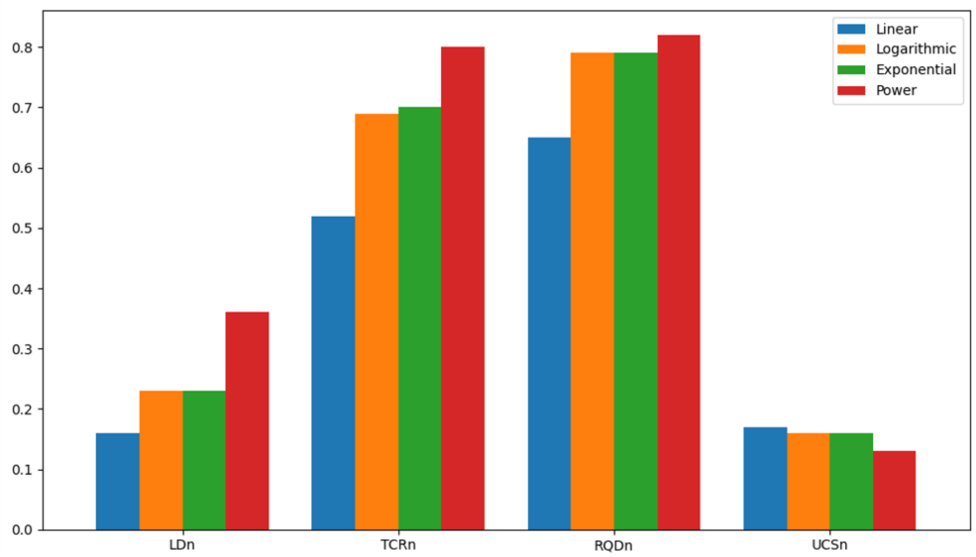

Figure 8. Grouped bar chart of regression analyses performed according to the dependent variable of MPAD

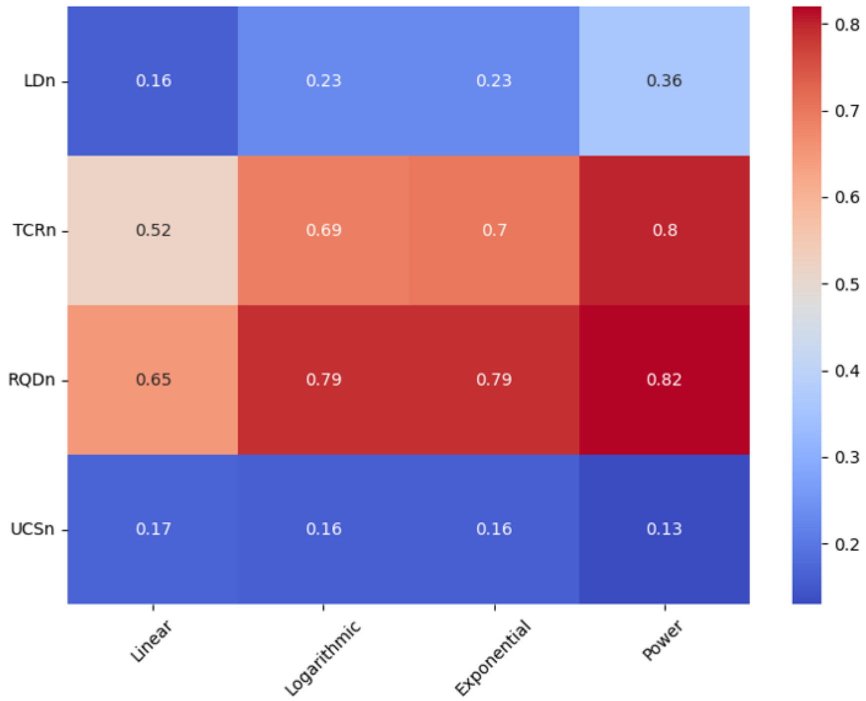

Figure 9. Heat map of regression analyses performed on the dependent variable of MPAD

ISSN: 0067-3064

The linear regression results are given in Tables 6-8. When Table 6 is inspected, the correlation coefficient R value of 0.835 indicates that there is a strong relationship between the dependent and independent variables. At the same time, the R^2 value of 0.697 indicates that the model explains 69.7% of the total variance in the dependent variable, and in this case, it is concluded that the model is enough explanatory. How-ever, in order to understand whether this explanatory power is statistically significant, the F Change and Sig. F Change values should be examined. Here, the F Change value of 2.871 indicates that there is an increase in the explanatory power of the model, however, whether this increase is significant can be understood by looking at the Sig. F Change value. Accordingly, the Sig. F Change value of 0.139 indicates that it is not statistically significant, in other words, it indicates that the effect of the independent variables of the model on the dependent variable MPAD may be coincidental and that the model needs to be improved. These values, which explain the general significance of the regression analysis, are also given in Table 7. Regression (3112.627) shows how much the model explains the dependent variable MPAD, and it is desired to be high in the model, on the other hand, Residual (1355.249) expresses the variance that the model cannot explain and it is desired to be low in the model. In Table 7, the Residual and Mean Square Residual values show that the variance that the model cannot explain is still significant.

Table 6. Model Summary- MPAD

Model summary								
R	R square	Adjusted R square	Std. error of the estimate	Change statistics				
				R square change	F change	df1	df2	Sig. F change
0.835	0.697	0.454	16.4635912	0.697	2.871	4	5	0.139

Table 7. ANOVA results- MPAD

ANOVA					
	Sum of squares	df	Mean square	F	Sig
Regression	3112.627	4	778.157	3	0.139
Residual	1355.249	5	271.050		
Total	4467.876	9			

Table 8 shows the effect of the independent variables in the regression model on MPAD and the statistical significance of these effects in detail, including the coefficients, standard errors, t statistics and significance levels of each independent variable. Here, it is seen that the constant term is statistically significant (0.008<0.05), while the other variables are not statistically significant. However, this situation is related to the number of case and it should be taken into account that it will not affect the general trend of the equation and the relative effect of the independent variables on the dependent variable.

Table 8. Coefficients of each variable- MPAD

Coefficients							
	Unstandardized Coefficients		Standardized Coefficients	t	Sig	95.0% Confidence Interval for B	
	B	Std. error	Beta			Lower bound	Upper bound
(Constant)	51.548	12.114		4.255	0.008	20.41	82.687
LDn	13.892	65.385	0.118	0.212	0.84	-154.185	181.97
TCRn	3.415	4.223	0.979	0.809	0.455	-7.44	14.269
RQDn	-8.403	5.238	-1.564	-1.604	0.17	-21.868	5.061
UCSn	-814.461	1240.087	-0.445	-0.657	0.54	-4002.206	2373.283

Correlation coefficients express the strength and direction of the simple relation-ship between two variables. The values vary between -1 and 1. "1" indicates a positive and excellent relationship while "-1" indicates an inverse excellent relationship, and finally "0" indicates no relationship. When Table 9 is examined, MPAD generally show a negative relationship with the independent variables. There is a negative strong effect between TCRn and MPAD, reaching -0.720, and between RQDn and MPAD, reaching -0.809 correlation coefficients.

