

Evaluation of Relationships Between Strength Properties of Rock Samples and Drilling Rate Index



Efe Aslan, Hakan Köpüklü, and H. Turan Durgunoğlu

Abstract A comprehensive subsurface investigation program was conducted to delineate the soil, rock and groundwater conditions in subject area of the project site located in Gulf Region consisted mainly of land-based geotechnical drilling. In the scope of this study, the onshore site characterization is based on an integrated approach that combines the site specific data collected from borings, field and laboratory tests. Within the scope of laboratory studies, relationships between strength properties of rock samples and drilling rate index were examined. For this purpose, uniaxial compression test, Schmidt hammer rebound test and drillability test were conducted for the rock samples which were collected from different rotary drilling boreholes. The experimental studies have shown that the drilling rate index (DRI) decreases with the increasing uniaxial compressive strength (UCS) and Schmidt Hammer Rebound Hardness (SHRH).

Keywords Drilling rate index · Brittleness test · Sievers' J-Miniature drill test · Uniaxial compressive strength · Schmidt hammer rebound hardness

1 Introduction

An accurate estimation of drillability became a mandatory factor in planning, design and construction stages of underground projects. For the excavation phases in mining, tunneling and underground constructions, drilling progress, cutter wear and related costs are becoming compulsive elements [5]. Therefore, in parallel with the accurate estimations, rock cutting tools and equipment may be optimized and drilling rate may provide beneficial data for underground excavations such as using tunnel boring machines (TBMs) or other excavators. Selection of these tools without physical, mechanical, and mineralogical information of the planned construction area can cause major problems for all stages of projects.

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Kahraman et al. [8], investigated the percussive blast hole drills in eight rock types and showed that uniaxial compressive strength (UCS), Brazilian tensile strength, point load strength and Schmidt hammer value were the dominant rock properties affecting the penetration rate of percussive drills. Yarali and Soyer [11], focused on relationships between DRI and strength properties were evaluated and stated that decreasing linear relationships were constituted between DRI and UCS, Schmidt rebound hardness, Shore scleroscope hardness, diametral and axial point load strength values. Adebayo and Adetula [1], conducted laboratory tests and stated that that UCS, texture and grain size, DRI and Equivalent Quartz Content (EQC) are important pa-rameters which affect drilling conditions. Demirdag et al. [7], studied the factors affecting the drilling rates in terms of physical and mechanical properties of the rocks. Uniaxial compressive strength, Brazilian tensile strength, impact strength, Bohme abrasion strength, P-wave velocity, porosity, unit volume weight, Schmidt hardness index and brittleness index values were correlated with the drilling rates. Shafique and Bakar [10], evaluated relations between DRI tests and porosity, density, P-wave velocity, UCS, Brazilian tensile strength and Schmidt hammer rebound number. Capik et al. [3], stated that DRI decreases with increasing UCS, point load strength, Bra-zilian tensile strength, and Schmidt rebound hardness. Yenice et al. [13], stated that correlations were found between DRI and uniaxial compressive strength and indirect tensile strength values. Yenice [14], studied the relation between UCS, Brazilian tensile strength and the DRI were determined using multiple regression analysis. Kamran [9], constituted a model for the evaluation of DRI by using the uniaxial compressive strength, Brazilian tensile strength, brittleness test, and Sievers' J-miniature drill values.

2 In-Situ Applications

2.1 Project Site Information

A comprehensive subsurface investigation program was conducted to delineate the soil, rock and groundwater conditions in subject area of the project site located in Gulf Region consisted mainly of land-based geotechnical drilling. Project site location is given in Fig. 1.

Wireline rotary drilling method has been employed utilizing PQ3 type core barrel equipment to generate high quality core samples with better core recovery. Exploratory boreholes were drilled vertically by rotary wash boring method producing core samples with nominal core diameter of 82 mm. A continuous coring was performed as per the BS 5930:2015. Core samples retrieved through each run were photographed first to show in situ position and orientation of cores without disturbance and then logged by geologist. The rock parameters were measured in-situ by the geologists. Samples were wrapped with plastic stretch to preserve natural water



Fig. 1 Project site location

content and were placed in proper core boxes for delivery purposes to laboratory. Appropriate sample selections were made for the laboratory tests.

