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An experimental study on water saturation effect on rock cutting force of a chisel pick

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Abstract

This work aims to investigate the effect of water saturation on cutting forces and chipping efficiency by performing a series of small-scale linear cutting tests with a chisel pick on twelve low- and medium-strength rock samples. The peak and mean cutting force acting on the chisel pick are measured and recorded under dry and saturated cutting conditions by the strain sensors that are embedded in the dynamometer. Also the amplitude of cutting force fluctuations in dry and saturated cutting conditions is compared by the standard deviation measurement of cutting force data, and its relationship with the size of cutting fragments is investigated. The results obtained show that the peak cutting force is reduced in saturated conditions compared to dry conditions. The mean cutting force in the synthetic sample cutting test is unchanged or in some cases increase, while in the natural samples it decreases. The relative increase in the mean cutting force in synthetic rock specimens is due to the paste state of fine materials produced from saturated cutting and chisel pick clogging. A strong correlation is found between the standard deviation of cutting force data and the average size of rock debris, indicating that the standard deviation of cutting force data is a useful measure for evaluating the chipping efficiency. The present study's findings reveal that to have an efficient excavation system in field operations, it is necessary to consider the presence of water and saturated conditions in designing the cutting machine's operating parameters and predicting the performance of mechanical excavators.

1. Introduction

Mechanical rock cutting with drag tools is widely used in tunneling, mining, and dredging operations. In mechanical cutting machines, to design the operating parameters, control the stability, and vibration of the machine, predict performance and evaluate the cuttability, knowledge of the forces on the cutting tools, and the characteristics of the fragments resulting from rock cutting is important. Cutting force, side force, and normal force are the three orthogonal components of force acting on the drag tools during cutting. Maximum cutting force plays an important role in the design of cutting tools and machine operational parameters such as torque and power required for the cutting process. Also the mean cutting force during the cutting process is the primary basis for calculating the specific energy and evaluating the cutting efficiency, and performance prediction of the mechanical machine.

Various theoretical and empirical models, numerical modeling, and rock cutting test methods have been proposed to estimate and determine the cutting force and evaluate the efficiency of the rock cutting process. Large-scale and small-scale linear cutting tests are successful, reliable, and efficient methods for studying tool-rock interaction and estimating cutting forces and specific energy [1, 2].

Numerous authors have examined the factors influencing the cutting force and specific energy using a rock cutting test. Factors affecting the results of the rock cutting test include the type and geometry of the drag pick (such as rake angle, clearance angle, and pick width) [3, 4], cutting geometry (such as cutting depth and distance

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between cuts and cutting speed) [5-15], and physical and mechanical properties of rock (such as porosity, rock strength, rock abrasion, spacing and orientation of discontinuities, humidity, confining pressures) [2, 5-7, 10-12, 16-23].

Within the past six decades, a number of researchers have theoretically studied the process of cutting rock and coal with chisel and conical picks, providing relationships to estimate the maximum cutting force exerted on the pick. Theoretical models with input parameters and their relationships are given exclusively for chisel picks in Figure 1. Although these theories have helped to better understand the cutting process, as noted by Bilgin [3], the laboratory and field studies of rock cutting show that in some cases the theoretical estimates of rock cutting force do not correspond well with the actual cutting forces due to the complex petrographic, mineralogical, and anisotropic nature of rock formations.

Another group of researchers has attempted to study the cutting mechanism and the process of cracking and formation of rock chips by numerical simulation [24-30].

One of the conditions that occurs in most excavation practical applications is exposure to wet conditions and rock saturation. In field operations, rocks are often excavated below the water table in the presence of water. In addition, in underwater drilling, tunneling, and mining operations including all operations in shallow, deep, and ultra-deep waters, rock excavation is generally performed in saturated rocks. On the other hand, the extraction of undersea resources becomes popular as land resources reduce. Under these conditions, the use of theoretical and experimental models of rock cutting as well as numerical modeling, regardless of the presence of water, will not bring real results.

Water saturation and the presence of water in the pores and surrounding rock can change the mechanical properties of sedimentary, metamorphic, and igneous rocks compared to dry conditions and leads to a decrease in rock material compressive strength (e.g. Cai et al. [31], Hawkins and McConnell [32], Tang [33], Yilmaz [34], Colback and Wiid [35], Dyke and Dobereiner [36], Jiang *et al*. [37, 38], Török and Vásárhelyi [38], Zhou *et al*. [39]), rock material tensile strength (Ojo and Brook [40], Lashkaripour [41], Vasarhelyi and Ván [42], Karakul and Ulusay [43], Guha Roy *et al*. [44], Maruvanchery and Kim [45], Erguler and Ulusay [46], Hashiba and Fukui [47], and Wong and Jong [48]), rock material elastic modulus (Kwasniewski and Oitaben [49], Karakul and Ulusay [43]; Guha Roy *et al.* [44], Maruvanchery and Kim [45], Hashiba and Fukui [47], Wong and Jong [48], Mann and Fatt [50], Shakoor and Barefield [51], and Burshtein [52]), and rock material shear strength (Pellet *et al.* [53], Zhao *et al*. [54], and Tang *et al*. [55]).

As expected, changes in the physical and mechanical properties of the rock due to the presence of water can affect the rock cutting mechanism, cutting forces, rock fracture mode, production capacity, chipping efficiency, specific energy (SE), cutter wear rate, flowability and particle transfer and heat transfer in mechanical excavation systems. On the other hand, in a laboratory-scale study on the rock cutting forces using a linear/rotary cutting machine contrary to the actual conditions of rock excavation using a mechanical excavator, any evaluation of rock cuttability may lead to unrealistic results of machine operational parameters such as specific energy and penetration rate, and consequently incorrect design parameters for the machine. Accordingly, as a result of incorrect and unrealistic estimation of technical and operational parameters of the mechanical excavator and project schedule, excavation operations and finally the project success will be technically / operationally, economically, and environmentally endangered.

A review of the literature shows that, unfortunately, cutting conditions such as water saturation and moisture are often overlooked when examining rock cuttability with cutting tools. A limited amount of research has been done so far to address the effects of water saturation on cutting efficiency

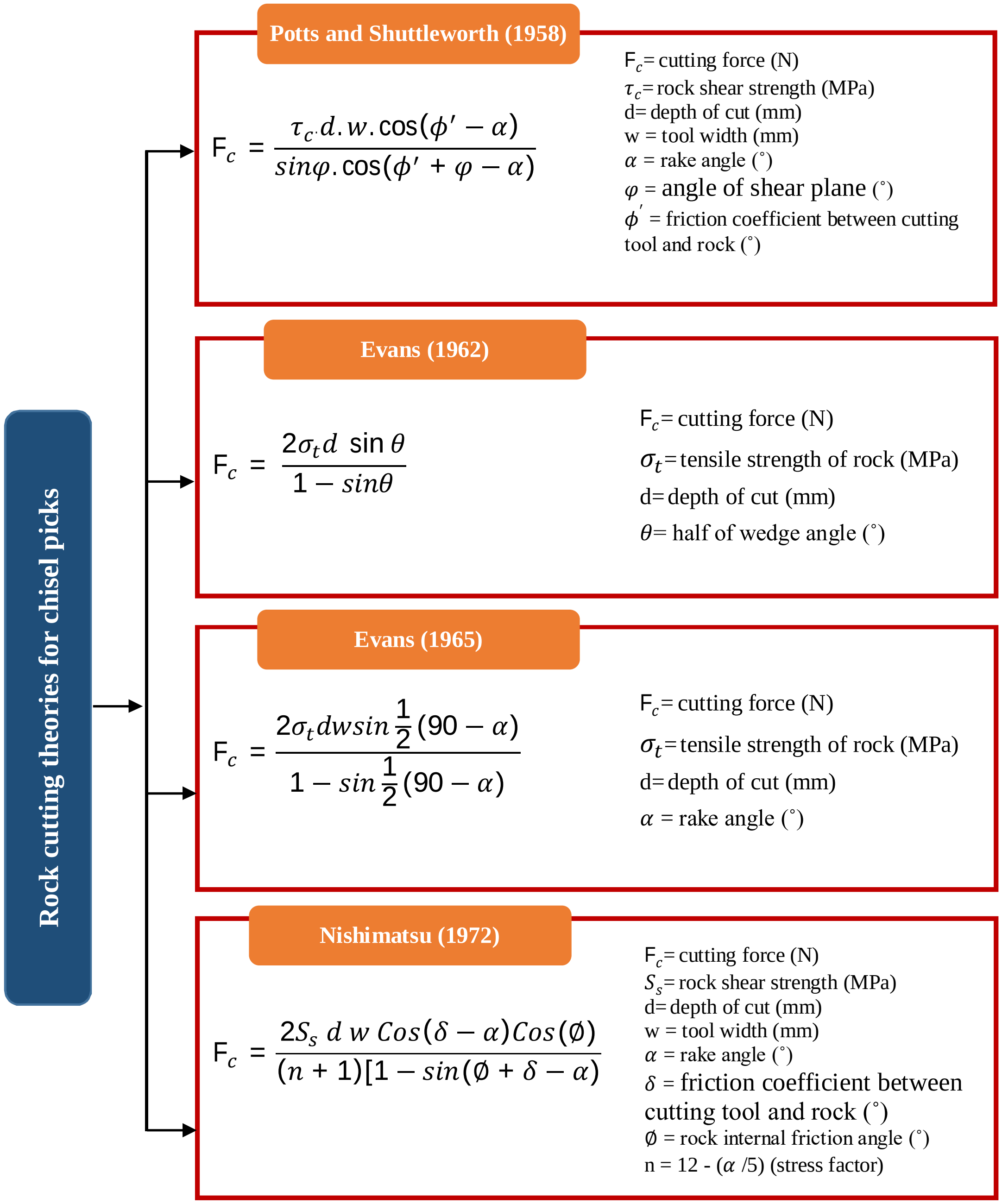


Figure 1. Rock cutting theories for chisel picks.