According to these results, especially RQDn and TCRn have strong negative effects on MPAD. This shows that the effect of these variables on the dependent variable is significant.

Table 9. Coefficient of correlations- MPAD

Correlations					
	MPAD	LDn	TCRn	RQDn	UCSn
MPAD	1.000				
LDn	-0.399	1.000			
TCRn	-0.720	0.691	1.000		
RQDn	-0.809	0.509	0.935	1.000	
UCSn	-0.412	0.892	0.714	0.493	1.000

3.2.2. Feature importance analysis

The feature importance is an important reference for feature selection and model in-terpretability [51]. The random forest (RF) is a powerful ensemble learning method based on classification and regression trees (CART). The first algorithm for random decision forests was proposed by Ho [52] and the extension of the algorithm was de-veloped by Breiman [53]. Random Forest (RF) is an ensemble model that leverages multiple regression trees for training samples in regression tasks [51, 54-56]. This analysis is widely used in engineering fields such as tunneling. Gokceoglu et al. [57] estimated the rate of penetration (ROP) of the tunnel boring machine (TBM) using the Random Forest algorithm, using the geological and geotechnical parameters of the Bahçe- Nurdağı tunnel and the basic TBM parameters. Cheng et al. [51] used a Random Forest model to estimate the amount of settlement caused by tunnel excavations. Feng et al. [58] employed the Random Forest model combined with the Artificial Bee Colony (ABC) algorithm to predict tunnel deformation. Feature Importance Analysis was applied to optimize the hyperparameters of the model and identify the most important factors affecting the deformation [58].

Yang et al. [59] used Random Forest model for rock mass classification for tunnel excavations. With data obtained from 5537 tunnel boring cycles, the researchers increased the classification accuracy by using Feature Importance Analysis. Yang et al. [59] combined Random Forest with other methods and achieved a significant improvement in the classification performance. Liu et al. [60] proposed a new method for controlling overbreak during tunnel blasting. In the method proposed by Liu et al. [60], Random Forest was considered to estimate the amount of the overbreak and to measure the effect of input parameters. The most critical factors were determined by Feature Importance Analysis, and these factors were combined with meta-heuristic algorithms to optimize the blasting process [60].

In this study, feature importance analysis was performed using the RF model to determine the effect of four independent variables (LDn, TCRn, RQDn, UCSn) on the dependent variable (MPAD) and the results are given in Figures 10. In Figure 10, the right axis contains the independent variables, while the left axis contains the values showing the effect of the independent variables on the dependent variable MPAD.

Accordingly, the variables with the highest effect on the dependent variable Mean Percent Absolute Difference (MPAD) are LDn and TCRn (approximately 0.30), followed by RQDn (approximately 0.25) and the variable with the lowest importance, UCSn (0.10). This analysis reveals that the dependent variable MPAD is affected more than the variables LDn, TCRn and RQDn, respectively. These results show that drilling parameters are quite effective on the correct rock mass classification of tunnel route.

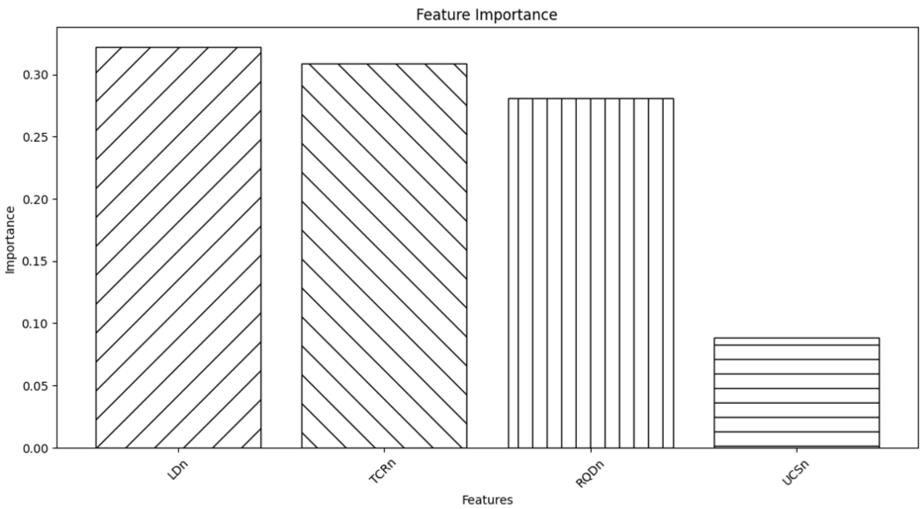

Figure 10. Random Forest- Feature Importance Analysis- MPAD

SHAP analysis is a method developed to explain the predictions of complex machine learning models. This analysis uses Shapley values to measure the contribution of each feature to the model prediction. SHAP measures feature importance based on Shapley values [61]. Evaluations using SHAP analysis are quite common in the literature. These studies generally cover studies on feature importance ranking and model explainability in tunnel engineering projects with SHAP analysis.

Chen et al. [62] employed SHAP analysis to analyze the effect of input parameters on tunnel deformation. In the study performed by Chen et al. [33], the parameters that have the highest effect on tunnel deformation were determined by SHAP analysis. In the study published by Liu et al. [63], SHAP analysis was considered to explain the mechanisms of the SSA- LGBM model and to evaluate the load- bearing capacity of the tunnel geometry and overburden. Kannangara et al. [64] considered SHAP analysis to under-stand the output of complex machine learning models and to determine the effective features on the settlement caused by tunnel excavation.

In this study, the Random Forest model was used to analyze the effect of 4 independent variables (LDn, TCRn, RQDn, UCSn) on the dependent variable MPAD using SHAP analysis, and SHAP feature importance graphs were obtained. Figure 11 shows that TCRn and RQDn variables have a strong negative effect on MPAD. This effect results in an effect that increases TCRn and RQDn and decreases MPAD. However, according to the results, it cannot be said that LDn and UCSn variables have a strong effect on MPAD. Nevertheless, it can be interpreted that the increase in LDn also has a negative effect on MPAD, although not as much as TCRn and RQDn. This result also confirms the accuracy of the inverse relationship functions reached in the regression analyses.

