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The Role of Horizontal Probe Drill Data in Tunnel Excavations: A Case Study from Istanbul Bosphorus Tunnel

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Abstract

Research methods are needed during excavations with TBM (Tunnel Boring Machine) to ensure safe excavation conditions because it is not possible to see and continuously monitor the excavation face completely. One of the most dangerous conditions expected in the tunnels that will be opened underwater is sudden and high water ingress. To detect possible water ingress, one of the most reliable methods that can be used is to perform horizontal probe drills. With water flow, the dimension of the danger increases more if weak ground conditions and fault and/or crush zones are monitored intensively. Such conditions may cause serious damage to TBM, and sudden washing can cause collapse and deviations in the vertical and horizontal axes. In this sense, considering the negativities of the geological and hydrogeological conditions of the Bosphorus Tunnel passing beneath the Bosphorus Strait, it was set as a contract condition that TBM excavation would be performed according to the results of the horizontal probe drills. During the excavation along the tunnel route, horizontal probe drills were performed at an average of 36 m. The Instantaneous Advance Speed (IAS) with 1-cm intervals, Thrust Pressure (TP), Torque (TQ), and washing water thrusts of the horizontal probe drills were recorded in this respect.

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In this article, the Instantaneous Advance Speed (IAS) values recorded during drilling were normalized with torque and thrust values, respectively. In this way, the changes in advance speeds were determined, and it was determined whether these changes were caused by increased thrusts, and/or torque or lithological changes. The relations between normalized Instantaneous Advance Speed (IAS) values and the RQD values at the tunnel excavation level of 14 vertical drillings built on the tunnel route were revealed. These relationships showed that the speed of Instantaneous Advance Speeds decreased as RQD values increased. This study must be proceeded by analyzing statistical data with a database containing more vertical drilling data to develop the TBM performance prediction model in such a way that the relations between formation characteristics and horizontal probe drill performance are revealed based on horizontal probe drill data.

Keywords: Bosporus Tunnel; Probe Drilling; RQD; TBM; Thrust Pressure; Tunneling

1. Introduction

While drilling in front of the cutterhead, especially in the close mode, the engineers are rather "blind" and without coring interpretation of drill, parameters are the only tool to protect themselves from no appreciable "surprises" [1]. The changes in Instantaneous Advance Speed (IAS), Thrust Pressure (TP), and Torque Thrust (TQ) values recorded during the horizontal probe drill are important. It is known that the changes in these data greatly reflect the characteristics and behaviors of the rocks' mass (in situ), which includes geological structure and discontinuity [2]. Concerning this, a lot of studies were done both at the laboratory level and on a project basis. In their study on the correlation between rock parameters and drilling performance, the authors in [3] determined that rock parameters like volume density, single-axis thrust resistance, tensile strength, cerchar's hardness, RQD, etc. were associated with the advance speed. The author in [4] conducted experiments in the laboratory on some sedimentary rocks and observed that there was a linear relationship between the "rate of thrust to drill rate" during drilling and single axis thrust resistance. As a result of the land and laboratory studies on drillability, the authors in [5] determined that there was an exponential relation between drilling speed, single axis thrust resistance, and tensile strength. The author in [6]; however, normalized the thrust by dividing it to the penetration rate to minimize the effect of thrust value on drilling, and compared the values obtained in this way with the results of single-axis thrust resistance and point load resistance. The author in [7] said that the torque thrust during drilling was directly affected by the feed thrust, and there was a definite relation between feed thrust and torque. Similarly, other studies [8, 9,10,11,12,13] reported successful results in predicting the in-situ properties of rocks with the help of uniaxial compressive strength, point load strength, RQD (Rock Quality Designation), etc. The penetration rate obtained from horizontal probe drills must be analyzed with a correct approach and must be freed from errors from the machine and operator to fully reflect the relevant characteristics. In this sense, the author in [9,10] reported that raw data should be normalized to purify the errors caused by the drill machine and the operator. He also emphasized that more consistent and comparable results could be achieved by normalizing instantaneous speed values (cm/min), feed thrust (bar), and torque (bar) based on the length of the drill. By evaluating these data, he concluded that detailed information about the geologic units and geometry of the tunnel excavation, especially the RQD values, would be obtained.

In the context of this study, the drilling speed (Instantaneous Advance Speed (IAS), Thrust Pressure (TP), and

Torque Thrust (TQ)) changes obtained with 1 cm intervals in horizontal probe drills made in Bosphorus Tunnel were normalized, and their relations with the RQD values at the tunnel excavation level were examined. With these controls and transformations, it was understood whether the changes in the advance speed were caused by increased thrust and/or torque or lithology change. In this way, based on the changes in the data records, the areas where different advance speeds occurred during the tunnel excavation were determined, and statistical analysis of the data groups of these regions were analyzed, the relations of hard, weak, and soft excavation environments with geological structure and lithology were examined.

2. Bosphorus Tunnel Project

The most important part of Melen Project, which was initiated to cover the water need of the city of Istanbul, was the "Bosphorus Tunnel", which constituted the Bosphorus crossing of Istanbul. The tunnel passes about 15 km north of the Bosphorus and connects the coasts of Beykoz on the Asian side, and Tarabya (Istinye) on the European side under the strait (Figure 1).

Figure 1: The location of the Istanbul Bosphorus Tunnel (Google Earth 2020).

The tunnel that was excavated by using EPB Hard Rock type TBM (Earth Pressure Balance Tunnel Boring Machine) in line with the geological and hydrogeological conditions of the excavation environment was 6.15 m in diameter, and 3145 m in length. The 2005 m section of the tunnel was excavated at a rate of 7.4% inclination, and the remaining 1140 m inclined as 0.14% (Table 1). The excavation of the Bosphorus Tunnel began in February 2008 and was completed in April 2009, as estimated.

Table 1: Bosphorus Tunnel technical data

Properties	Unit
TBM Diameter	6,15 m
Project face pressure	~ 4 bar
Segment thickness	0,35 m
Segment length	1,20 m
Segment ring inner diameter	5,11 m
Tunnel’s maximum depth	135,00 m
Minimum rock cover thickness	35,00 m
Tunnel length	3145,00 m

3. Tunnel Route and Geologic Structure

In the bathymetry studies conducted in the section of the first tunnel route, an erosion pit that contained canyons and sediment deposits was detected formed by lower current eroding. According to seismic data, the deepest part of the pit goes down to -175m. Because of this erosion pit, the first route for the Bosphorus Tunnel was changed and was shifted to about 200 m further north and excavated in the parent rock. The depth of the water mass on the newly designated tunnel route was measured as a maximum of 70 m.