By conducting full-scale laboratory rock cutting tests using various types of cutting picks and discs in lower-chalk in dry and wet conditions, Roxborough and Rispin [56] reported that the cutting force is the same for dry and wet cutting exclusively for drag tools. They did not provide a reason for not changing the cutting force in the wet cutting test compared to the dry cutting, while the uniaxial compressive strength of dry gypsum was 5 times higher than that of wet gypsum. Also they reported that the specific energy is 50% higher in wet conditions compared with dry conditions. They attributed the increase in specific energy in wet conditions to the low values of the coarseness index (CI). O'Reilly *et al.* [57] investigated the difference between rock cutting with drag and disc tools in the dry and saturated chalk by performing the large-scale cutting tests in both relieved and unrelieved cutting modes. The results of their study showed that the specific energy required for cutting saturated and dry chalk was the same, while the compressive strength in the dry state was on average 5 times higher than in the saturated state. Phillips and Roxborough [58] performed cutting tests with drag tools on dry and saturated gypsum and sandstone, claiming that if a rock remained competent after saturation, its cutting forces would be higher in the wet state than in the dry state. However, they did not give a fully understood reason for it, and attributed it to the dispersion of pore water from the cracks created due to the high concentration of local stress around the pick. Ford and Friedman [59] investigated the effect of rock saturation on the cutting forces by conducting their drag tool cutting tests on limestone and sandstone. Their results found that water saturation reduces cutting forces by 50% compared to dry conditions. They attributed the reduction in saturated rock cutting forces to the reduction of frictional forces between the cutting tool and rock interface due to lubrication, as well as the lowering in the rock strength due to saturation. However, they stated that due to the coefficient difference of friction in dry and saturated conditions, lubrication of the contact surface of the rock and the cutting tool alone cannot reduce the cutting forces. However, they stated that the coefficient reduction of friction in saturated conditions and lubrication of the contact surface of the rock, and the cutting tool alone cannot reduce the cutting forces. Mammen *et al*. [60] investigated the effect of different levels of sandstone moisture on rock cutting performance (specific energy, cutting, and normal forces), rock compressive strength, elastic modulus, cutter wear rate, and rich wear index (CAI) as well as produced chip. They used small-scale linear cutting experiments to evaluate the cutting performance at different water content levels. Their study showed that the water content reduced the cutting and normal forces up to 40% and 49% respectively. Also the results showed that there was no significant difference between the chips produced from the cutting test of dry and saturated samples. Abu Bakar and Gertsch [61] and Abu Bakar *et al*. [62] explored cutting performance by performing a series of full-scale linear cutting tests with disc cutter in different ratios of cut spacing to penetration on dry and saturated Roubidoux sandstone with a porosity of 18%. The authors correlated the coarseness index and absolute size constant of the Rosin-Rammler distribution with the production rate and specific energy, and revealed that in both dry and saturated cutting conditions, with increasing CI and x′, the production rate increases and the corresponding specific energy decreases. The authors also reported reductions of 27.5%, 44%, 48%, and 8% in normal, rolling, and side-forces from dry to saturated conditions, respectively. In addition, Abu Bakar and Gertsch [15] evaluated the cutting performance of chisel-type drag pick by conducting full-scale linear cutting tests on sandstone in both dry and saturated conditions. The results obtained from this study are different from the results obtained from the rock cutting tests with a disc cutter on the same rock. The authors reported that water saturation increased cutting and normal forces as well as specific energy by 9.9%, 9.4%, and 28%, respectively. Their study also confirmed the relation between the coarseness index and absolute particle size of Rosin-Rammler [63] distribution with the specific energy.

A review of research history shows that relatively extensive studies have examined the effect of water saturation or the presence of water on the physical-mechanical behavior of rock and failure mechanics. At the same time, a small number of studies have investigated the effect of saturation on rock cutting mechanics in mechanical excavation, and the results of these studies have often been contradictory. Meanwhile, the effect of water saturation on peak and mean cutting force, the amplitude of force fluctuations and its relationship with chip size, rock cutting process mechanisms, and breakout angle under saturated condition has not been investigated yet.

The main objective of this paper is to investigate the effect of water saturation on the maximum cutting force, mean cutting force, and cutting force fluctuations obtained from small-scale rock cutting experiments. Furthermore, the size of cutting particles produced in dry and saturated conditions and its relationship with force fluctuations is highlighted in this study. Possible reasons for changing the peak and mean cutting forces in saturated conditions relative to dry conditions were proposed.

2. Preparation of Rock Samples

In order to study water saturation on chisel pick cutting forces and rock debris produced in cutting test, nine rocks including five sandstones (S1, S2, S3, S4, and S5) and four gypsums (G1, G2, G3, and G4) were collected from different regions of Iran, and block samples were transferred to the laboratory. Gypsums were taken from three Gypsum mines around Garmsar and Tehran cities situated in Semnan and Tehran provinces, respectively. Sandstones were collected from rock slopes in road cuts near Tehran. In addition to natural rock samples and in order to increase the variability of specimens, three synthetic specimens (CP, DPP1, and DPP2) with more porosity than rock samples with a combination of dental and building plaster and concrete were made based on the research objectives.

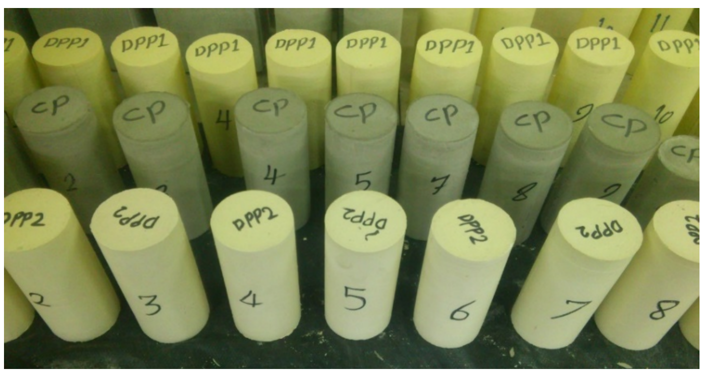
After transferring the rock blocks to the laboratory, NX cylindrical core specimens with an approximate diameter of 54 mm were prepared from each of the rock blocks by core drilling for the determination of physical and mechanical properties. Multi-piece polyethylene molds with a diameter of 54 mm and a length of 120 mm were used to prepare synthetic cylindrical specimens. Figure 2 shows some cylinder specimens prepared for physical and mechanical testing of the rock.

To evaluate the cuttability of rock using a small-scale linear cutting machine, rectangular cube specimens with a length up to 30 cm, a height up to 35 cm, and a width up to 30 cm were prepared. This was done using a rock-cutting saw machine available in the laboratory. Plexiglas and cast iron molds with dimensions of 12 x 15 x 20 cm have also been used to prepare synthetic cubic specimens.

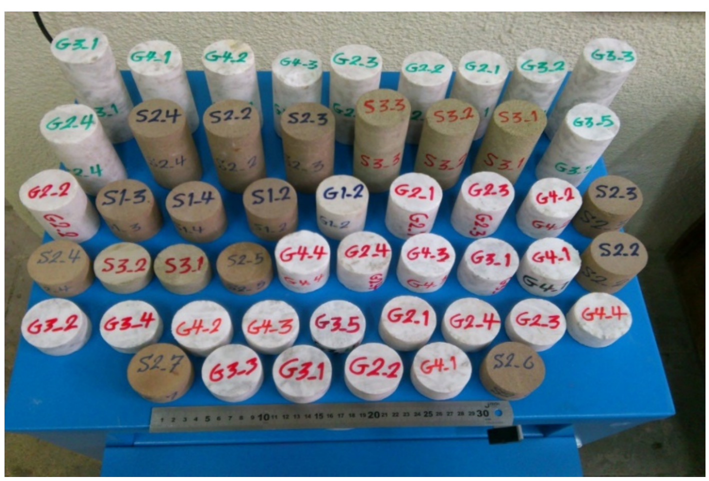
Physical and mechanical tests of rock, as well as rock cutting tests, were performed under dry and saturated conditions. Rock samples were saturated according to the International Society for Rock Mechanics (ISRM) [64] standard using a desiccator and a vacuum pump. For water saturation, the samples were immersed in water and saturated in a vacuum of less than 800 Pa for at least one hour (Figure 3).