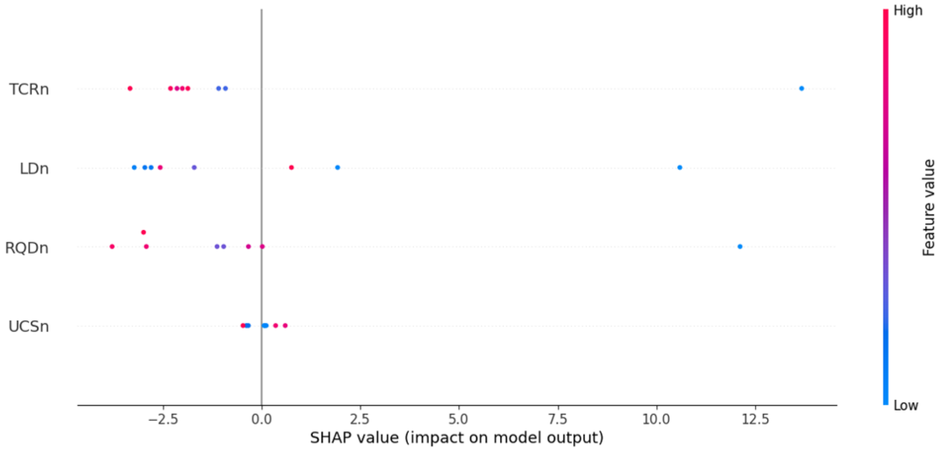

Figure 11. SHAP-Analysis- MPAD

3. Conclusions

The conclusions obtained from the study can be drawn as follows:

(a) The present study is based on the difference between the results of the rock mass classification predicted during the tunnel investigation phase and the results of the rock mass classification obtained from the lithological units encountered in the excavation face during the construction of the tunnel. This difference was revealed as mean percent absolute difference (MPAD) within the scope of the study.

(b) The amount and quality of the field and laboratory studies performed during the geological and geotechnical investigation phase of a tunnel project, such as the total core recovery (TCRn) and rock quality designation (RQDn), were evaluated as factors affecting MPAD.

(c) Accordingly, a two- stage statistical evaluation was applied to reveal the relationships between the length of the drillings (LDn) carried out during the design phase, the total core recovery (TCRn), the rock quality designation (RQDn) and the uniaxial compressive strength tests carried out with MPAD. Regression analyses were used as the first stage in the statistical evaluations, and feature importance analysis was used as the second stage.

(d) In feature importance analyses, LDn, TCRn and RQDn are the most important variables supporting the regression models, supporting the established relationships. All analyses and outputs conducted within the scope of the study determined the importance of drilling length, total core recovery and rock quality designation during the investigation phase of the tunnels. The study presented a quantitative approach to the inverse relationship between these variables and the differences in order to minimize the differences encountered during the investigation and construction phases.

(e) In the present study, the rock classification differences performed in the investigation and excavation phases, and the independent variables is expressed numerically. Accordingly, if the MPAD is 10%, it corresponds to the values LDn=0.20, TCRn=7, RQDn=4.5, UCSn=0.026. In case the MPAD increases, these values decrease depending on the relationship.

(f) Consequently, more homogeneous geological conditions, better drilling quality during the tunnel design phase and high TCR values will reduce the MPAD, together with better presentation of the geological conditions. The relationships presented in the present study need to be further developed by increasing the data sets and conducting studies according to different geological conditions, and this should be considered as a limitation of the study.

Acknowledgment : This study is produced from the PhD thesis of the first author, Recep Temiz. Other two authors of the study are co-supervisor and supervisor of the PhD thesis.

Author Contributions: "Conceptualization, R.T. and C.G.; methodology, R.T. and E.B.A.; soft-ware, R.T.; validation, R.T., E.B.A. and C.G.; formal analysis, R.T.; investigation, R.T. and E.B.A.; resources, R.T. and G.G.; data curation, R.T.; writing—original draft preparation, R.T. and E.B.A.; writing—review and editing, C.G.; visualization, R.T. and E.B.A.; supervision, E.B.A. and C.G.; project administration, C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Data Availability Statement: Whole dataset employed in the study is given as Appendix.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LDn	The ratio of drilling length to tunnel length
TCRn	The ratio of the arithmetic mean of the TCR (total core recovery) values to tunnel length
RQDn	The ratio of the arithmetic mean of the RQD (rock quality designation) values to tunnel length
UCSn	The ratio of the arithmetic mean of the number of UCS (uniaxial compressive strength) test to tunnel length
MPAD	Mean percent absolute difference

 ISSN: 0067-3064

Appendix A

Table A.1. Yüksekova T-1 Tunnel Left Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	37	39	5.13	38	41	42	2.38
2	37	39	5.13	39	41	42	2.38
3	45	39	-15.4	40	41	42	2.38
4	45	42	-7.14	41	41	42	2.38
5	45	42	-7.14	42	41	42	2.38
6	45	42	-7.14	43	41	42	2.38
7	45	42	-7.14	44	41	42	2.38
8	45	42	-7.14	45	41	42	2.38
9	45	42	-7.14	46	41	42	2.38
10	45	42	-7.14	47	41	42	2.38
11	45	42	-7.14	48	41	42	2.38
12	45	42	-7.14	49	41	42	2.38
13	41	42	2.38	50	41	42	2.38
14	41	42	2.38	51	41	42	2.38
15	41	42	2.38	52	41	42	2.38
16	41	42	2.38	53	41	42	2.38
17	41	42	2.38	54	41	42	2.38
18	41	42	2.38	55	41	42	2.38
19	41	42	2.38	56	41	42	2.38
20	41	42	2.38	57	41	42	2.38
21	41	42	2.38	58	41	42	2.38
22	41	42	2.38	59	41	42	2.38
23	41	39	-5.13	60	41	15	-173.33
24	41	39	-5.13	61	41	15	-173.33
25	41	39	-5.13	62	41	15	-173.33
26	41	39	-5.13	63	41	15	-173.33
27	41	39	-5.13	64	41	15	-173.33
28	41	42	2.38	65	41	15	-173.33
29	41	42	2.38	66	41	15	-173.33
30	41	42	2.38	67	41	15	-173.33
31	41	42	2.38	68	41	15	-173.33
32	41	42	2.38	69	41	15	-173.33
33	41	42	2.38	70	41	15	-173.33
34	41	42	2.38	71	41	15	-173.33
35	41	42	2.38	72	41	15	-173.33
36	41	42	2.38	73	41	15	-173.33
37	41	42	2.38	74	41	15	-173.33