A total of 14 vertical probe drills were performed including 11 on the first designated route and 3 on the newly determined route to reveal the geological model and determine its geomechanical properties (Figure 2). According to borehole logs, the deepest point of the tunnel was passed at 135 m depth above the sea level, where there was a 30-m thick bedrock on the tunnel crown and a 35-m nautical alluvial (silted, clayey, and full of shells with gravel-sand). There are units of Paleozoic age as the bedrock on both sides of the Bosphorus. These bedrock formations are Dolayoba and Kartal formations. Paleozoic-age bedrock Dolayoba and Kartal formations were passed as bedrocks during the excavation of the tunnel of 3145 m. These were Dolayoba Formation with blueish-gray, blackish-gray with different layer thicknesses and different facies consisting of limestone, and the Kartal Formation that consisted of micaceous shale in line with it. These rock units are cut in thickness and different characteristics with many volcanic diabase dyke and magmatic rocks varying between tens of meters or a few centimeters.

Most of the units on the tunnel route lost their primary positions as a result of the tectonic movements that happened in different geological periods. These units were deformed depending on the strength of the rocks and the thickness of the layers and acquired a curved and broken structure. Three or more crack teams were usually developed in the rocks that were encountered along the route, depending on the directions of these movements. Besides large fractures-faults and crushing zones were formed in parts where excessive deformations could not be met with curvature, which are often observed with volcanic intrusions and were frequently encountered along the route (Figure 3) [14].

In the post-excavation assessments, Kartal Formation is cut in 68% of the tunnel excavation, Dolayoba Formation is cut in 19%, Diabase-Andesite dykes are cut in approximately 8%, and fault-crushed zones are cut at approximately 5%. The dykes with a thickness of 1-2 m and the thickest of the which with approximately 75 m were encountered at an average of 70 meters.

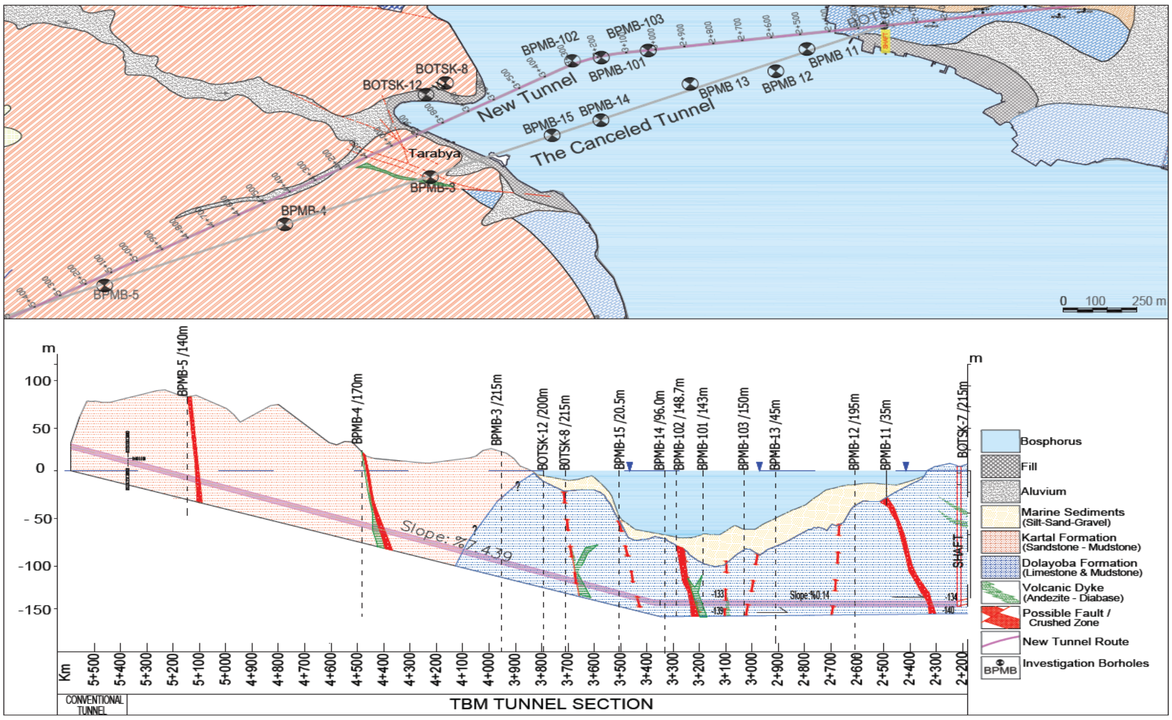

Figure 2: Geological cross-section of the Tunnel route prepared before the excavation [14].

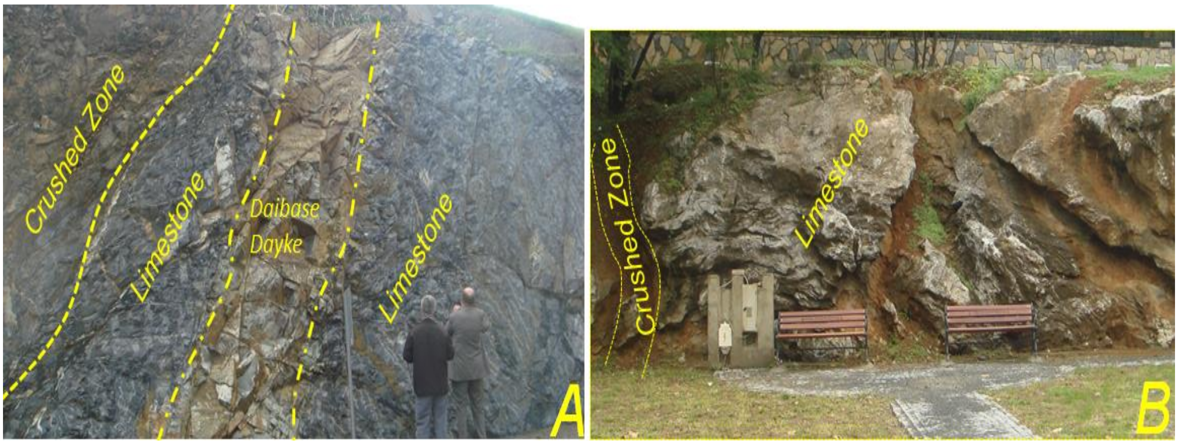

Figure 3: (A) Kartal Formation limestone level cut by volcanic dykes (around Baltalimanı). (B) Dolayoba Formation Reef limestone level and its karstic structure (around Cape Istinye)

4. Application of Horizontal Probe Drills

Two hydraulic drillers are mounted at TBM (Figure 4). One of them is the front drill machine, which is assembled close to the cutter head. The other one is the drill machine mounted on the Gantry to apply the rear drill injection of 7.5º outwards.