3. Physical and Mechanical Properties

The rock mechanics tests were performed in accordance with the available ASTM standards in dry and saturated conditions (ASTM D2938-95 [65], ASTM D3967-95 [66], ASTM D4543-08 [67]). Also the dry density and saturation of rock samples, porosity, and water content percentage of samples were measured according to suggested methods by ISRM [64]. Table 1 summarizes the physical and mechanical properties of rock samples. As seen in the Table, soft to medium rocks according to Bieniawski [68] suggested classification for intact rock UCS were used to investigate the cuttability of dry and saturated rocks in this study.



a) synthetic specimens



b) sandstone and gypsum specimens

Figure 2. Cylindrical specimens used in rock physical and mechanical tests.

Figure 3. Saturation of rock samples with vacuum saturation equipment.

Table 1. Summary of samples' physical and mechanical properties.

Type of rock	Density (g/cm^3)		Water content (%)	Porosity (%)	Uniaxial compressive strength (MPa) ± sd		Brazilian tensile strength (MPa) ± sd	
	Dry	Saturated			Dry	Saturated	Dry	Saturated
Sandstone 1	2.298	2.430	6	13	31.40±2.9	17.91±1.8	2.61±0.41	1.59±0.13
Sandstone 2	2.284	2.380	4	8	37.51±5.1	20.15±1.4	3.59±1.23	3.30±0.34
Sandstone 3	2.261	2.415	7	10	43.40±4.2	27.10±2.4	2.29±0.52	1.48±0.21
Sandstone 4	2.177	2.347	8	17	10.72±1.4	4.81±0.8	2.04±0.46	1.30±0.24
Sandstone 5	2.289	2.428	6	15	25.63±3.3	18.21±1.1	2.24±0.23	1.38±0.14
Gypsum 1	2.121	2.190	3	7	10.30±1.2	5.16±0.4	2.40±0.27	0.89±0.17
Gypsum 2	2.276	2.284	0.4	1	21.78±2.7	11.20±1.2	3.38±0.43	1.94±0.31
Gypsum 3	2.288	2.294	0.3	1	24.54±2.1	16.98±2.1	3.19±0.57	2.20±0.43
Gypsum 4	2.233	2.259	1	3	11.02±1.6	6.17±0.7	1.91±0.18	1.27±0.15
CP	1.209	1.744	44	53	13.62±1.4	5.52±0.6	2.32±0.48	0.87±0.33
DPP1	1.466	1.773	21	31	24.62±2.9	7.26±0.9	3.88±0.51	1.16±0.45
DPP2	1.435	1.765	23	33	21.15±2.6	5.65±0.4	4.18±0.61	1.24±0.21

4. Small-scale Rock Cutting Tests

In this research work, rock cutting experiments were performed using a small-scale linear cutting machine (SSLCM) at the Mechanized Excavation Laboratory (MEL) of Tarbiat Modares University (TMU). This test rig is the modified Klopp shaping machine, which has a power of 5.9 kW and a maximum cutting stroke of 900 mm. The cutting stroke position in the test rig can be adjusted according to the length of the rock sample in the cutting direction. Figure 4 shows a picture of the SSLCM machine along with its main parts for running rock cutting experiments in the laboratory. Adjusting the cutting depth to an accuracy of 0.1 mm is done by rotating the pilot wheel, which rotates each complete revolution of the wheel, equivalent to 5 mm of the vertical tool head slide. The sample placement frame is placed on the work table and can accommodate samples up to 30 x 35 x 30 cm. It is possible to move the work table in the Y direction and adjust the distance between the cutting grooves to an accuracy of 0.1 mm by turning the hand wheel.

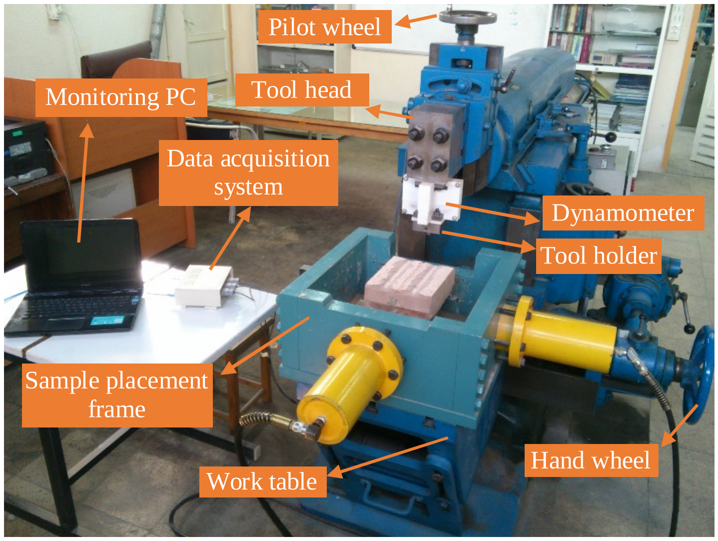


Figure 4. Components of the testing system with linear rock cutting machine.

A strain gauge 3-D dynamometer was installed under the tool head for measuring the cutting forces exerted by the cutting tool (i.e. chisel in the present study). The dynamometer was connected to the data collection system consisting of necessary hardware and software running on MS windows-based personal computer for recording and processing of cutting forces signals. The cutting tool is fixed with a tool holder directly to the dynamometer.

Fluctuations in cutting force during a typical rock cutting test are shown in Figure 5. In general, the cutting force-time (or displacement) plot from a small-scale linear rock cutting test can be divided into three parts. The first part is the initial contact or indentation, in which an initial peak cutting force is usually created along with a large chip. The next part is the steady-state cutting. In this part, during the cutting process, the cutting force applied to a drag pick is constantly changed due to the brittle nature of the rock and the formation of chips and fine materials. The last part is when the drag pick approaches the end of the rock sample and a slight drop in force occurs due to changes in boundary conditions.

In this study, the analysis of cutting force and size of cutting particles was performed based on data of the steady-state cutting part. In the steady-state cutting section, the cutting force was evaluated with three values peak cutting force (PCF), which is the maximum amount of cutting force recorded to create grooves during cutting the trial, mean cutting force (MCF), which is the average of all cutting force data on each test, and mean peak cutting force (PCF′), which is the average of the three peak forces, as suggested by Barker [69], in the force-time plot in dry and saturated cutting conditions, as shown in Figure 5.

Rock cutting tests were performed using a flat chisel pick on dry and saturated rock samples under the conditions given in Table 2 and shown in Figure 6. The depth of cut in the experiments was 1, 3, and 5 mm. The tests were repeated at least three times at each cutting depth for each rock sample, and the results were averaged. In case of large discrepancies in the test results, the number of tests was replicated more than three times. After each test, powders and chips were carefully collected and weighed, and the cutting length was measured.

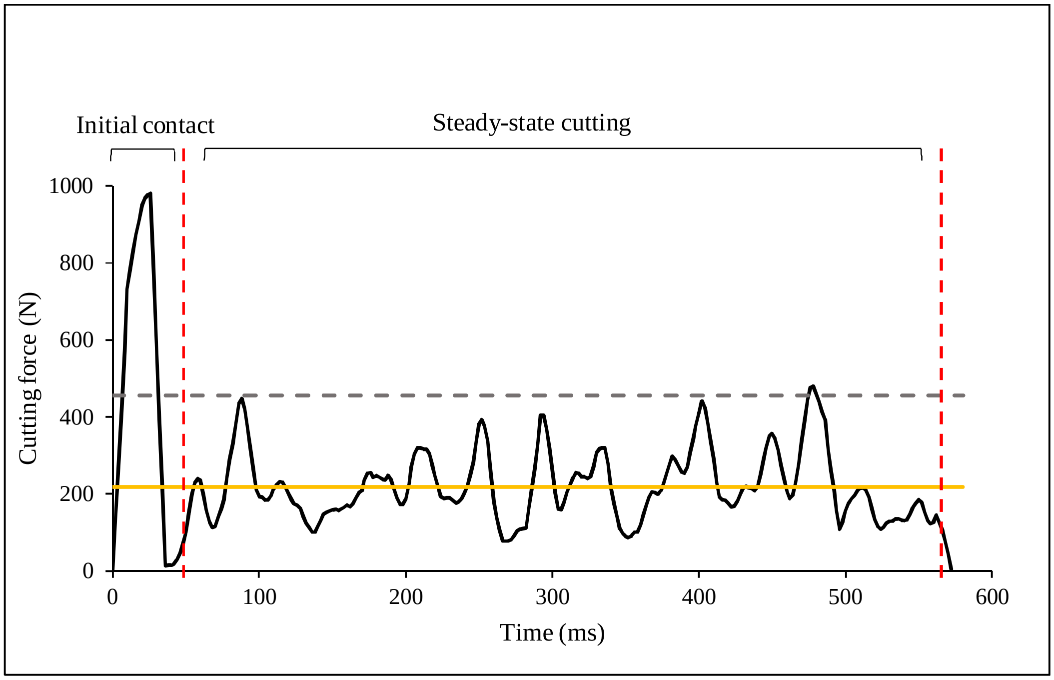


Figure 5. Fluctuations in cutting force during a typical rock cutting test.