ISSN: 0067-3064

Table A.1. Yüksekova T-1 Tunnel Left Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
75	41	15	-173.33	112	41	13	-215.38
76	41	39	-5.13	113	41	13	-215.38
77	41	39	-5.13	114	41	13	-215.38
78	41	39	-5.13	115	41	13	-215.38
79	41	39	-5.13	116	41	13	-215.38
80	41	39	-5.13	117	41	13	-215.38
81	41	39	-5.13	118	41	13	-215.38
82	41	39	-5.13	119	41	13	-215.38
83	41	39	-5.13	120	41	13	-215.38
84	41	39	-5.13	121	41	13	-215.38
85	41	39	-5.13	122	41	13	-215.38
86	41	39	-5.13	123	41	13	-215.38
87	41	39	-5.13	124	41	13	-215.38
88	41	39	-5.13	125	41	13	-215.38
89	41	39	-5.13	126	41	13	-215.38
90	41	39	-5.13	127	41	13	-215.38
91	41	39	-5.13	128	41	13	-215.38
92	41	39	-5.13	129	41	13	-215.38
93	41	39	-5.13	130	41	13	-215.38
94	41	39	-5.13	131	41	13	-215.38
95	41	39	-5.13	132	41	13	-215.38
96	41	39	-5.13	133	41	13	-215.38
97	41	39	-5.13	134	41	13	-215.38
98	41	39	-5.13	135	41	13	-215.38
99	41	39	-5.13	136	41	13	-215.38
100	41	39	-5.13	137	41	13	-215.38
101	41	39	-5.13	138	41	13	-215.38
102	41	39	-5.13	139	41	39	-5.13
103	41	39	-5.13	140	41	39	-5.13
104	41	39	-5.13	141	41	39	-5.13
105	41	13	-215.38	142	41	39	-5.13
106	41	13	-215.38	143	41	39	-5.13
107	41	13	-215.38	144	41	39	-5.13
108	41	13	-215.38	145	41	39	-5.13
109	41	13	-215.38	146	41	39	-5.13
110	41	13	-215.38	147	41	39	-5.13
111	41	13	-215.38	148	41	39	-5.13

ISSN: 0067-3064

Table A.1. Yüksekova T-1 Tunnel Left Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
149	41	15	-173.33	186	41	39	-5.13
150	41	15	-173.33	187	41	39	-5.13
151	41	15	-173.33	188	41	39	-5.13
152	41	15	-173.33	189	41	39	-5.13
153	41	15	-173.33	190	41	39	-5.13
154	41	15	-173.33	191	41	39	-5.13
155	41	15	-173.33	192	41	39	-5.13
156	41	15	-173.33	193	41	39	-5.13
157	41	39	-5.13	194	41	15	-173.33
158	41	39	-5.13	195	41	15	-173.33
159	41	15	-173.33	196	48	15	-220.00
160	41	15	-173.33	197	48	15	-220.00
161	41	15	-173.33	198	45	15	-200.00
162	41	15	-173.33	199	45	39	-15.38
163	41	15	-173.33			**MPAD**	**73.05**
164	41	15	-173.33				
165	41	15	-173.33				
166	41	39	-5.13				
167	41	39	-5.13				
168	41	39	-5.13				
169	41	15	-173.33				
170	41	15	-173.33				
171	41	15	-173.33				
172	41	39	-5.13				
173	41	39	-5.13				
174	41	39	-5.13				
175	41	39	-5.13				
176	41	39	-5.13				
177	41	39	-5.13				
178	41	39	-5.13				
179	41	39	-5.13				
180	41	39	-5.13				
181	41	42	2.38				
182	41	42	2.38				
183	41	39	-5.13				
184	41	39	-5.13				
185	41	39	-5.13				

Table A.2. Yüksekova T-1 Tunnel Right Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	37	38	2.63	38	41	42	2.38
2	37	38	2.63	39	41	42	2.38
3	45	38	-18.42	40	41	42	2.38
4	45	38	-18.42	41	41	42	2.38
5	45	38	-18.42	42	41	42	2.38
6	45	38	-18.42	43	41	38	-7.89
7	45	42	-7.14	44	41	38	-7.89
8	45	42	-7.14	45	41	38	-7.89
9	45	42	-7.14	46	41	38	-7.89
10	45	42	-7.14	47	41	38	-7.89
11	45	42	-7.14	48	41	38	-7.89
12	45	42	-7.14	49	41	38	-7.89
13	41	42	2.38	50	41	42	2.38
14	41	42	2.38	51	41	42	2.38
15	41	42	2.38	52	41	42	2.38
16	41	42	2.38	53	41	42	2.38
17	41	42	2.38	54	41	42	2.38
18	41	42	2.38	55	41	42	2.38
19	41	42	2.38	56	41	42	2.38
20	41	42	2.38	57	41	42	2.38
21	41	42	2.38	58	41	42	2.38
22	41	42	2.38	59	41	42	2.38
23	41	42	2.38	60	41	42	2.38
24	41	42	2.38	61	41	42	2.38
25	41	42	2.38	62	41	38	-7.89
26	41	38	-7.89	63	41	38	-7.89
27	41	38	-7.89	64	41	38	-7.89
28	41	38	-7.89	65	41	38	-7.89
29	41	42	2.38	66	41	38	-7.89
30	41	42	2.38	67	41	42	2.38
31	41	42	2.38	68	41	42	2.38
32	41	42	2.38	69	41	42	2.38
33	41	42	2.38	70	41	42	2.38
34	41	42	2.38	71	41	38	-7.89
35	41	42	2.38	72	41	38	-7.89
36	41	42	2.38	73	41	38	-7.89
37	41	42	2.38	74	41	38	-7.89

ISSN: 0067-3064

Table A.2. Yüksekova T-1 Tunnel Right Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
75	41	38	-7.89	112	41	15	-173.33
76	41	38	-7.89	113	41	15	-173.33
77	41	38	-7.89	114	41	15	-173.33
78	41	38	-7.89	115	41	15	-173.33
79	41	38	-7.89	116	41	15	-173.33
80	41	38	-7.89	117	41	15	-173.33
81	41	38	-7.89	118	41	15	-173.33
82	41	38	-7.89	119	41	15	-173.33
83	41	38	-7.89	120	41	15	-173.33
84	41	38	-7.89	121	41	15	-173.33
85	41	38	-7.89	122	41	15	-173.33
86	41	38	-7.89	123	41	15	-173.33
87	41	38	-7.89	124	41	15	-173.33
88	41	38	-7.89	125	41	15	-173.33
89	41	38	-7.89	126	41	15	-173.33
90	41	38	-7.89	127	41	15	-173.33
91	41	38	-7.89	128	41	15	-173.33
92	41	38	-7.89	129	41	15	-173.33
93	41	38	-7.89	130	41	15	-173.33
94	41	38	-7.89	131	41	15	-173.33
95	41	38	-7.89	132	41	15	-173.33
96	41	38	-7.89	133	41	15	-173.33
97	41	38	-7.89	134	41	15	-173.33
98	41	38	-7.89	135	41	15	-173.33
99	41	38	-7.89	136	41	15	-173.33
100	41	38	-7.89	137	41	15	-173.33
101	41	38	-7.89	138	41	15	-173.33
102	41	38	-7.89	139	41	15	-173.33
103	41	38	-7.89	140	41	15	-173.33
104	41	38	-7.89	141	41	15	-173.33
105	41	38	-7.89	142	41	38	-7.89
106	41	38	-7.89	143	41	38	-7.89
107	41	38	-7.89	144	41	38	-7.89
108	41	38	-7.89	145	41	38	-7.89
109	41	38	-7.89	146	41	38	-7.89
110	41	38	-7.89	147	41	38	-7.89
111	41	15	-173.33	148	41	38	-7.89