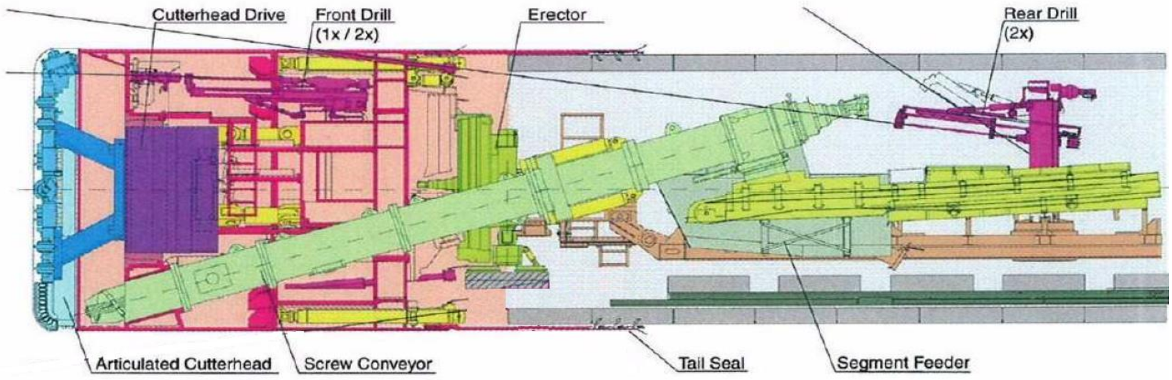

Figure 4: Practical drilling limitations at TBM in Bosphorus Tunnel [1]

Horizontal Probe Drills were performed once at an average of 36 m by using the ports in the upper half of the TBM cutterhead. The principles for execution of the probe drilling and pre-grouting with holes through A-ports in the cutter head (for almost horizontally holes) and through the B-ports from the "back position" (holes inclined 7.5º outwards) - to create an array of grouting holes (umbrella) or to complete grouting at the same chainage done preliminary with A-ports holes are shown in Figure 5. The overlap lengths of the drills were set to be at least one tunnel diameter (D=6m). With this application, the horizontal probe drills opened previously were drilled again to meet the last 6 meters on the overlap zone to minimize the deviations. Typical probe/grout hole patterns, shown originating in the periphery and in the face, are shown in Figure 6.

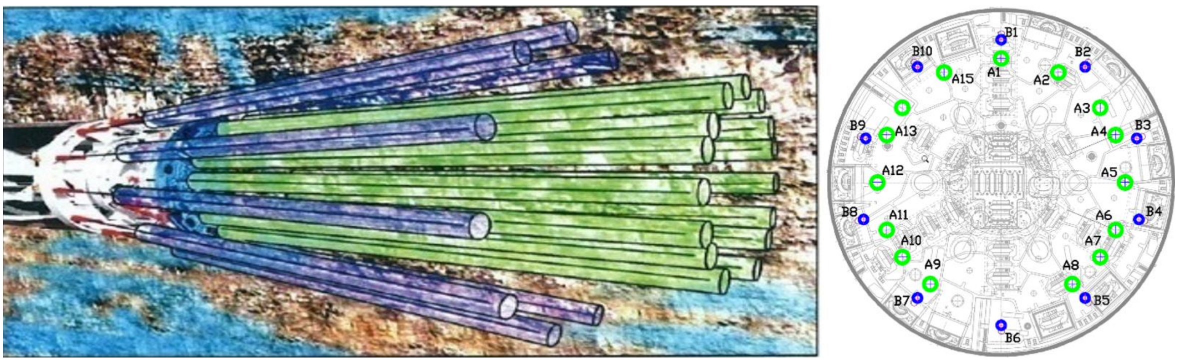

Figure 5: The principles for execution of the probe drilling and pre-grouting with holes through A-ports in the cutter head green holes and through the B-ports from the "back position- Gantry" inclined 7.5º outwards – blue holes [1].

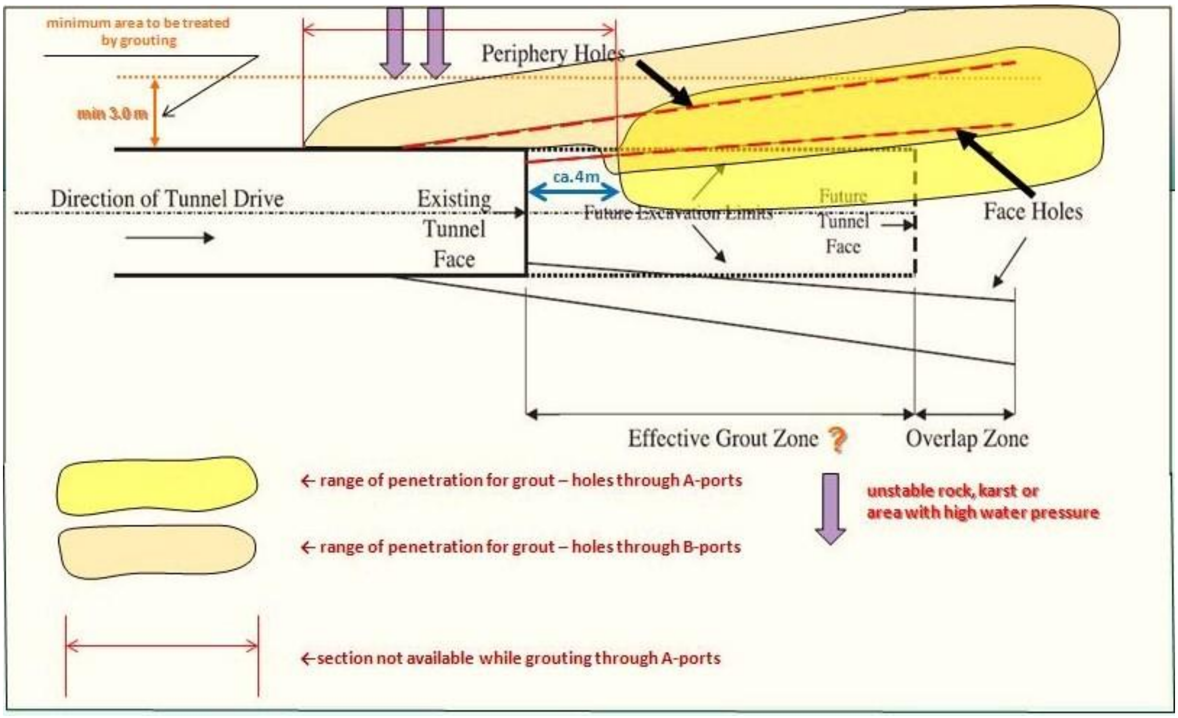

Figure 6: Horizontal probe drill overlap zone plan and drilling for pre grouting (umbrella) from the back position (B-ports) and through the cutterhead [1].