Table 2. Parameters of linear rock cutting test.

Test condition	Dry and saturated
Cutting tool	Chisel pick
Pick width (mm)	12
Rake angle (degree)	0
Clearance angle (degree)	12
Cutting speed (cm/s)	12
Depth of cut (mm)	1, 3, and 5
Data sampling rate (Hz)	1000

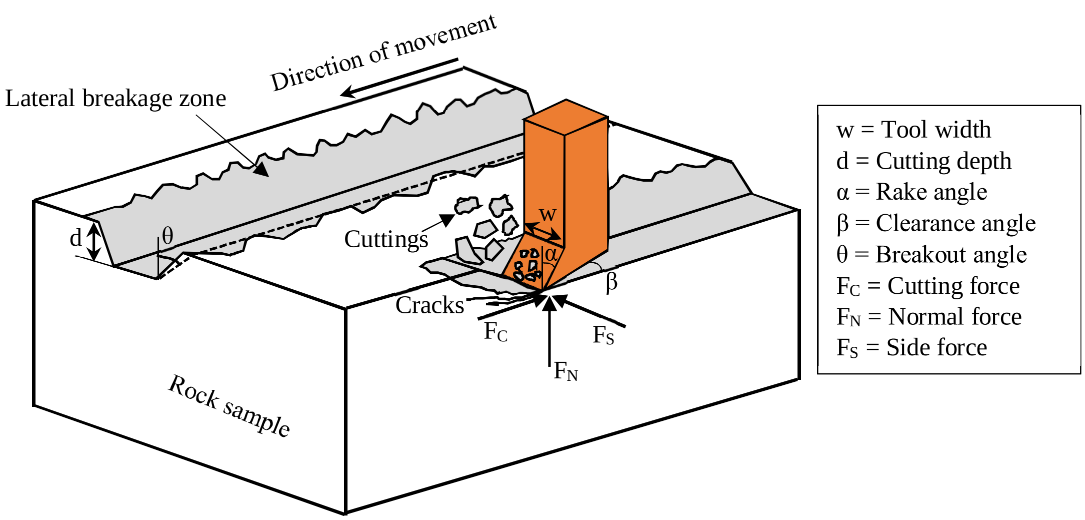


Figure 6. Parameters of rock cutting with a chisel-type pick.

5. Sieve Tests and Debris Size Analysis

In this study, median particle size was used to evaluate the effect of saturation on the chipping process efficiency. The median particle size is the value of the particle diameter at 50% in the cumulative frequency distribution that is also called the d_{50}. It divides the particle size distribution into equal amounts of “smaller” and “larger” particles. It corresponds to the 50th percentile diameters on a cumulative frequency curve, where half the particles by weight are larger and half are smaller than the median.

Sieve tests of chips and fine materials produced in each cutting experiment performed using a sieve set included the aperture of 16 mm, 8 mm, and mesh 4, 8, 16, 30, 50, and 100. Rock cuttings were separated into nine groups based on their sizes. By accurately weighing the rock cuttings in each of the nine groups and plotting the size distribution curve for each cutting test, median particle size (d_{50}) were calculated.

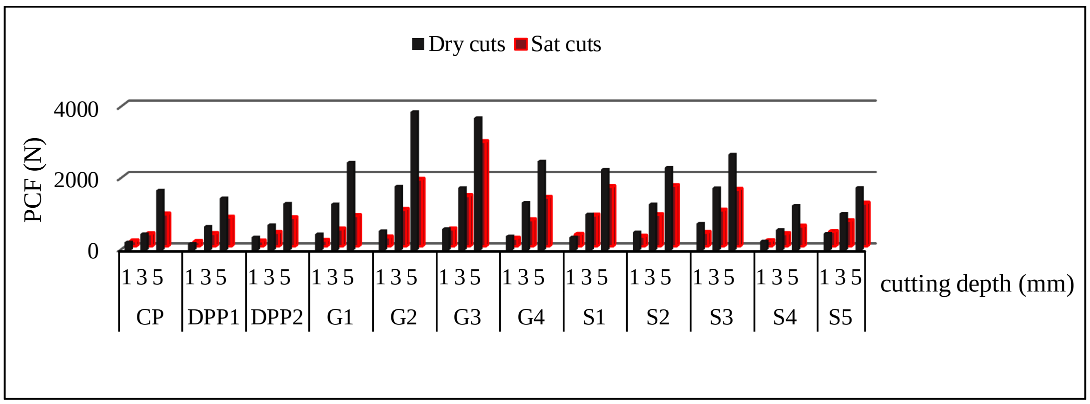
6. Results of Analysis and Discussion

6.1. Water saturation effect on cutting forces

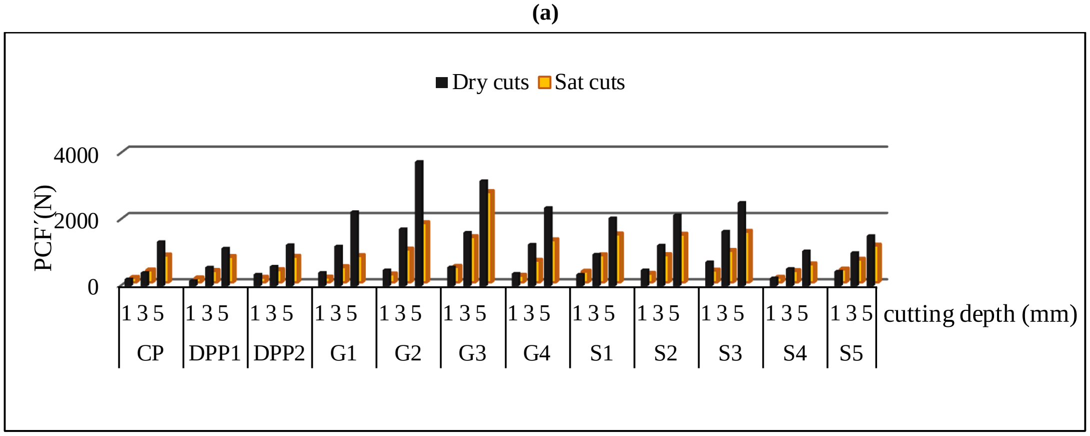
Cutting forces (PCF, PCF´, and MCF) of chisel pick in dry and saturated cutting conditions versus cutting depths of 1, 3, and 5 mm for different rock samples are shown in Figures 7 and 8.

The results show that due to the saturation of rock samples, the PCF and PCF´ have decreased compared to dry conditions. In other words, due to the saturation of the rock samples and corresponding reduction in the mechanical properties of the rock, the cutting force required for rock breakage and chip formation is reduced. The relative variation of PCF and MCF in the cutting experiment of saturated rock samples compared to dry rock for different cutting depths is shown in Figure 9. The required torque of cutting machines is determined based on the cutting force. Therefore, the cutting force variation in saturated conditions affects the required torque. Excessive cutting force or required torque may result in tool breakage or irreversible damage to mechanical cutting units.

It is interesting to note that the relative changes of the mean cutting force under saturated conditions are different in the natural and artificial rock samples. In natural rock samples, the mean cutting force decreases due to the saturation of the samples, such as the peak cutting force, so that the reduction values in the percentage of PCF and MCF changes are almost the same. However, in the saturated synthetic rock samples, although the PCF decreased, the MCF remained unchanged or even increased.



(a)



(b)

Figure 7. Variation of a) peak cutting force b) mean peak cutting force versus cutting depth in dry and saturated samples.