ISSN: 0067-3064

Table A.2. Yüksekova T-1 Tunnel Left Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
149	41	38	-7.89	186	41	38	-7.89
150	41	38	-7.89	187	41	38	-7.89
151	41	38	-7.89	188	41	38	-7.89
152	41	38	-7.89	189	41	38	-7.89
153	41	38	-7.89	190	41	38	-7.89
154	41	38	-7.89	191	41	38	-7.89
155	41	38	-7.89	192	41	38	-7.89
156	41	38	-7.89	193	41	38	-7.89
157	41	38	-7.89	194	48	38	-26.32
158	41	38	-7.89	195	48	38	-26.32
159	41	38	-7.89	196	48	15	-220.00
160	41	15	-173.33	197	48	15	-220.00
161	41	15	-173.33	198	45	15	-200.00
162	41	38	-7.89	199	45	15	-200.00
163	41	38	-7.89			MPAD	38.95
164	41	38	-7.89				
165	41	38	-7.89				
166	41	38	-7.89				
167	41	38	-7.89				
168	41	38	-7.89				
169	41	38	-7.89				
170	41	38	-7.89				
171	41	38	-7.89				
172	41	15	-173.33				
173	41	15	-173.33				
174	41	38	-7.89				
175	41	38	-7.89				
176	41	38	-7.89				
177	41	38	-7.89				
178	41	38	-7.89				
179	41	38	-7.89				
180	41	38	-7.89				
181	41	38	-7.89				
182	41	42	2.38				
183	41	42	2.38				
184	41	42	2.38				
185	41	38	-7.89				

ISSN: 0067-3064

Table A.3. Boztepe Tunnel Left- Right Tube MPAD calculation

Left Tube				Right Tube			
No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	41	22	-86.36	1	41	24	-70.83
2	44	41	-7.32	2	44	41	-7.32
3	44	50	12.00	3	44	44	0.00
4	44	50	12.00	4	44	44	0.00
5	44	50	12.00	5	44	44	0.00
6	44	50	12.00	6	44	41	-7.32
7	44	50	12.00	7	44	44	0.00
8	44	50	12.00	8	44	44	0.00
9	44	50	12.00	9	44	44	0.00
10	44	50	12.00	10	44	44	0.00
11	53	41	-29.27	11	44	44	0.00
12	53	50	-6.00	12	44	44	0.00
13	53	41	-29.27	13	44	44	0.00
14	53	41	-29.27	14	53	44	-20.45
15	53	41	-29.27	15	53	44	-20.45
16	44	41	-7.32	16	53	44	-20.45
17	44	41	-7.32	17	53	44	-20.45
18	44	41	-7.32	18	44	44	0.00
19	44	41	-7.32	19	44	41	-7.32
20	44	41	-7.32	20	44	41	-7.32
21	44	41	-7.32	21	44	41	-7.32
22	44	41	-7.32	22	44	41	-7.32
23	44	41	-7.32	23	44	41	-7.32
24	44	41	-7.32	24	44	41	-7.32
25	44	41	-7.32	25	44	41	-7.32
26	44	41	-7.32	26	44	41	-7.32
27	44	41	-7.32	27	44	41	-7.32
28	44	41	-7.32	28	44	41	-7.32
29	44	41	-7.32	29	44	41	-7.32
30	44	41	-7.32	30	44	41	-7.32
31	44	41	-7.32	31	44	41	-7.32
32	36	41	12.20	32	44	41	-7.32
33	36	41	12.20	33	44	41	-7.32
		MPAD	**6.47**	34	36	41	12.20
				35	36	41	12.20
				36	36	41	12.20
						MPAD	**6.68**

ISSN: 0067-3064

Table A.4. Bahçecik Tunnel Left- Right Tube MPAD calculation

Left Tube				Right Tube			
No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	39	41	4.88	1	39	41	4.88
2	48	41	-17.07	2	48	41	-17.07
3	48	41	-17.07	3	48	41	-17.07
4	48	41	-17.07	4	48	41	-17.07
5	48	41	-17.07	5	48	41	-17.07
6	48	41	-17.07	6	48	41	-17.07
7	48	41	-17.07	7	48	41	-17.07
8	48	41	-17.07	8	48	41	-17.07
9	48	41	-17.07	9	48	41	-17.07
10	48	41	-17.07	10	48	41	-17.07
11	51	41	-24.39	11	51	41	-24.39
12	51	41	-24.39	12	51	41	-24.39
13	51	41	-24.39	13	51	41	-24.39
14	45	41	-9.76	14	45	41	-9.76
15	45	41	-9.76	15	45	41	-9.76
16	45	41	-9.76	16	45	41	-9.76
17	45	41	-9.76	17	45	41	-9.76
18	45	41	-9.76	18	45	41	-9.76
19	45	41	-9.76	19	35	30	-16.67
20	45	41	-9.76	20	35	30	-16.67
21	45	41	-9.76	21	35	30	-16.67
22	43	30	-43.33	22	35	30	-16.67
23	43	30	-43.33	23	35	30	-16.67
24	43	30	-43.33	24	35	30	-16.67
25	35	30	-16.67	25	35	30	-16.67
26	35	30	-16.67	26	35	30	-16.67
27	35	30	-16.67	27	35	30	-16.67
28	35	30	-16.67	28	35	30	-16.67
		MPAD	**17.74**			**MPAD**	**15.62**

Table A.5. T-4-B Tunnel Left Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	41	39	-5.13	38	46	48	4.17
2	46	41	-12.20	39	46	48	4.17
3	46	41	-12.20	40	46	48	4.17
4	46	41	-12.20	41	46	48	4.17
5	46	41	-12.20	42	51	48	-6.25
6	46	41	-12.20	43	51	41	-24.39
7	46	41	-12.20	44	51	41	-24.39
8	46	41	-12.20	45	51	41	-24.39
9	46	41	-12.20	46	51	41	-24.39
10	46	41	-12.20	47	51	41	-24.39
11	46	41	-12.20	48	51	41	-24.39
12	46	41	-12.20	49	51	41	-24.39
13	46	41	-12.20	50	51	41	-24.39
14	46	41	-12.20	51	51	41	-24.39
15	46	41	-12.20	52	51	41	-24.39
16	46	41	-12.20	53	51	41	-24.39
17	46	41	-12.20	54	51	41	-24.39
18	46	41	-12.20	55	51	41	-24.39
19	46	41	-12.20	56	51	41	-24.39
20	46	48	4.17	57	51	41	-24.39
21	46	48	4.17	58	51	41	-24.39
22	46	48	4.17	59	51	41	-24.39
23	46	48	4.17	60	51	41	-24.39
24	46	48	4.17	61	41	41	0.00
25	46	48	4.17			**MPAD**	**9.48**
26	46	48	4.17				
27	46	48	4.17				
28	46	48	4.17				
29	46	48	4.17				
30	46	48	4.17				
31	46	48	4.17				
32	46	48	4.17				
33	46	48	4.17				
34	46	48	4.17				
35	46	48	4.17				
36	46	48	4.17				
37	46	48	4.17				