2.2 Geotechnical Formations

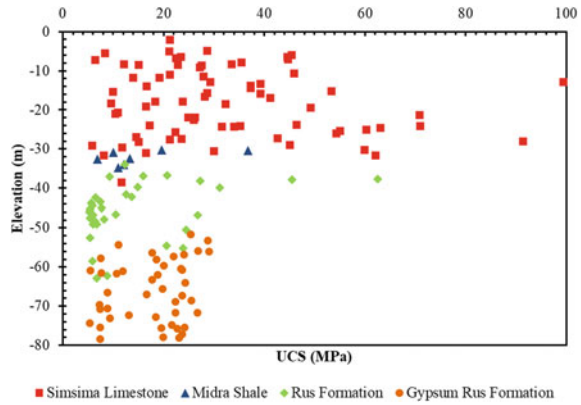
Cavelier [4], presented the basic structure for the project site. The formations of the Gulf region are entirely of Tertiary to Quaternary age. The subsurface soil/rock stratigraphy in project area, as encountered in the geotechnical boreholes presented in Table 1.

The greater part of the land consists of a uniform limestone horizon of middle Eocene age, the Simsima Limestone. The Simsima Limestone forms part of the Upper Dammam Formation and is underlain by the Midra Shales member of the Lower Dammam Formation from middle Eocene in age. This is in turn underlain by the Rus Formation, which is lower Eocene in age. The solid geology is overlaid by shallow cover of loose to medium dense silty, gravelly sand.

Table 1 Range of approximate observable thickness of formations encountered in boreholes

Geotechnical Formations	Observable thickness range encountered in boreholes	
	Minimum (m)	Maximum (m)
Fill Material/Made Ground	0.20	0.50
Quaternary Aeolian Sand	0.30	11.90
Quaternary Cap Rock	1.35	8.75
Weathered Simsima Limestone	0.30	7.50
Simsima Limestone	26.45	38.75
Midra Shale	1.70	5.90
Rus Formation Limestone	5.10	25.10
Rus Formation Gypsum	7.80	25.50

Fig. 2 Uniaxial compressive strength test results



3 Experimental Research

In the scope of this experimental research, rock samples which were collected from different formations were examined. Drillability tests, uniaxial compressive strength tests and Schmidt hammer rebound hardness tests were conducted to evaluate the relationships between strength properties and drilling rate index of rock samples.

3.1 Uniaxial Compressive Strength Test

Uniaxial compression tests were performed on 157 rock core samples which had a diameter of PQ size (82 mm) and length to diameter ratio of 2.0–2.5. The stress rate was applied within the limits of 0.5–1.0 MPa/s in accordance with ASTM D7012. Test results are given in Fig. 2.

In addition to that, compressive strength and elastic moduli of intact rock core tests were performed on 115 samples. Modulus of elasticity (E) was determined as the average value of tangent modulus of elasticity and secant modulus of elasticity. Poisson's ration (μ) determined as the ratio of the Modulus of elasticity (E) and slope of diametric curve. Test results are given in Fig. 3.

3.2 Schmidt Hammer Rebound Hardness Test

Schmidt hammer rebound hardness tests were performed on 95 rock specimens. Proceq silver rock L-Type Schmidt hammer having impact energy of 0.74 Nm was used in accordance with the ISRM. The orientation of hammer was on vertical downwards position and 20 impacts were conducted and separated by at least the diameter of the plunger. The lower %50 of the rebound values were eliminated and the average