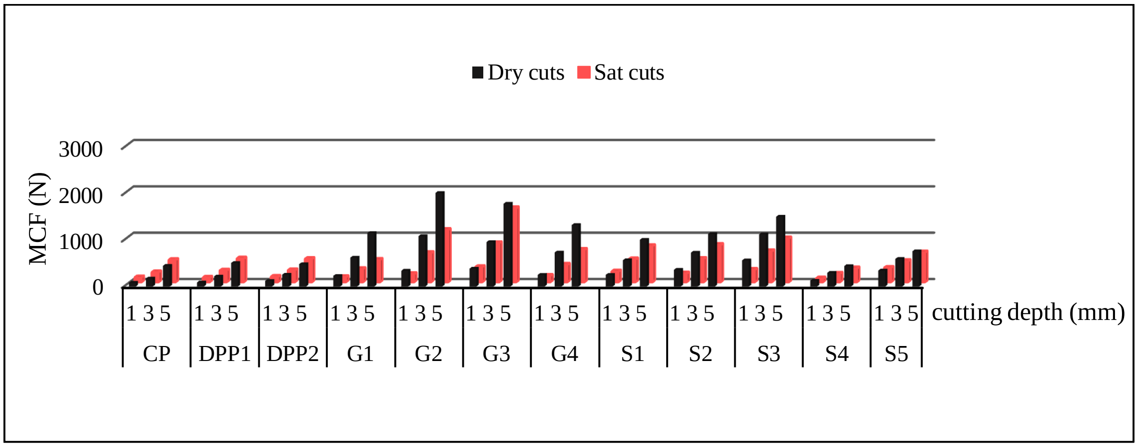


Figure 8. Variation of mean cutting force versus cutting depth in dry and saturated samples.

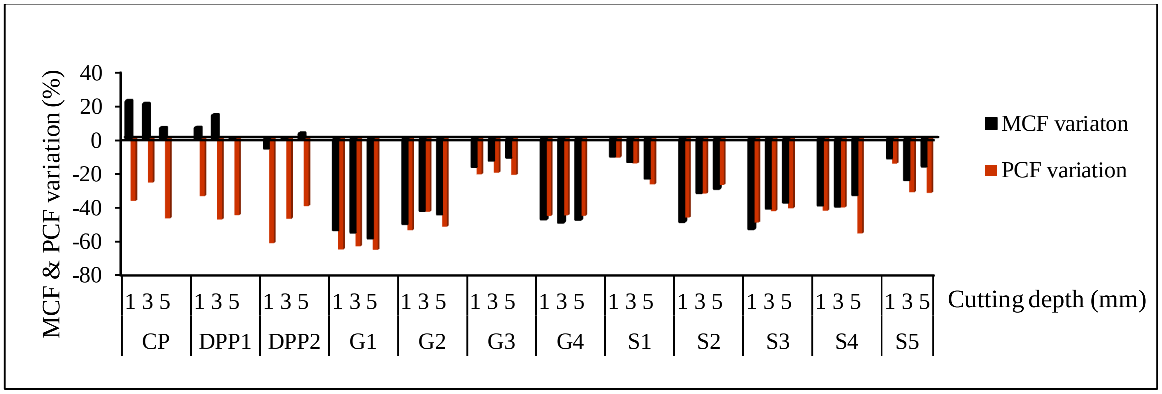
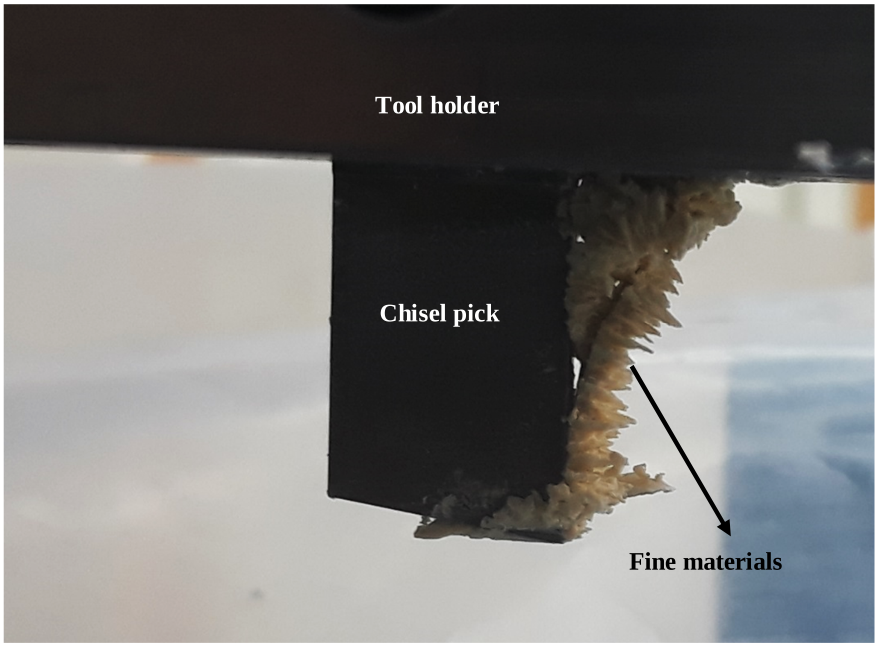


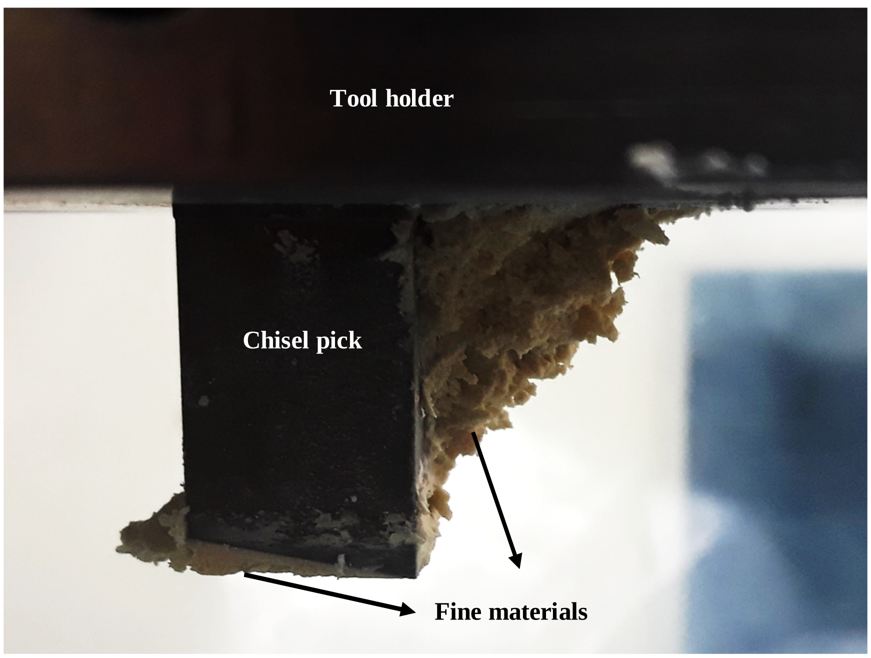
Figure 9. Relative variation of peak and mean cutting force of chisel pick after saturation of samples at different depths of cut.

It seems that the reason for the lack of change or relative increase in the mean cutting force of rock in saturated conditions is not related to the process of particle formation produced by cutting but related to post-cutting. In the saturated synthetic rock samples, the powders produced from the cutting test form a slurry that causes the crushed material to accumulate in front of the cutting tool, which in turn causes the chisel pick to clog. Chisel tool clogging after cutting synthetic specimens is shown in Figure 10. This case was less seen during the cutting test of natural saturated rock samples. Roxborough [70] obtained similar results by performing rock-cutting experiments on saturated sandstone, noting that debris in the form of small sandy material clings to each other in the presence of water, and a paste is formed near the cutter-rock contact.

Pushing the paste attached to the cutting tool during the cutting process is one of the main reasons for increasing the cutting force of synthetic rock samples in saturated conditions.



(a)



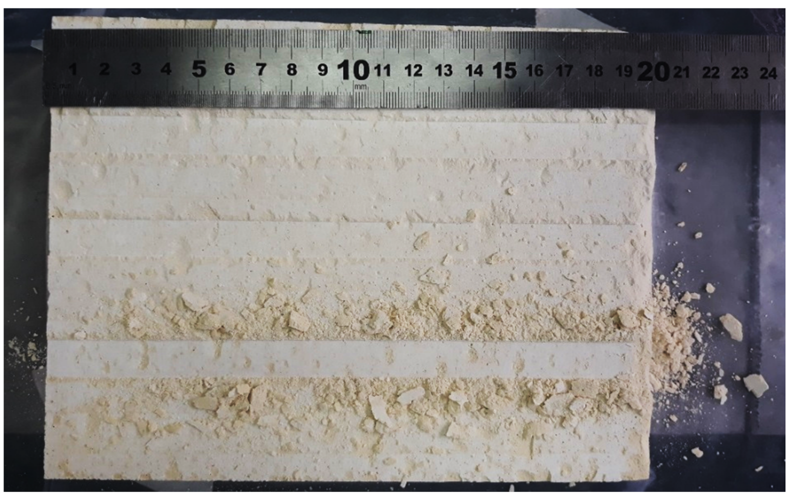
(b)

Figure 10. Chisel pick clogging with fine materials produced in cutting test in saturated DPP1 synthetic sample a- d = 1 mm, b- d = 5 mm.