ISSN: 0067-3064

Table A.6. T-4-B Tunnel Right Tube MPAD calculation

No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	41	39	-5.13	38	46	48	4.17
2	46	39	-17.95	39	46	48	4.17
3	46	41	-12.20	40	46	48	4.17
4	46	41	-12.20	41	46	48	4.17
5	46	41	-12.20	42	51	48	-6.25
6	46	41	-12.20	43	51	41	-24.39
7	46	41	-12.20	44	51	41	-24.39
8	46	41	-12.20	45	51	41	-24.39
9	46	41	-12.20	46	51	41	-24.39
10	46	41	-12.20	47	51	41	-24.39
11	46	41	-12.20	48	51	41	-24.39
12	46	41	-12.20	49	51	41	-24.39
13	46	41	-12.20	50	51	41	-24.39
14	46	41	-12.20	51	51	41	-24.39
15	46	48	4.17	52	51	41	-24.39
16	46	48	4.17	53	51	41	-24.39
17	46	48	4.17	54	51	41	-24.39
18	46	48	4.17	55	51	41	-24.39
19	46	48	4.17	56	51	41	-24.39
20	46	48	4.17	57	51	41	-24.39
21	46	48	4.17	58	51	41	-24.39
22	46	48	4.17	59	51	41	-24.39
23	46	48	4.17	60	51	41	-24.39
24	46	48	4.17	61	41	41	0.00
25	46	48	4.17			**MPAD**	**8.23**
26	46	48	4.17				
27	46	48	4.17				
28	46	48	4.17				
29	46	48	4.17				
30	46	48	4.17				
31	46	48	4.17				
32	46	48	4.17				
33	46	48	4.17				
34	46	48	4.17				
35	46	48	4.17				
36	46	48	4.17				
37	46	48	4.17				

ISSN: 0067-3064

Table A.7. Gölçayır Tunnel Left- Right Tube MPAD calculation

Left Tube				**Right Tube**			
No	RMR		Difference,%	No	RMR		Difference,%
	Project	Construction			Project	Construction	
1	36	47	23.40	1	36	46	21.74
2	48	47	-2.13	2	48	46	-4.35
3	48	47	-2.13	3	48	46	-4.35
4	48	47	-2.13	4	48	46	-4.35
5	48	47	-2.13	5	48	46	-4.35
6	48	47	-2.13	6	48	46	-4.35
7	48	47	-2.13	7	48	46	-4.35
8	48	47	-2.13	8	48	46	-4.35
9	48	47	-2.13	9	48	46	-4.35
10	48	47	-2.13	10	48	46	-4.35
11	48	47	-2.13	11	48	46	-4.35
12	48	47	-2.13	12	48	46	-4.35
13	48	47	-2.13	13	48	46	-4.35
14	48	47	-2.13	14	48	46	-4.35
15	48	47	-2.13	15	48	46	-4.35
16	48	47	-2.13	16	48	46	-4.35
17	48	47	-2.13	17	48	46	-4.35
18	48	47	-2.13	18	48	46	-4.35
19	48	47	-2.13	19	48	46	-4.35
20	48	47	-2.13	20	48	46	-4.35
21	36	47	23.40	21	48	46	-4.35
22	36	47	23.40	22	48	46	-4.35
23	36	47	23.40	23	36	46	21.74
		MPAD	**2.31**	24	36	46	21.74
				25	36	46	21.74
						MPAD	**0.17**

ISSN: 0067-3064

References

1. Goodman, R., E., 1995. Block theory and its application. Geotechnique, 45 (3), 383-423, https://doi.org/10.1680/geot.1995.45.3.383

2. Spross, J., Stille, H., Johansson, F., Palmstrom, A., 2020. Principles of Risk-Based Rock Engineering Design. Rock Mech Rock Eng 53, 1129–1143, https://doi.org/10.1007/s00603-019-01962-x

3. Benardos, A.G., Kaliampakos D.C., 2017. A methodology for assessing geotechnical hazards for TBM tun-nel-ling—illustrated by the Athens Metro, Greece. International Journal of Rock Mechanics and Mining Sciences, 41 (6), 987-999, https://doi.org/10.1016/j.ijrmms.2004.03.007

4. Miranda, T., Correia, A.G., Ribeiro e Sousa, L., 2009. Bayesian methodology for updating geomechanical pa-rameters and uncertainty quantification. International Journal of Rock Mechanics and Mining Sciences, 46 (7), 1144-1153, https://doi.org/10.1016/j.ijrmms.2009.03.008

5. Pandit, B., Tiwari, G., Latha, G.M., Babu, G.L.S., 2019. Probabilistic Characterization of Rock Mass from Limited La-boratory Tests and Field Data: Associated Reliability Analysis and Its Interpretation. Rock Mech Rock Eng, 52, 2985–3001, https://doi.org/10.1007/s00603-019-01780-1

6. Carter, T.G., Barnett, W.P., 2022. Improving Reliability of Structural Domaining for Engineering Projects. Rock Mech Rock Eng 55, 2523–2549, https://doi.org/10.1007/s00603-021-02544-6

7. Karahan, S., Gokceoglu, C., 2025. Assessment for shallow and large tunnel construction in weak ground con-ditions: Application of tunnel boring machines. Deep Underground Science and Engineering, 4, 132–148, https://doi.org/10.1002/dug2.12083

8. Gokceoglu, C., Aygar, E.B., Nefeslioglu, H.A., Karahan, S., Gullu, S., 2022. A Geotechnical Perspective on a Complex Geological Environment in a High-Speed Railway Tunnel Excavation (A Case Study from Türkiye). Infra-structures, 7, 155. https://doi.org/10.3390/infrastructures7110155

9. Seo, Y., Macias, F.J., Jakobsen, P.D., Bruland, A., 2018. Influence of Subjectivity in Geological Mapping on the Net Penetration Rate Prediction for a Hard Rock TBM. Rock Mech Rock Eng 51, 1599–1613, https://doi.org/10.1007/s00603-018-1408-2

10. Isaksson, T., Stille, H., 2005. Model for Estimation of Time and Cost for Tunnel Projects Based on Risk Evalua-tion. Rock Mech. Rock Engng. 38, 373–398, https://doi.org/10.1007/s00603-005-0048-5

11. Perello, P., 2011. Estimate of the Reliability in Geological Forecasts for Tunnels: Toward a Structured Approach. Rock Mech Rock Eng 44, 671–694, https://doi.org/10.1007/s00603-011-0164-3

12. Bjureland, W., Spross, J., Johansson, F., Prästings, A., Larsson, S., 2017. Reliability aspects of rock tunnel design with the observational method. International Journal of Rock Mechanics and Mining Sciences, 98, 102-110, https://doi.org/10.1016/j.ijrmms.2017.07.004

13. Fookes, P.G., 1997. Geology for Engineers: the Geological Model, Prediction and Performance. In: The Quarterly Journal of Engineering Geology, Vol. 30, (Part 4, November), pp.293-424.