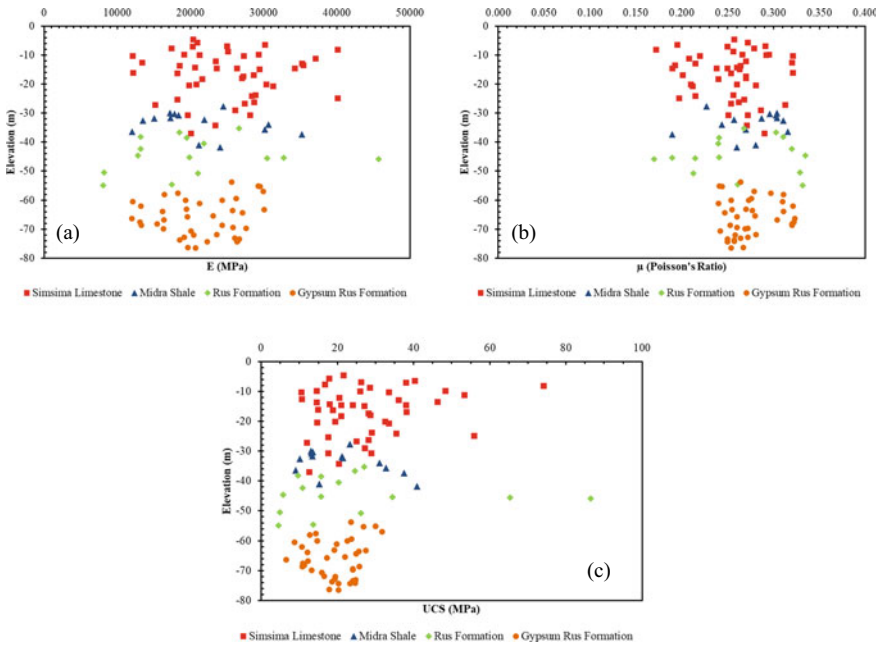
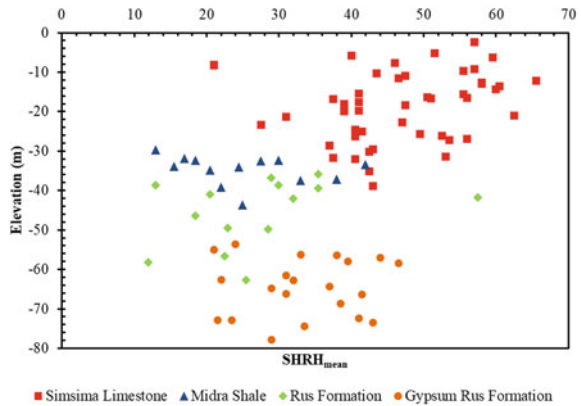


Fig. 3 Uniaxial compressive strength test results **a** E (MPa), **b** Poisson's ration (μ), and **c** UCS (MPa)

value was recorded as the Schmidt hammer rebound hardness ($SHRH_{mean}$) number. Test results are given in Fig. 4.

Fig. 4 Schmidt hammer rebound hardness test results



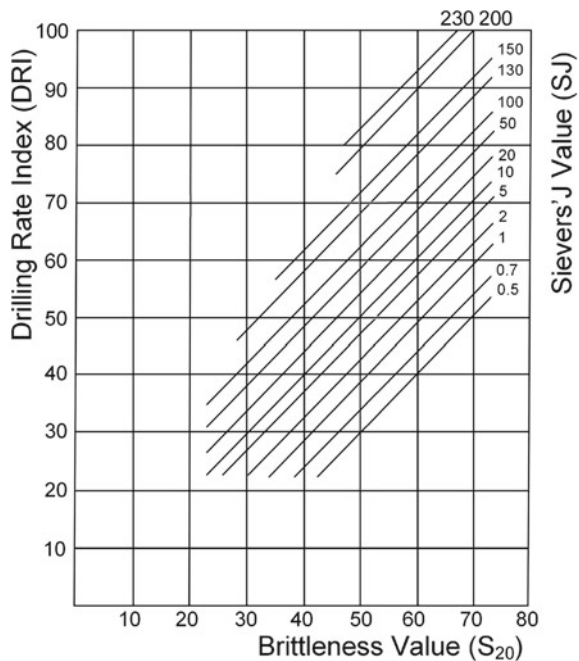
3.3 Drillability of Rock Core Samples

NTNU/SINTEF drillability test method was developed at the Department of Geology and Mineral Resources Engineering at NTNU in 1960s for evaluating drillability of rocks by percussive drilling [11]. The Drilling Rate Index (DRI) is assessed on the basis of two laboratory tests, the Brittleness Value (S_{20}) test and the Sievers' J-Value (SJ) miniature drill test. These indices are recognized as providing practical characterization of rocks applicable in time and cost prediction models available for hard rock tunneling and surface excavation. The chart which determines DRI value is given in Fig. 5.