Also in saturated rock samples, due to the filling of the void space of the rock by water and the high viscosity of water relative to the air, the chips are not easily separated from the rock (the host rock matrix) during the cutting test and are placed next to and under the chisel pick. Therefore, another reason for increasing the mean cutting force in the saturated cutting test compared to dry cutting is the placement of the cutting fragments under the chisel tool and their re-crushing. Jackson *et al.* [71] reported similar findings in their study on a sub-sea mechanical trenching wheel, and stated that the viscosity of the water reduces the speed at which the chip can leave the host rock matrix compared to the same situation in the air. This delay increases the remaining chips in the trench and can result in a negative re-grinding effect.

The configuration and scattering of rock debris in both dry and saturated modes for the DPP1 synthetic rock and S5 natural rock are shown in Figures 11 and 12, respectively. As it can be seen, in dry samples, the cutting particles are scattered around the cutting groove during cutting but in saturated samples, the dispersion is less. In saturated synthetic specimens, the particles are placed at the end of the cutting path.

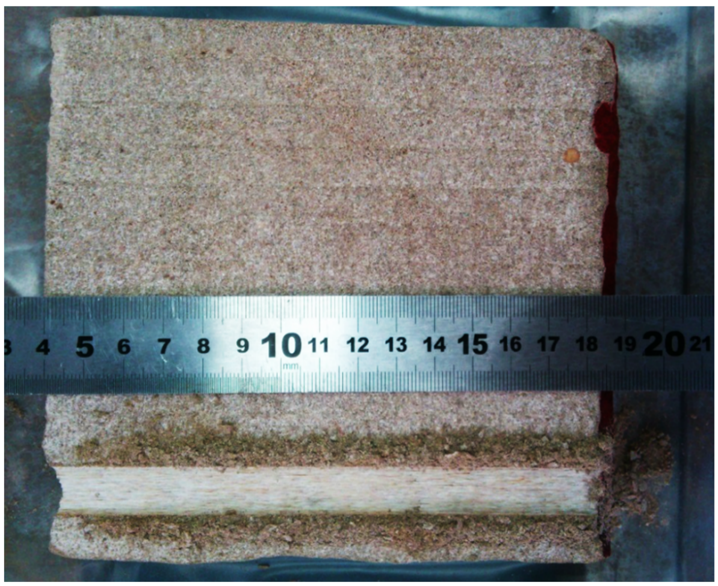
(a)



(b)

Figure 11. Configuration and scattering of rock debris in both dry and saturated modes for the DPP1 synthetic rock; d = 1 mm, a- Dry cut, b- Saturated cut.

(a)

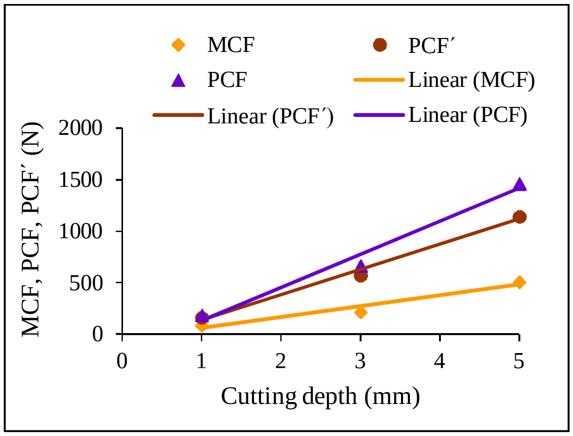


(b)

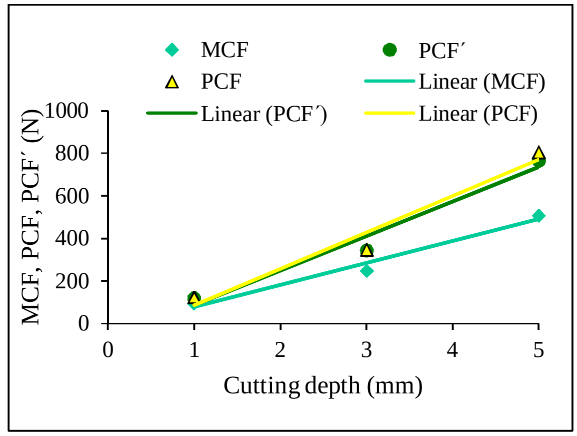
Figure 12. Configuration and scattering of rock debris in both dry and saturated modes for S5 natural rock; d = 1 mm, a- Dry cut, b- Saturated cut.

The cutting test results at cutting depths of 1, 3, and 5 mm show that in both dry and saturated conditions, the cutting force increases linearly with depth of cut. For example, MCF, PCF, and PCF´ changes based on the depth of cut and linear regression diagrams for DPP1, S1, and G1 samples in dry and saturated conditions are shown in Figure 13. Correlation analysis relationships for all dry and saturated rock samples are given in Tables 3 and 4, respectively. As shown in these Tables, the coefficients of determination between cutting forces and depth in both dry and saturated conditions vary from 0.8665 to 1. Similar relationships reported by Yashar and Yilmaz [72, 73] when conducting a series of cutting tests with a chisel pick on five different volcanic rock (red andesite, green tuff, grey tuff, brown vitric tuff and yellow vitric tuff) and examining the correlation between cutting force and cutting depth. Yasar and Yilmaz [74] also reported linear relationships in rock cutting tests with a conical pick. Also the strong correlation between the cutting forces and depth of cut is in agreement with findings of Potts and Shuttleworth [75], Evans [76, 77], Evans and Pomeroy [78],Allington [79], Nishimatsu [80], Bilgin [3], Copur [12], Rostamsowlat *et al*. [81, 82], and Mohammadi *et al*. [83].

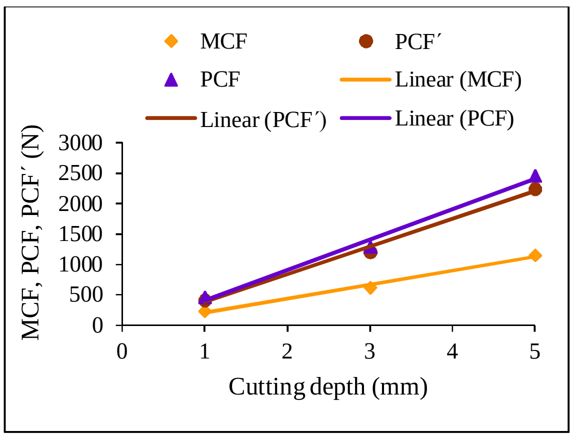
Due to the linearity of the force increase trend at different cutting depths and the high correlation coefficient between cutting force and depth, in field operations where the depth of cut is greater, these relationships and trends can be used to predict mean and peak cutting force.



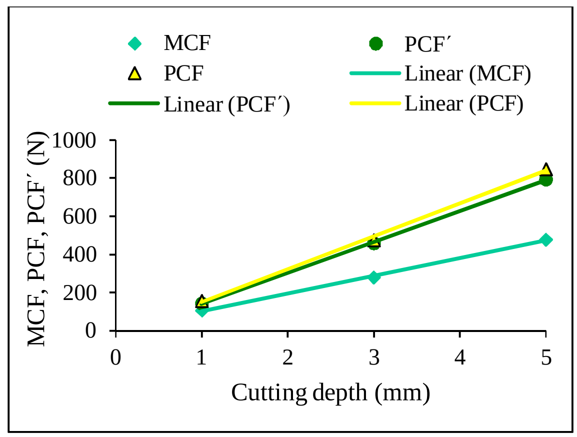
a) DPP1 sample – Dry cuts



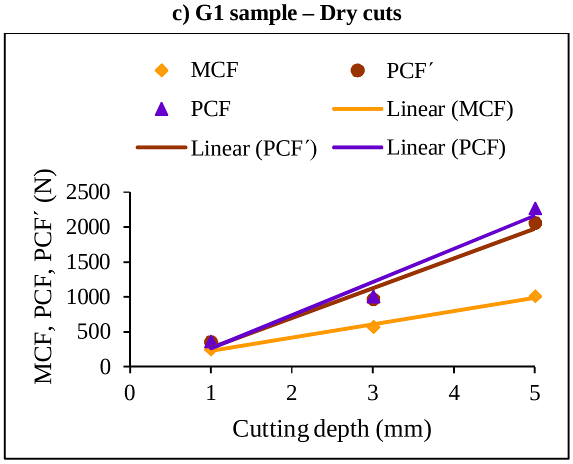
b) DPP1 sample – Sat cuts



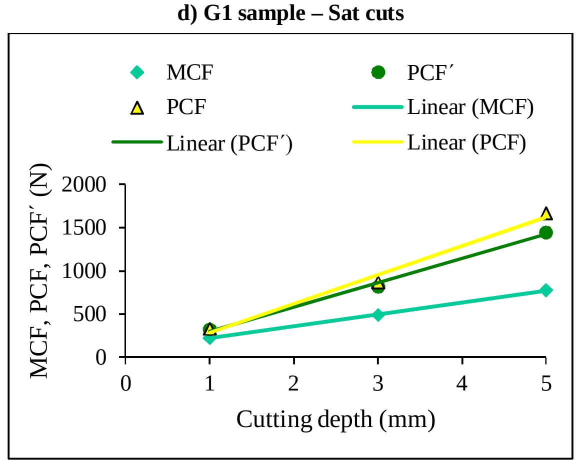
c) G1 sample – Dry cuts



d) G1 sample – Sat cuts



e) S1 sample – Dry cuts



f) S1 sample – Sat cuts

Figure 13. Variation of MCF, PCF, and PCF´ with cutting depth in both dry and saturated cutting modes for rock samples DPP1, G1 and S1.