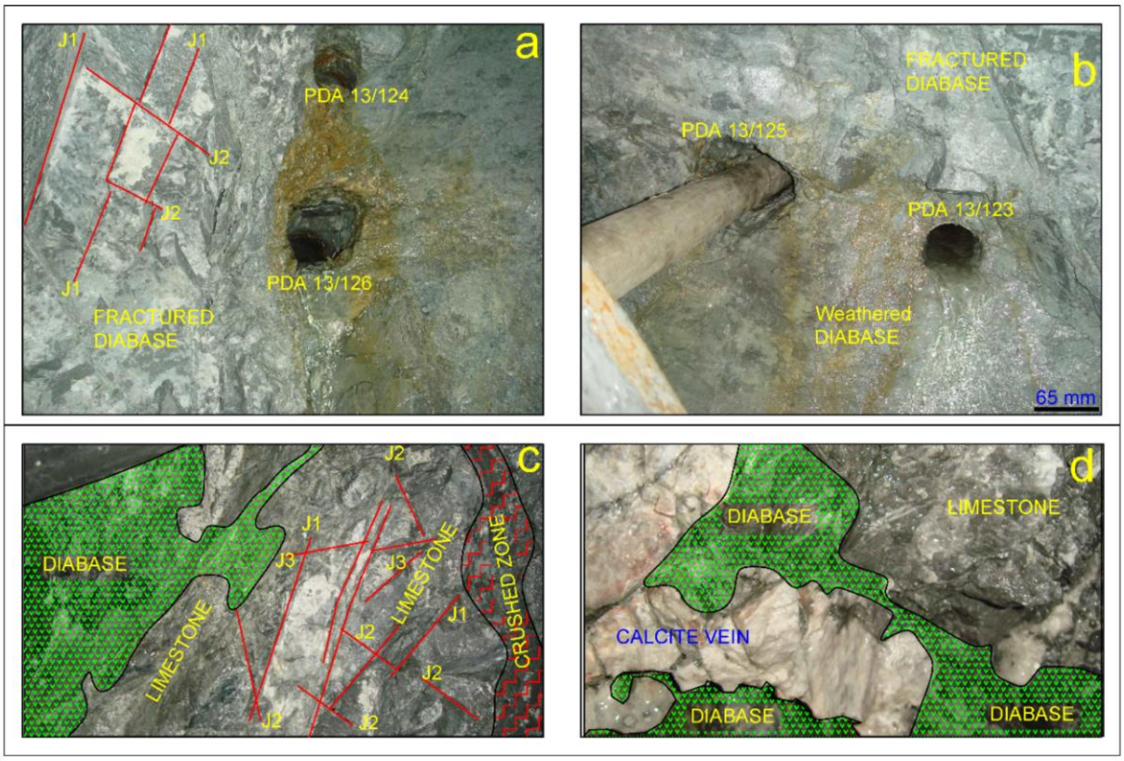

Figure 7: Photographing and documenting works in the tunnel face after the probe drilling works were completed. Weathered diabase dyke and previous probe drill locations (a & b); Typical joint set in tunnel face (J1-J2-J3) with Calcite vein at the limestone-diabase contact (c & d).

The stopping times during the horizontal probe drill, reasons for stopping, and operator errors were recorded, the color and flow changes of water coming from the drills were observed. When drilling ended, detailed photographing and face-mapping were carried out on the surface of the excavation face, and layer and crack measurements were performed (Figure 7). The correlation and calibration of horizontal probe drill parameters were realized with the data obtained from the detailed geological mapping studies carried out on the excavation surface, which increased the reliability of the data collected for evaluation.

5. Distribution of RQD Values on Tunnel Route

A total of 14 vertical drilling wells were carried out with a total length of 1692,15 meters during tunnel route geotechnical investigation [15]. A total of 1128 RQD values were calculated in these drillings (Table 2). The distribution histogram was obtained by calculating the average RQD values (Figure 8). When these distributions were examined closely, it was found out that 40.7% of RQD values were between 0 and 10. The average RQD value was found to be 30.4, and the standard deviation value of the data showing the distribution of the data according to the average was found to be 31,1.

Table 2: Statistical distribution of RQD values of the vertical drills along the tunnel route.

BOREHOLE ID	**RQD values for whole length of each borehole**				
	Number of Data Points	Minimum	Maximum	Average	Standard deviation
BPMB-102	51	0	98	38	29.34
BPMB-101	41	0	85	28	25.32
BPMB-103	47	0	93	32	25.31
BPMB-14	37	0	80	26	24.37
BPMB-4	130	0	95	24	29.38
BPMB-3	176	0	90	17	21.3
BPMB-12	77	23	90	69	13.56
BOTSK-12	116	0	100	41	36.35
BOTSK-8	140	0	100	19	27.16
BOTSK-7	121	0	100	49	34.57
BPMB-5	136	0	68	13	17.59
BPMB-15	12	6	85	45	20.28
BPMB-13	22	7	93	60	25.02
BPMB-11	22	0	74	22	23.19

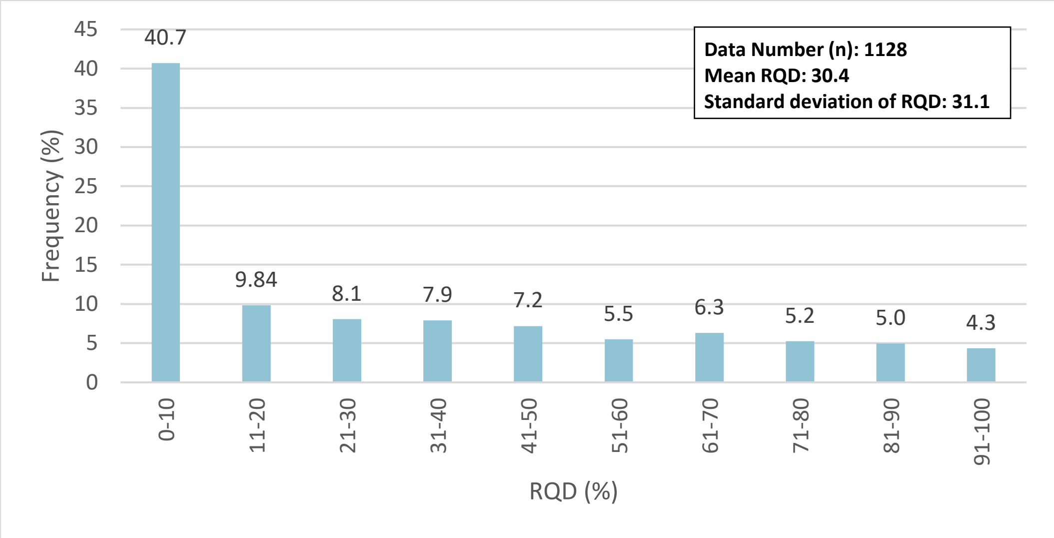

Figure 8: RQD distribution of vertical drills along the tunnel route.

When RQD distributions were examined according to the author in [16], it was seen that 54.2% of the rock units, which made up the route were very poor, 19.5% were poor, and the remaining 26.3% were in “medium-good-very good” rock quality (Figure 9).