14. Boyd, L., D., Walton, G., WhitneyT-G.,2020. Geostatistical estimation of Ground Class prior to and during ex-cavation for the Caldecott Tunnel Fourth Bore Project. Tunnelling and Underground Space Technology, Volume 100.

15. Dong, M., Neukum, C., Hu, H., Azzam, R., 2015. Real 3D geotechnical modeling in engineering geology: a case study from the inner city of Aachen, Germany, Bull Eng Geol Environ (2015) 74:281–300.

16. Erharter, G. H., Weil J., Bacher L., Heil F., Kompolschek P., 2023. Building information modelling based ground modelling for tunnel projects – Tunnel Angath/ Austria, Tunnelling and Underground Space Technology, Volume 135.

17. Fang, G., Nilot, E.A., Li, Y.E., Tan, Y.Z., Cheng, A., 2024. Bayesian updating of tunneling risk predictions using continuous seismic data: Applications in urban tunneling. Tunnelling and Underground Space Technology, 147, 105702.

18. Fellin, W., Lessmann, H., Oberguggenberger, M., Vieider, R., 2010. Analyzing risk in engineering: A probabilistic approach. Structural Safety, 32(6), 425-436.

19. Fortsakis, P., Nikas, K., Marinos, V., Marinos, P., 2012. Anisotropic behaviour of stratified rock masses in tun-nelling. Engi-neering Geology, 141–142, 74–83.

20. Gangrade, R.M., Grasmick, J.G., Mooney, M.A., 2022. Probabilistic assessment of void risk and grouting volume for tunneling applications. Rock Mechanics and Rock Engineering, 55, 2771–2786.

21. Hack, R., Price, D., Rengers, N., 2006. A new approach to rock slope stability—a probability classification (SSPC). Bulletin of Engineering Geology and the Environment, 65(2), 169–184.

22. Hao, Y., Rong, X., Ma, L., Fan, P., Lu, H., 2016. Uncertainty analysis on risk assessment of water inrush in karst tunnels. Mathematical Problems in Engineering, 2016, Article ID 2947628, 11 pages.

23. Hao, K., Zhang, L., Zhou, C., 2018. A probabilistic approach for assessing the stability of rock slopes with cor-related variables. Arabian Journal of Geosciences, 11(2), 2648.

24. Li, C., Zhang, L., Zhou, W., 2021. Probabilistic analysis of tunnel face stability in spatially variable soils using random finite element method. Tunnelling and Underground Space Technology, 108, 103703.

25. Madsen, R.B., Høyer, A.-S., Andersen, L.T., Møller, I., Hansen, T.M., 2022. Geology-driven modeling: A new probabilistic approach for incorporating uncertain geological interpretations in 3D geological modeling. Engineering Geology, 309, Article ID 106833.

26. Mahmoodzadeh, H., Moosavi, M., Ghasemi, H., 2021. A novel probabilistic approach for risk assessment in mechanized tunneling projects. Soft Computing, 25(6), 5006–5022.

27. Mahmoodzadeh, H., Moosavi, M., Ghasemi, H., 2022. A hybrid approach for probabilistic risk assessment of tunnel construction projects. Geotechnical and Geological Engineering, 40(3), 2803–2820.

28. Panthi, K.K., Nilsen, B., 2007. Uncertainty analysis of tunnel squeezing for two tunnel cases using the conver-gence-confinement approach. Tunnelling and Underground Space Technology, 22(1), 3–21.

29. Sarma, M., Singh, T.N., Singh, V., 2022. Probabilistic analysis of slope stability using random field theory and Monte Carlo simulation. Acta Geotechnica, 17(3), 2971–2985.

30. Xiong, W., Zhang, L., Zhou, W., 2018. Probabilistic analysis of tunnel stability in spatially variable soils using the random finite element method. Tunnelling and Underground Space Technology, 71, 664–678.

31. Merrie, M. (2009). Trials and Tribulations–An Overview of slurry tunnelling in challenging ground conditions. Underground Singapore, 12-32.

32. Li, S., Li, S., Zhang, Q., Xue, Y., Liu, B., Su, M., Wang, Z., & Wang, S., 2010. Predicting geological hazards during tunnel construction. Journal of Rock Mechanics and Geotechnical Engineering, 2(3), 232–242. https://doi.org/10.3724/SP.J.1235.2010.00232

33. Alija, S., Torrijo, F.J., Quinta-Ferreira, M., 2014. Study of the unexpected collapse of the Ampurdán tunnel (Spain) using a finite elements model, Bulletin of Engineering Geology and the Environment, Volume 73, Issue 2, Pages 451-463.

34. Thum, L. and De Paoli, R., 2015. 2D and 3D GIS- based geological and geomechanical survey during tunnel excavation. Engineering Geology, 192, 19- 25.

35. Ye, G.-L., Zhang, D., Zhang, L., Zhang, N., 2015. Mechanism of unusual settlement due to improper backfill grouting in DOT shield tunnelling, Tunnelling and Underground Space Technology, Volume 49, Pages 79-91.

36. Huang, H., Zhang, D., Hu, H., 2016. Deformational responses of operated shield tunnel to extreme surcharge: A case study, Structure and Infrastructure Engineering, Volume 12, Issue 3, Pages 354-367.

37. Çoruh, E., Köksal, A. O., Kaplan, C., Demirci, M., 2017. Kop Tüneli Yapım Çalışmaları ve Metodolojisi. Ordu Üniversitesi Bilim ve Teknoloji Dergisi, 7(2), 275-288.

38. Liu, D., Zhang, D., Zhang, C., Zhang, L., 2020. Structural responses of shield tunnel under differential settlement caused by leakage: A case study, Tunnelling and Underground Space Technology, Volume 103, Article 103471.