Table 3. Regression equations for MCF, PCF, and PCF′ in dry cutting tests.

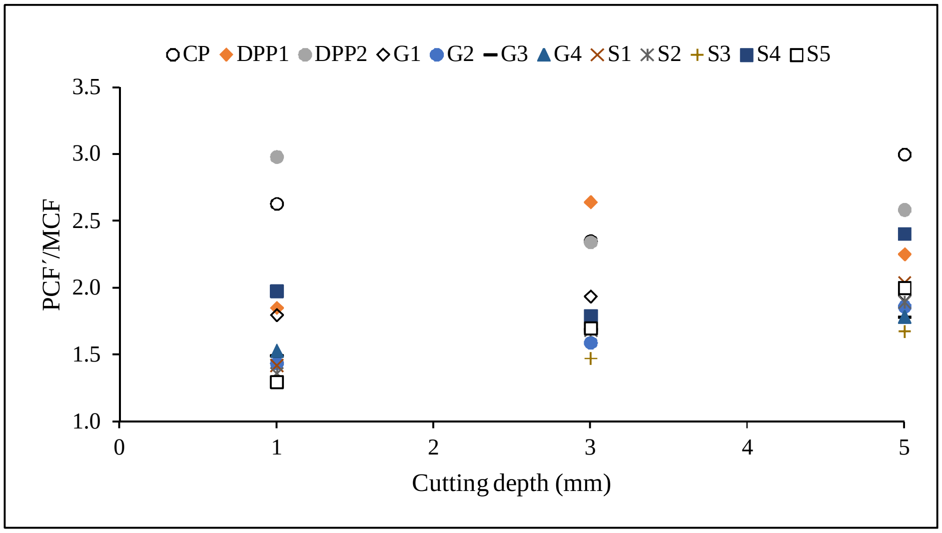
Rock sample	Equation	R^2	Rock sample	Equation	R^2
CP	MCF = 91.402d - 39.261	0.925	G4	MCF = 269.3d - 36.579	0.9967
	PCF′ = 281.79d - 188.58	0.8754		PCF′ = 495.97d - 149.99	0.9956
	PCF = 363.59d - 302.35	0.8665		PCF = 524.25d - 163.99	0.9964
DPP1	MCF = 104.74d - 42.568	0.9525	S1	MCF = 189.23d + 42.148	0.9906
	PCF′ = 244.96d - 106.6	0.9912		PCF′ = 425.28d - 148.83	0.9732
	PCF = 319.47d - 186.61	0.9794		PCF = 475.42d - 209.34	0.9666
DPP2	MCF = 90.718d + 14.967	0.9791	S2	MCF = 193.2d + 162.89	0.9995
	PCF′ = 222.39d + 69.87	0.9337		PCF′ = 414.08d + 49.083	0.9964
	PCF = 235.58d + 90.406	0.9761		PCF = 452.2d + 18.744	0.9939
G1	MCF = 231.4d - 24.348	0.9926	S3	MCF = 235.35d + 359.67	0.9876
	PCF′ = 458.33d - 85.63	0.9941		PCF′ = 447.13d + 296.79	0.9997
	PCF = 501.63d - 100.25	0.9913		PCF = 484.18d + 275.53	0.9997
G2	MCF = 419.33d - 107.99	0.9958	S4	MCF = 79.071d + 50.921	0.9981
	PCF′ = 815.81d - 454.53	0.9809		PCF′ = 203.75d + 3.3056	0.9692
	PCF = 833.44d - 428.79	0.9796		PCF = 248.93d - 51.175	0.9579
G3	MCF = 350.16d - 5.932	0.9892	S5	MCF = 103.67d + 256.66	0.9861
	PCF′ = 650.32d - 159.24	0.9875		PCF′ = 268.19d + 190.05	0.9992
	PCF = 776.35d - 307.35	0.9783		PCF = 320.99d + 126.14	0.9944

Table 4. Regression equations for MCF, PCF, and PCF′ in saturated cutting tests.

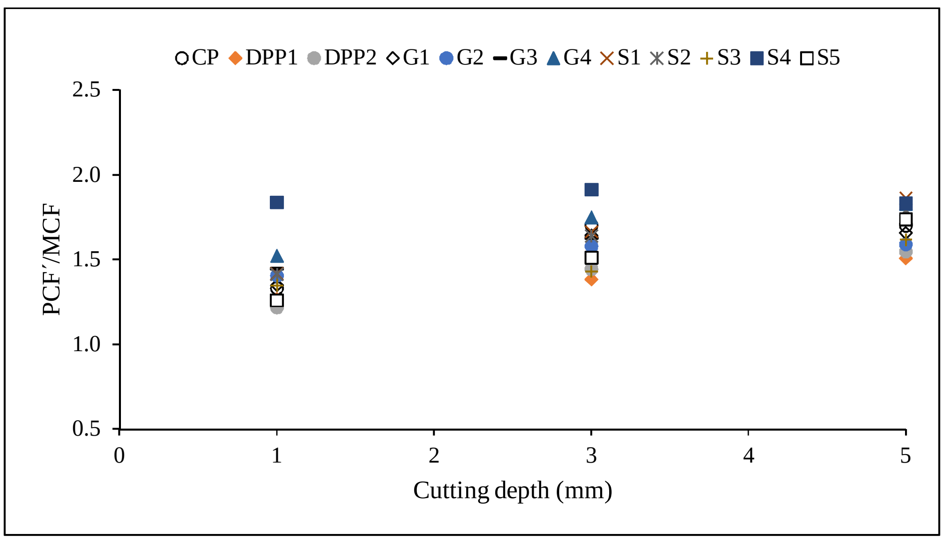
Rock sample	Equation	R^2	Rock sample	Equation	R^2
CP	MCF = 94.091d - 19.384	0.9463	G4	MCF = 140.84d - 22.628	0.9931
	PCF′ = 169.04d - 72.416	0.9645		PCF′ = 267.28d - 94.352	0.9919
	PCF = 187.53d - 103.27	0.9305		PCF = 286.31d - 88.158	0.997
DPP1	MCF = 103.29d - 26.029	0.9782	S1	MCF = 137.01d + 86.508	0.9995
	PCF′ = 161.44d - 74.074	0.9691		PCF′ = 280.72d + 18.907	0.9953
	PCF = 170.74d - 85.969	0.9627		PCF = 333.66d - 48.353	0.9879
DPP2	MCF = 96.231d + 0.9748	0.9765	S2	MCF = 154.21d + 32.477	0.9999
	PCF′ = 158.22d - 48.074	0.9753		PCF′ = 293.96d - 43.042	0.9992
	PCF = 162.5d - 50.844	0.9749		PCF = 354.7d - 116	0.9925
G1	MCF = 92.971d + 9.1509	0.9985	S3	MCF = 169.45d + 115.32	0.9891
	PCF′ = 162.5d - 21.889	0.9998		PCF′ = 292.21d + 67.319	0.9999
	PCF = 172.78d - 24.342	0.9976		PCF = 301.71d + 85.329	0.9996
G2	MCF = 238.15d - 74.363	0.9993	S4	MCF = 54.92d + 19.013	0.9981
	PCF′ = 386.67d - 154.74	0.9997		PCF′ = 100.5d + 40.167	0.9999
	PCF = 404.83d - 166.74	0.9993		PCF = 101.45d + 44.417	0.9993
G3	MCF = 317.44d - 33.903	0.9884	S5	MCF = 82.75d + 217.51	0.9947
	PCF′ = 563.64d - 173.4	0.9862		PCF′ = 180.54d + 185.32	0.9892
	PCF = 611.38d - 231.6	0.9812		PCF = 198.41d + 176.61	0.9815