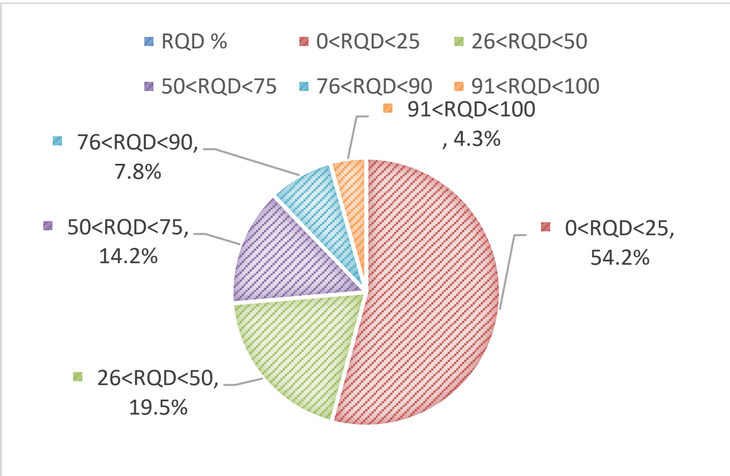

Figure 9: Distribution of all drills along the tunnel route.

When the RQD values at the tunnel level were determined, the average of the RQD values was taken of approximately 7-8 meters of drilling length, by including about 1 meter above the tunnel top and 1 meter below the tunnel bottom elevation to make a more accurate assessment. In this respect, 11 vertical drilling logs that cut the tunnel level were examined, and 67 RQD values were determined. It was found that the RQD values varied between 0-98%, and the average value was 29%. The standard deviation of the RQD values at tunnel level was 27.48 (Table 3).

Table 3: The statistical description of RQD for each borehole at tunnel level.

BOREHOLE ID	**RQD vaues for each borehole at tunnel level**				
	Number of RQD Data Points	Minimum	Maximum	Average	Standard deviation
BPMB-102	5	38	98	70	26,33
BPMB-101	8	7	75	40	27,48
BPMB-103	5	0	15	6	7,70
BPMB-14	5	0	63	26	32,81
BPMB-4	7	0	46	17	16,42
BPMB-3	5	13	65	48	20,31
BPMB-12	5	74	90	79	6,56
BOTSK-12	6	0	30	11	12,81
BOTSK-8	6	0	25	11	10,68
BOTSK-7	5	0	10	4	5,48
BPMB-5	10	0	65	7	20,55

6. Evaluation of Probe Drill Data

In the evaluation stage of the data, firstly, the kilometer range overlapping the vertical drilling that interrupted the tunnel level was determined, and accordingly, the horizontal probe drills on these sections were determined (Figure 10).

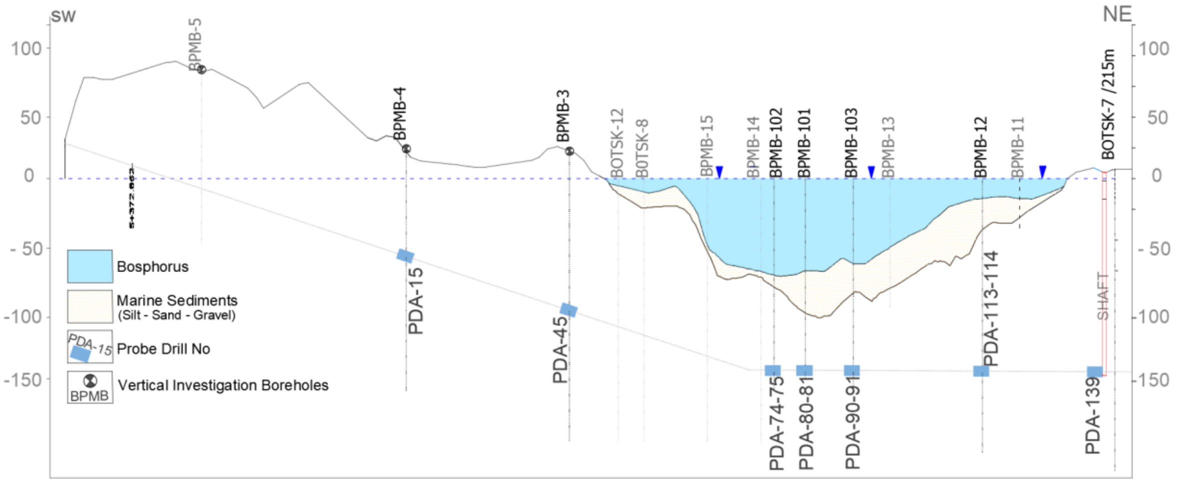

Figure 10: Vertical investigation boreholes and horizontal probe drill locations included in the evaluations.

After determining to which vertical drills corresponded to horizontal probe drills, the data of the intersections of vertical drills with horizontal probe drills were collected and analyzed. As a sample application, the horizontal probe drills of BPMB 101, which intersected at tunnel level, were based on PDA-80 and PDA-81. The averages of both horizontal probe drills data and the vertical drills at BPMB-101 were compared after taking the averages of the Tunnel-level RQD values at tunnel level. In this respect, the average of the Instantaneous Advance Speeds was 85 cm/min, and the average tunnel-level RQD value was measured as 40% in average (Figure 11). Similarly, the comparisons of horizontal probe drill data and RQD values from vertical drills were made separately for all probe and vertical drills (Table 4).

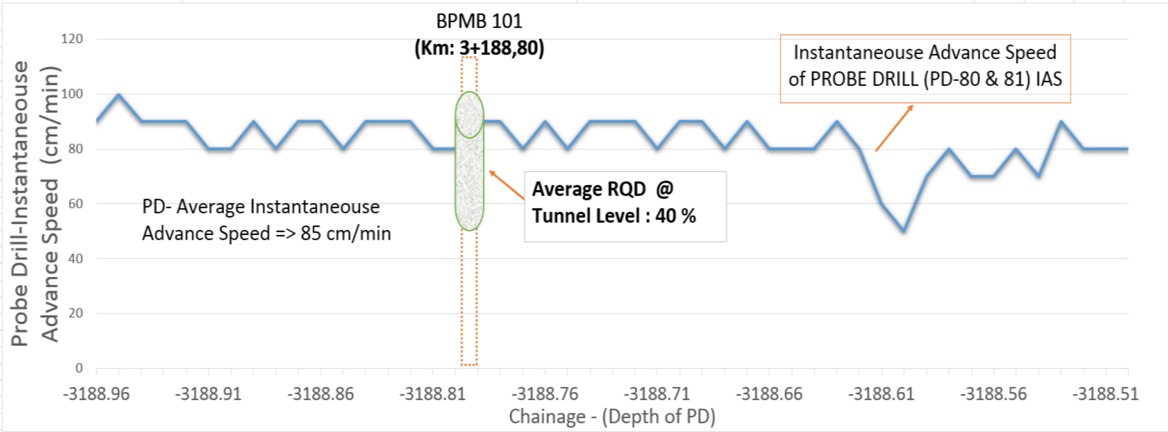

Figure 11: Average Instantaneous Advance Speed of probe drill at the point where the BPMB 101 drill and 80 and 81 probe drills intersected.