Sievers' J-Miniature Drill Test. The Sievers drill test was developed by Sievers in the 1950s for estimating cutter life [12]. The Sievers' J-value is determined by using a rock sample drilled for a minute with 200 revolutions per minute of the 8.5 mm miniature drill bit under 20 kg of static load. Thereafter, the drill hole height was measured. SJ-value is determined as the mean value of the measured drill hole depth in 1/10 mm of 4–8 repetitive drill holes.

Brittleness (S_{20}) Test. The brittleness test was developed in Sweden for evaluation of the quality of aggregates [11]. The S_{20} value shows the resistance of a rock specimen to mechanical impacts. Rock sample was crushed in a jaw crusher and sieved through the 16 mm and 11.2 mm sieves. Crushed and sieved rock sample is used for the test. A hammer of 14 kg was dropped on the mortar containing rock material for 20

Fig. 5 Drilling rate index chart [6]



times. This procedure was repeated for three to five times for each rock sample. Afterwards, rock material was sieved through an 11.2 mm sieve. The percentage of material passing the sieve was determined as the S_{20} value [6].

Drilling Rate Index (DRI). Figure 5 was used for the evaluation of drilling rate index (DRI) which includes the brittleness value (S_{20}) and the Sievers' J-value (SJ_{mean}). The classification of each sample is given in Table 2.

4 Evaluation of Experimental Research

In this experimental research, 20 different rock core samples were tested for the drilling rate index in the laboratory. In order to evaluate the relations between strength properties of rock samples and DRI, the closest uniaxial compression test and Schmidt hammer rebound hardness test results were selected within a range of ± 2.0 m distance from the DRI test samples. The correlations between DRI and strength parameters of the rock samples are stated in Fig. 6. UCS results range from 5.8 to 55.9 MPa, modulus of elasticity range from 12,120 to 40,132 MPa, Poisson's ratio range from 0.197 to 0.335, Schmidt hammer rebound hardness range from 13 to 58. It was observed that the DRI values of all the tested rock specimens classified from medium to extremely high. DRI values of rus formation samples were classified as extremely high. In addition to that, gypsum samples were classified between high to extremely high. Dolomitic limestone samples were classified as medium to high.

5 Conclusions

The performance and cost evaluations in tunneling, mining and other underground projects are commonly attributed to drillability of rocks. Intact rock properties have a significant part in excavation.

In this study, the correlations between DRI and strength properties of rocks were investigated. Rock samples were collected from different geotechnical formations and the properties of all samples were determined by laboratory experiments. Then, correlations between these results were obtained. The DRI decreases with increasing UCS, $SHRH_{\text{mean}}$ and E. In addition to this, DRI increases with increasing Poisson's ratio. After all these interpretations, it can be stated that DRI and strength parameters can represent well correlations, although further studies should be conducted for improving these results. Further studies could investigate the mineralogical properties of rocks in order to determine their influences on the DRI. The estimation of the DRI could also be associated with in-situ tests by executing diagraphy drilling. Thus, experimental results could be supported with the field data where drilling speed (m/h) could be correlated with the varying geotechnical formations.

Table 2 Drillability tests summary

No	Depth (m)	Elevation (m)	Lithologic Unit	Formation	S ₂₀	SJ	DRI	Class
1	28.20	-26.45	Dolomitic Limestone	Simsima Limestone	58	84.80 ± 8.81	68	High
2	27.00	-25.28	Dolomitic Limestone	Simsima Limestone	44	92.00 ± 10.56	54	Medium
3	17.80	-16.01	Dolomitic Limestone	Simsima Limestone	47	89.60 ± 37.43	58	High
4	16.50	-13.61	Dolomitic Limestone	Simsima Limestone	53	78.8 ± 19.02	66	High
5	16.10	-13.52	Dolomitic Limestone	Simsima Limestone	37	111.25 ± 1.66	50	Medium
6	26.30	-23.72	Dolomitic Limestone	Simsima Limestone	42	104.00 ± 1.65	56	Medium
7	19.90	-18.21	Dolomitic Limestone	Simsima Limestone	56	95.80 ± 20.63	67	High
8	24.50	-21.35	Dolomitic Limestone	Simsima Limestone	54	83.80 ± 0.78	66	High
9	38.00	-36.08	Mudstone	Rus	75	158.00 ± 39.60	96	Extremely high
10	35.00	-33.56	Mudstone	Rus	72	124.25 ± 37.14	86	Extremely high
11	49.80	-47.73	Calcarenite	Rus	77	154.40 ± 2.92	96	Extremely high
12	54.90	-51.75	Calsisiltite	Rus	77	97.67 ± 0.40	88	Extremely high
13	36.80	-32.69	Limestone	Midra Shale	55	109.80 ± 0.61	70	High
14	46.10	-42.95	Limestone	Midra Shale	54	82.60 ± 0.59	65	High
15	58.60	-57.16	Gypsum	Gypsum Rus	59	86.80 ± 4.97	69	High
16	58.50	-56.71	Gypsum	Gypsum Rus	65	157.00 ± 37.42	92	Extremely high
17	67.70	-64.81	Gypsum	Gypsum Rus	57	79.60 ± 2.51	67	High
18	57.10	-55.41	Gypsum	Gypsum Rus	56	136.80 ± 12.79	74	Very high
19	65.00	-60.89	Gypsum	Gypsum Rus	53	151.25 ± 3.40	76	Very high
20	71.30	-68.15	Calsisiltite	Gypsum Rus	69	148.75 ± 1.31	79	Very high