39. Yum, S.-G., Ahn, S., Bae, J., Kim, J.-M., 2020. Assessing the Risk of Natural Disaster-Induced Losses to Tun-nel-Construction Projects Using Empirical Financial-Loss Data from South Korea. Sustainability, 12(19), 8026. https://doi.org/10.3390/su12198026

40. Aygar, E., Gokceoglu, C. (2020). Support system for Oceli highway tunnel excavated in fault zone (Ordu Ring Road Project, Turkey). ISRM International Symposium Eurock 2020 – Hard Rock Engineering, Trondheim, Norway, 14-19 June.

41. Gokceoglu, C., 2022. Assessment of rate of penetration of a tunnel boring machine in the longest railway tunnel of Turkey. SN Appl. Sci. 4, 1–12.

42. Hong, Q., Lai, H., Liu, Y., Chen, R., Liu, C., Xie, J., 2021. Deformation control method of a large cross-section tunnel overlaid by a soft-plastic loess layer: A case study, Bulletin of Engineering Geology and the Environment, Volume 80, Issue 5, Pages 4721-4730.

43. Yu, H., Mooney, M. (2023). Characterizing the as-encountered ground condition with tunnel boring machine data using semi- supervised learning. Computers and Geotechnics, 154, 105159. https://doi.org/10.1016/j.compgeo.2022. 105159

44. Yousuf, M., Ameen, D., & Chanouria, R., 2025. Applications of NATM in Himalayan Tunneling: Innovative Strategies to Tackle Geological Complexities and Construction Challenges. Indian Geotechnical Journal. https://doi.org/10.1007/s40098-025-01334-z

45. Karahan, S., Posluk, E., Buyukdemirci, F.B., Gokceoglu, C., 2025. Re-design of a railway tunnel intersected by surface rupture of the Erkenek fault segment during the 6 February 2023 Pazarcik (Mw 7.7) Earthquake (Türkiye). Bulletin of Engineering Geology and the Environment, 84, 198, https://doi.org/10.1007/s10064-025-04217-y

46. Apostolaki, S., Karahan, S., Riga, E., Grigorios, T., Gokceoglu, C., Pitilakis, K., 2025. Seismic performance of tunnels and verification of available seismic risk models for the 2023 Kahramanmaraş earthquakes. Tunnelling and Underground Space Technology, 156, 106185, https://doi.org/10.1016/j.tust.2024.106185

47. Langford, J.C., Diederichs, M.S., 2015. Quantifying uncertainty in Hoek–Brown intact strength envelopes. In-terna-tional Journal of Rock Mechanics and Mining Sciences, 74, 91-102, https://doi.org/10.1016/j.ijrmms.2014.12.008

48. Komu, M.P., Guney, U., Kilickaya, T.E., Gokceoglu, C., 2020. Using 3D numerical analysis for the assessment of tunnel–landslide relationship: Bahce–Nurdag tunnel (south of Turkey). Geotech. Geol. Eng. 38, 1237–1254.

49. Can, A., Baskose, Y., Gokceoglu, C., 2022. Stability assessments of a triple-tunnel portal with numerical analysis (south of Turkey). Geotech. Res. 40, 1–13.

50. Gokceoglu, C., 2022. Assessment of rate of penetration of a tunnel boring machine in the longest railway tunnel of Turkey. SN Appl. Sci. 4, 1–12.

51. Cheng Y., Zhou W-H., Xu T., 2022. Tunneling-induced settlement prediction using the hybrid feature selection method for feature optimization, Transportation Geotechnics, Volume 36.

52. Ho, T.K., 1995. Random decision forests. In: Proceedings of 3rd International Conference on Document Analysis and Recognition, vol. 1. IEEE, pp. 278–282.

53. Breiman, L. Random forests. Mach. Learn.2001, 45, 5–32. [Google Scholar] [CrossRef]

54. Armaghani, D.J., Liu Z., Khabbaz, H., Fattahi H., Li D., Afrazi M., 2024. Tree-Based Solution Frameworks for Predicting Tunnel Boring Machine Performance Using Rock Mass and Material Properties, CMES - Computer Mod-eling in Engineering and Sciences, Volume 141, Issue 3, Pages 2421-2451.

55. Zhang, W., Wu, C., Zhong, H., Li, Y., Wang L., 2021. Prediction of undrained shear strength using extreme gradient boosting and random forest based on Bayesian optimization, Geoscience Frontiers, Volume 12, Issue 1, Pages 469-477

56. Zhou, J., Li, E., Wei, H., Li, C., Qiao, Q., & Armaghani, D. J. 2019. Random Forests and Cubist Algorithms for Predicting Shear Strengths of Rockfill Materials. Applied Sciences, 9(8), 1621. https://doi.org/10.3390/app9081621.

57. Gokceoglu, C., Bal., C., Aladag, C.H., 2023. Modeling of Tunnel Boring Machine Performance Employing Ran-dom Forest Algorithm. Geotechnical and Geological Engineering, 41, 4205–4231, https://doi.org/10.1007/s10706-023-02516-3

58. Feng, T., Wang, C., Zhang, J., Wang, B., Jin, Y.-F., 2022. An improved artificial bee colony-random forest (IABC-RF) model for predicting the tunnel deformation due to an adjacent foundation pit excavation. Underground Space, 7, 514–527.

59. Yang, W., Chen, Z., Zhao, H., Chen, S., Shi, C., 2025. Feature fusion method for rock mass classification predic-tion and interpretable analysis based on TBM operating and cutter wear data. Tunnelling and Underground Space Technology, 157, Article ID 106351. https://doi.org/10.1016/j.tust.2024.106351.

60. Liu, Y., Li, A., Wang, S., Yuan, J., Zhang, X., 2024. A feature importance-based intelligent method for controlling overbreak in drill-and-blast tunnels via integration with rock mass quality. Alexandria Engineering Journal, 108, 1011–1031. https://doi.org/10.1016/j.aej.2024.09.084.

61. Lundberg, S. M., Lee, S.-I., 2017. A Unified Approach to Interpreting Model Predictions. Advances in Neural Information Processing Systems (NIPS), 31, 4765–4774.

62. Chen, H., Liu, J., Shen, G.,Q., Feng, Z., 2025. Control of existing tunnel deformation caused by shield adjacent undercrossing construction using interpretable machine learning and multiobjective optimization, Automation in Construction, Volume 170.

63. Liu, W., Chen, Y., Liu, T., Liu, W., Li,J., Chen, Y., 2025. Shield tunneling efficiency and stability enhancement based on interpretable machine learning and multi-objective optimization, Underground Space, Volume 22, Pages 320-336.

64. Kannangara, K.K.P.M., Zhou, W., Ding, Z., Hong Z., 2022. Investigation of feature contribution to shield tun-neling-induced settlement using Shapley additive explanations

method, Journal of Rock Mechanics and Geotechnical Engineering, Volume 14, Issue 4, Pages 1052-1063.