In the sections that were evaluated, the average "Instantaneous Advance Speed", which was determined by taking the averages of horizontal probe drill data and the average values obtained by normalizing the Instantaneous Advance Speeds according to thrust and torque thrust values are given collectively in Table 5. As seen in Table 4, Instantaneous Advance Speed values vary between 25 cm/min and 404 cm/min.

The "Normalized Penetration Rate per bar Thrust" values, which was normalized according to thrust and torque thrust values of Instantaneous Advance Speed ranged between 0.95 and15.60 [(cm/min)/(Bar)]" and "Normalized Penetration Rate per bar Torque 0.16 - 2.84 [(cm/min)/(Bar)]" values (Fig.11).

Table 4. Statistical evaluation of RQD values corresponding to tunnel excavation face (D) and Probe drill data.

Evaluated Probe Drill No	Evaluated Vertical Borehole No	Average RQD @ Tunnel Level (%)	Instantaneous Advance Speed – IAS (cm/min)	Normalized IAS per Thrust (cm/min) / (Bar)	Normalized IAS per bar Torque (cm/min) / (Bar)	Rock Mass Quality (Deere 1963)
PDA 139	BOTSK-7	4	404	15,60	2,84	Very Poor Rock
PDA 90-91	BPMB-103	6	250	7,44	1,61	
PDA 54	BOTSK-8	11	220	7,60	1,43	
PDA 15	BPMB-4	17	125	3,20	0,8	

PDA 80-81	BPMB-101	40	85	2,78	0,58	Poor Rock
PDA 45	BPMB-3	48	75	2,91	0,49	
PDA 74-75	BPMB-102	70	60	1,58	0,29	Fair Rock
PDA 113-114	BPMB-12	79	25	0,95	0,16	Good Rock

7. Evaluation of Probe Drill Data

There are many studies suggesting that the changes in penetration and torque rates reflect rock resistance and the geology of the environment accurately. The authors in [17] found that torque values increased depending on rock strength, and the author in [9,10] found that the changes in normalized torque, torque values, normalized penetration rates, and penetration rates could be used to classify the rock type directly. In this sense, the graphics were drawn for the normalized values of the Instantaneous Advance Speed according to thrust and torque thrust values (Figure 12 & 13), and the power regression analysis was used to determine their relations with each other. The determination coefficients (R^2) were calculated to test whether there was a relation between the Instantaneous Advance Speeds normalized according to the values of Instantaneous Advance Speed (R^2=0.91), Torque (R^2:0.83), and Thrust (R^2=0.46) with different RQD values.

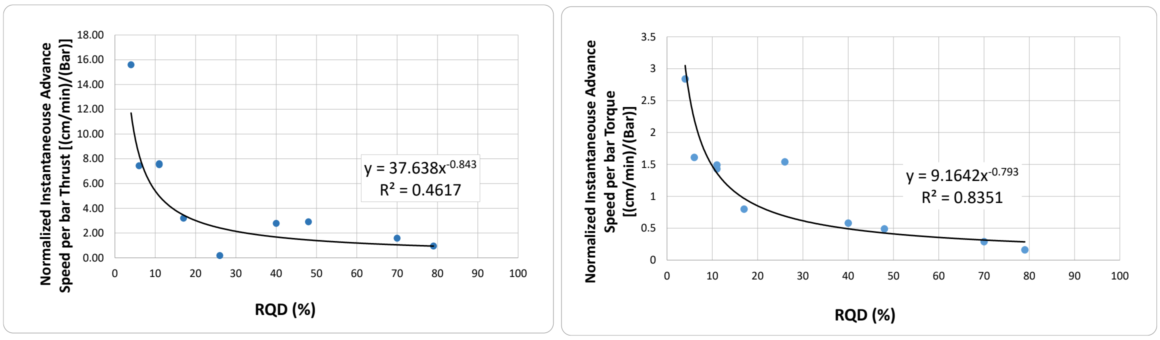

Figure 12: Relation between Instantaneous Advance Speed normalized according to thrust pressure and torque values and RQD values.

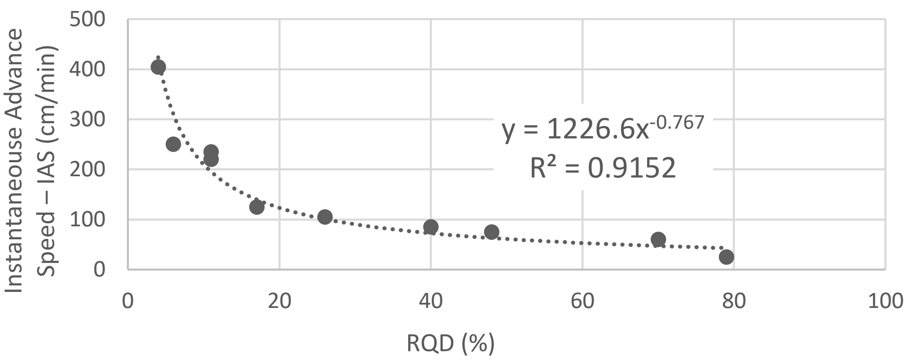

Figure 13: Relation between RQD and raw instantaneous advance speeds.

"Thrust Pressure", which is controlled by the drill operator, and which is considered as a dependent variable, cannot generally be considered as an indicator in that it reflects the geology of the environment. Many studies concluded these results [10, 18]. However, the authors in [17] found that the thrust increased with the force applied, concluded that the thrust decreased on the soft zone and rock crossings, and reported that increased in harder and massive rock crossings. In the scope of the present study, the R^2 value of the normalized thrust was found to be 0.46. This value had a lower correlation value compared to the Instantaneous Advance Speed and the normalized torque thrust. This shows that there are results that are in line with the literature studies that have been conducted. In this sense, although thrust is largely dependent on the operator, it should be examined whether it can be used as an indicator of geological environments and rock types.

All parameters show a correlation negative to RQD. In other words, the higher the rock quality indicator (RQD), the lower the Instantaneous Advance Speeds and normalized penetration rates. However, the validity of these correlation expressions based on limited drilling data will increase by adding more data in this respect. Also, it is seen that graphics created for Instantaneous Advance Speed follow a similar advance and were compatible (Figure 13). This is important in that the data reflect the environmental conditions accurately, and confirm the reliability.

8. Evaluation of Excavation Environment according to the Obtained Data

The penetration rate, torque, and thrust data obtained from horizontal probe drills were normalized to analyze data with the correct approach and to fully reflect the characteristics of the environment.

In the scope of the study, more consistent and comparable results were obtained by dividing the Instantaneous Advance Speed (cm/min), thrust (bar), and torque (bar) depending on drill length. The Instantaneous Advance Speeds obtained from horizontal probe drills classified according to RQD values were evaluated with observations made on the excavation surface and the geological environments were predicted. In this respect, the geological environments could be assessed in terms of drillability, and the hard, weak and soft rock segments could be classified (Figure 14).