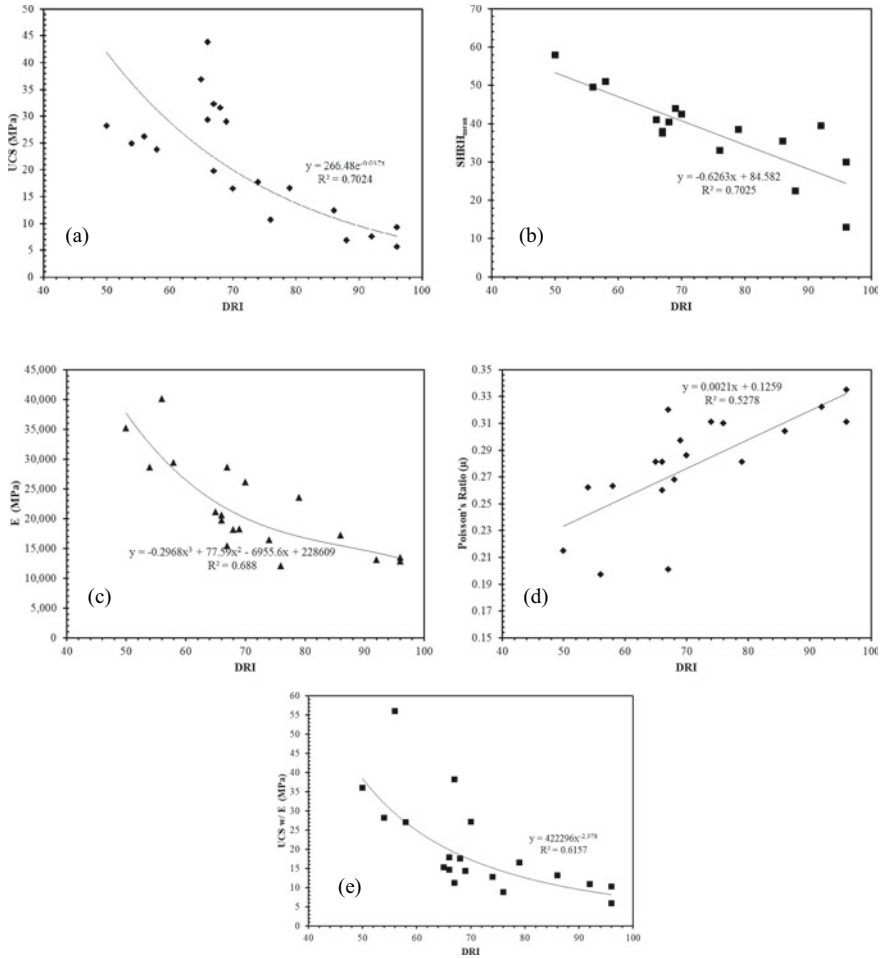


Fig. 6 Correlations between DRI and strength parameters **a** UCS and DRI, **b** SHRHL_{mean} and DRI, **c** E and DRI, **d** μ and DRI and **e** UCS w/E and DRI

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