With the evaluations made, geological models were prepared to determine the structures like units, fault zones, karstic cavities, water flow, etc., which are possible to encounter in the excavation environment at drilling distance. Based on the geological models prepared, a tunnel excavation decision or injection decision could be made quickly (Figure 15) [14, 15].

Based on the classification made according to RQD and Instantaneous Advance Speed, 38.260 data of 22 horizontal probe drills, corresponding to 383 m of tunnel excavation, were evaluated, and the rates of the environments passed during the tunnel excavation were determined (Figure 16).

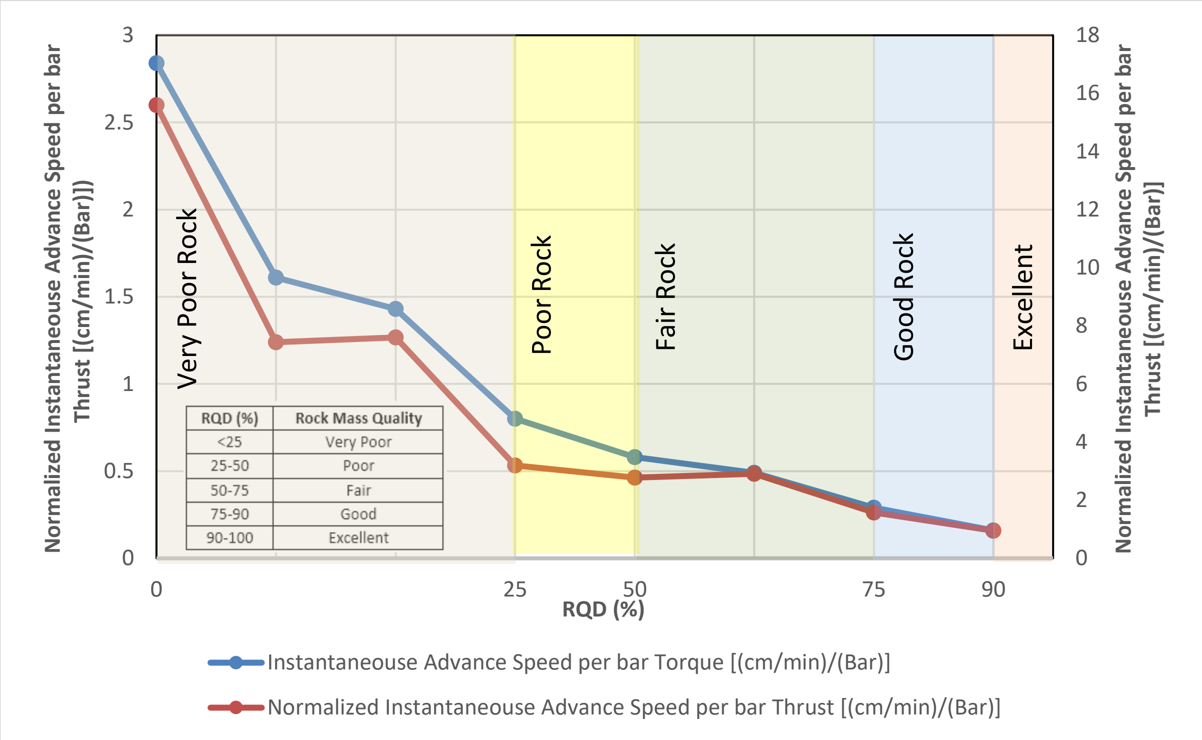

Figure 14. Comparison of normalized penetration ratio and RQD values according to the torque and thrust at the intersection with probe drill.

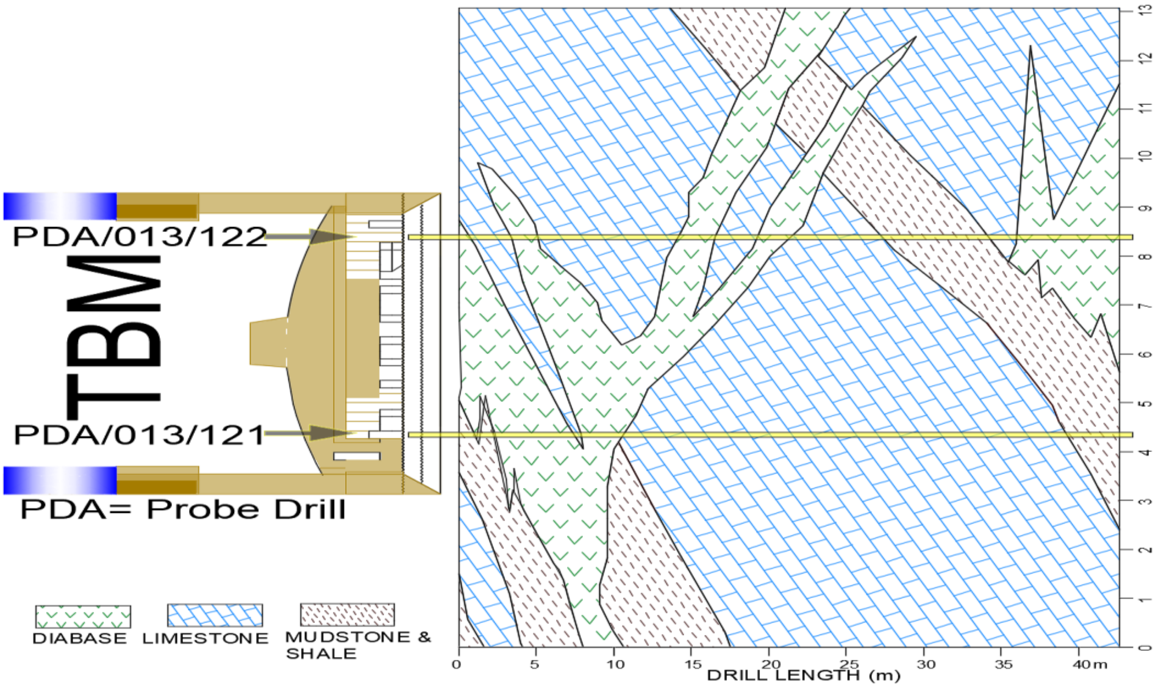

Figure 15: The geological model (image of the plan) created by evaluating the two drills made on the right and left side of the tunnel face (PDA (Probe Drill A port).

In this respect, the zones passed in tunnel excavation;

- The Instantaneous Advance Speeds in units defined as Good-Excellent Rock Zone were found to be approximately 25 cm/min. This section constitutes about 1% of the tunnel route.
- The Instantaneous Advance Speeds in units defined as Fair Rock Zone were found to be about 60 cm/min. This section constitutes about 57% of the tunnel route.
- The Instantaneous Advance Speeds in units defined as Poor Rock Zone were found to be about 87 cm/min. This section constitutes about 39% of the tunnel route.
- The Instantaneous Advance Speeds in units defined as Very Poor Rock or Crushed Zone were found to be about 180 cm/min. This section constitutes about 3% of the tunnel route.

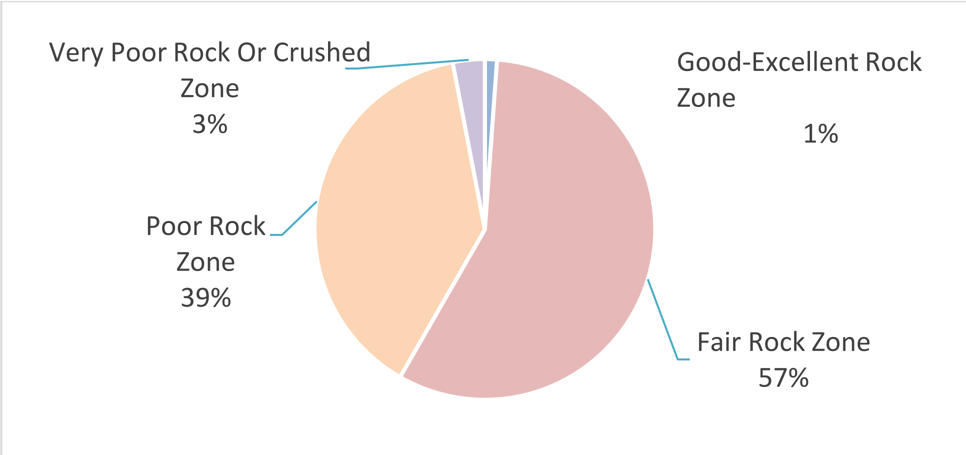

Figure 16: The excavation environments identified based on probe drill data determined according to RQD values along the tunnel route.

9. Discussion

Especially in tunnels to be opened with TBM, it is important to be able to predict the geological and hydrogeological conditions in front of the tunnel face. Horizontal probe drilling results made for this purpose must be interpreted correctly. In this study, a series of horizontal probe drill data and RQD values obtained from vertical drills are evaluated together and the relationships between them is interpreted. In the analyzes, the variations in the horizontal probe drilling parameters, the properties of the rock mass drilled, and the behavior of the excavation environment were determined. Based on these relationships, excavated geological environments have been classified.

Instantaneous Advance Speeds recorded during the horizontal probe drill showed sharp increases and decreases as can be seen in Figure 11. It has been evaluated that it depends on the changing geological conditions in the transition zones. During the tunnel excavation, it was not possible to observe the joint set and bedding in the excavation area. Despite this limiting factor, it was predicted that the sharp increases and decreases in Instantaneous Advance Speeds may be related to rock hardness, bedding, and joint sets. However, it is not fully known whether these sharp increases and decreases are due to machine and operator errors. It has been left as a subject to be evaluated separately. In the present study, it is seen that the use of Instantaneous Advance Speeds and normalized penetration rates interpreted according to RQD values was the correct approach in terms of describing the construction environment. However, the validity of these correlation expressions that are based on a limited number of drilling data must be confirmed with new studies and more data.

In addition it is considered that the environmental evaluations obtained through this study have great importance and will bring benefits in terms of determining the tunnel construction method, the selection of the machine park, predicting the problems that might be encountered during the construction process, as well as in decreasing the construction costs in the project stage of tunnel constructions that will be built for different purposes at different points along the Bosphorus Strait axis under the same or different geological conditions. For similar excavation environments, using the horizontal probe drill data determined in Table 4, TBM performance parameters can be estimated with a precise approach. Accordingly, it is thought that the price and performance relations of TBM machines will be determined more accurately.

10. Conclusion

Along the tunnel route, 14 research drillings were carried out, and the RQD values obtained from these drillings were evaluated together with horizontal probe drill parameters that corresponded to the segments where vertical drills were carried out, and the RQD values at tunnel level varied between 0% and 98% in a broad spectrum, and the average RQD value was 29%. The standard deviation of the RQD values at tunnel level was $\boldsymbol{\sigma}$ = 27.48.

According to the author in [16], when the RQD distributions were examined, it was seen that 54.2% of the rock units that made up the route were very poor, 19.5% were poor, and the remaining 26.3% were of “medium-good-very good” rock quality (Figure 11).

The RQD charts were drawn with normalized values according to thrust and torque thrust values of Instantaneous Advance Speeds, and power regression analysis was used to determine the relations among them. The determination coefficients (R^2) were calculated for the trends of Normalized Instantaneous Advance Speeds according to Instantaneous Advance Speed (R^2=0.91), Torque (R^2= 0.83), and Thrust (R^2=0.46) with different RQD values. In this sense, it was determined that there is a strong relation between RQD and the Instantaneous Advance Speeds used; and high correlation values were obtained with the Normalized Instantaneous Advance Speed (R^2=0.83) parameters according to torque and probe drill Instantaneous Advance Speeds (R^2=0.91). In other words, the better the rock quality indicator (RQD) was, the lower the penetration rates that were normalized according to Instantaneous Advance Speeds and torque were. This is important in that it shows that the Instantaneous Advance Speeds and torque are strongly affected by the geological state of the environment, reflecting the features of the environment well.

Normalized Instantaneous Advance Speed can be considered as a good indicator to detect environmental conditions beyond the tunnel face. In this sense, it was determined that the probe drill evaluations performed in Bosphorus Tunnel Project showed sharp increases and decreases in transition areas due to the changing geological conditions. It was understood that the change in the Instantaneous Advance Speeds obtained from horizontal probe drills were related to the change in rock resistance, the cracks, and the heterogeneity of the environment. Depending on these evaluations, it was concluded that the advance speed increased in soft zone and rock crossings, and decreased in harder and massive rock crossings. With the help of these relations, much safer predictions will be made for excavation environments based on horizontal probe drill data detected in this study for tunnel projects planned for different purposes, especially in different parts of Bosphorus. Also, the TBM performance parameters can be estimated at a specific approximation by using the geomechanical dimensions obtained from drills.

Based on the classification depending on RQD and Instantaneous Advance Speed, the environmental ratios were determined along with the tunnel excavation, and it was determined that 1% of the environment was in the “Good-excellent Rock Zone” class, 57% of the environment was in the “Fair Rock Zone” class, 39% of the environment showed “Poor Rock Zone” characteristics, and finally, 3% was “Very Poor Rock or Crushed Zone”.

11. Recommendations

RQD values obtained from a limited number of boreholes are used in this study. Results should be verified by using more drillings and RQD data. One of the results obtained in this study is that the low correlation coefficient of advance speeds normalized according to thrust (R^2 = 0.46) must be researched in detail to determine the structured environment and rock types. According to the results, the research should be continued to develop a TBM performance prediction model.

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