6.2. Water saturation effect on PCF′/MCF ratio

The variation of the ratio of peak to mean forces (PCF′/MCF) in terms of cutting depth for both dry and saturated cutting modes is shown in Figure 14, and is summarized in Table 5. The results showed that in dry cutting conditions, the ratio of peak to mean force changed between 1.3 and 3, while in saturated conditions, it was between 1.3 and 1.9. It can be concluded that the ratio of peak to mean forces is affected by water saturation and is less in saturated cutting conditions than in dry conditions. High values of the ratio of peak to mean forces have a great effect on the vibration of the cutting head, which leads to mechanical breakdown. Therefore, the rock-cutting machine in dry conditions experiences more cutting head vibration than in saturated conditions, which may result in cyclic loading and breakdown of the cutting head due to fatigue. The results also showed that there was no significant trend between the PCF′/MCF ratio and the depth of cut in a given rock sample, and the ratio remains almost constant with changes in the depth of cut. For example, the ratio of peak to mean forces in the cut of dry rock sample G1 at the cutting depth of 1, 3, and 5 mm was obtained as 1.8, 1.9, and 1.9, respectively. The PCF′/MCF value along with theoretical models, which are used to find the maximum force, can be useful. With the aid of the PCF′/MCF ratio and having the amount of maximum cutting force, the amount of mean cutting force can be estimated.



a) Dry cuts



b) Sat cuts

Figure 14. Variation of PCF′/MCF versus depth of cut; a- Dry cut, b- Saturated cut.

Table 5. Variation range of PCF/MCF ratio in dry and saturated cutting conditions.

Cutting depth (mm)	PCF′/MCF	
	Dry cuts	Sat cuts
1	1.3 - 3	1.3 - 1.8
3	1.5 - 2.6	1.4 - 1.9
5	1.7 - 3	1.5 - 1.9

6.3. Water saturation effect on force fluctuations and chip size

In order to better understand the difference in the amplitude of force-time fluctuations in the cutting test of dry and saturated rock samples, the standard deviation (SD) of the cutting force data was used. The standard deviation of cutting force data in dry and saturated conditions for different rock samples is given in Table 6. The results showed that the standard deviation of cutting force data in saturated conditions was less than in dry conditions. In other words, the amplitude of fluctuations of the cutting force in saturated conditions was less than in dry conditions. For example, Figure 15c shows a force-time fluctuation diagram for DPP1 synthetic rock under both dry and saturated cutting test conditions. As shown in Figure 15 (c), the dispersion of cutting force relative to its mean in saturated cutting conditions is lower when compared to the dry cutting conditions.

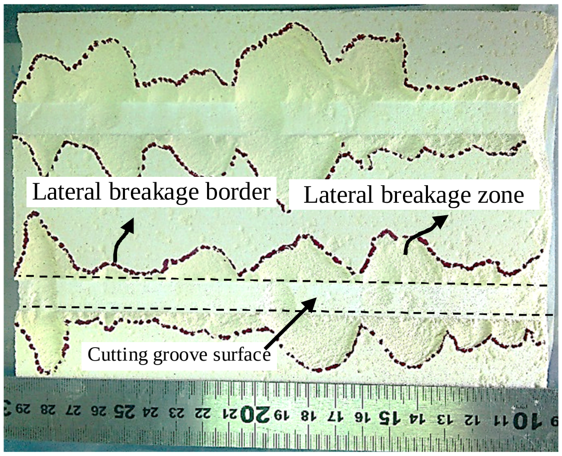
Table 6. Standard deviation of cutting force data and median size values of fragments obtained from dry and saturated cutting test in all rock samples.

Rock sample	d (mm)	SD		d_{50} (mm)		Rock sample	d (mm)	SD		d_{50} (mm)	
		Dry cuts	Saturated cuts	Dry cuts	Saturated cuts			Dry cuts	Saturated cuts	Dry cuts	Saturated cuts
CP	1	20	14	3.32	0.52	G4	1	51	24	0.25	0.24
	3	95	58	5.69	1.59		3	239	113	1.12	1.09
	5	282	202	15.7	2.9		5	498	236	4.1	2.73
DPP1	1	32	12	3.27	0.76	S1	1	50	40	0.56	0.51
	3	136	49	5.66	1.92		3	169	133	3.99	3.45
	5	345	117	12.27	2.85		5	368	259	6.73	5.75
DPP2	1	47	12	3.31	0.56	S2	1	63	30	0.41	0.31
	3	119	49	5.7	1.37		3	223	133	3.5	2.55
	5	301	122	12.71	2.72		5	424	264	6.92	5.5
G1	1	78	22	0.61	0.27	S3	1	113	42	0.28	0.24
	3	239	83	3.31	0.5		3	304	155	2.26	0.95
	5	520	156	4.17	0.97		5	493	278	4.80	2.67
G2	1	74	29	0.26	0.14	S4	1	30	15	0.14	0.14
	3	359	169	1.4	0.49		3	105	57	0.92	0.67
	5	825	319	4.62	2.84		5	215	96	2.15	1.46
G3	1	85	61	0.79	0.34	S5	1	52	38	0.28	0.31
	3	314	211	3.34	1.99		3	177	126	2.9	2.37
	5	732	496	5.38	3.12		5	315	246	8.02	4.93

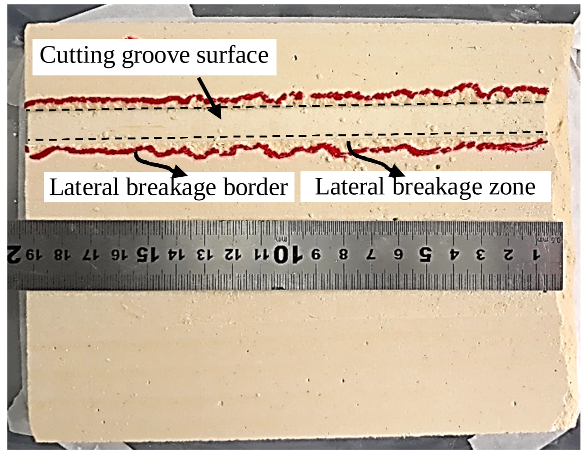
In this study, the relationship between the amplitude of force fluctuations and the median particle size of cuttings has also been investigated.

Figure 16 shows the median particle size versus standard deviation values for all rock samples. The results showed that with increase in the standard deviation of the cutting force data in both dry and saturated cutting conditions, the median size of the rock debris increased linearly with high determination coefficients in all samples. For example, the standard deviation of the cutting force data of dry sample S1 at the cutting depth of 1, 3, and 5 mm is 50, 169, and 368, respectively, and the corresponding median size of the rock debris is 56, 99, and 73 mm, respectively.

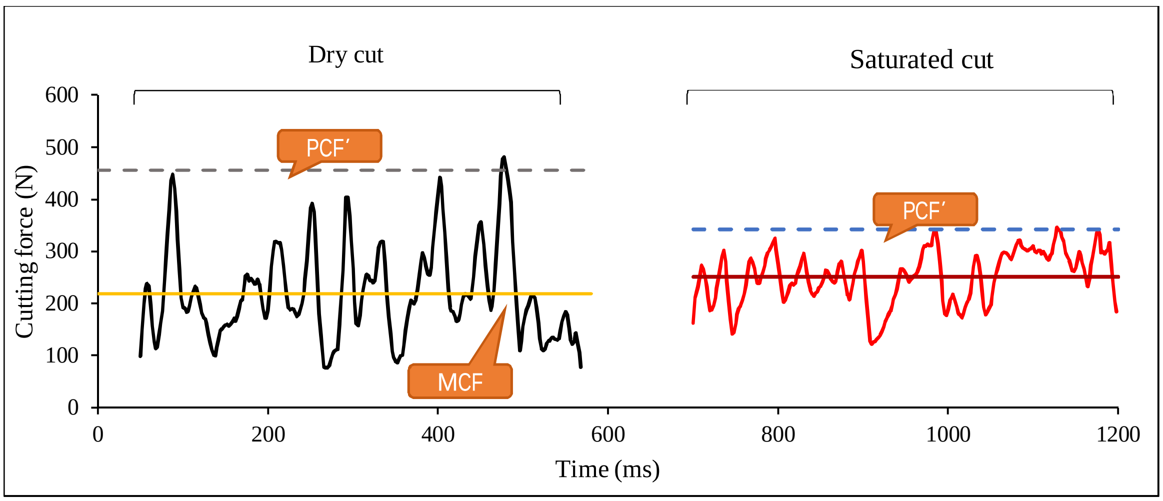
In a general summary, it can be stated that in a specific rock sample, the amplitude of cutting force data fluctuations based on cutting time can be used as a criterion for estimating the size of cutting fragments. This matter is important because, in excavation field operations, the cutting machine operator can control the chip size without analyzing the chips and only by calculating the standard deviation of the cutting force data during excavation.



(a)



(b)

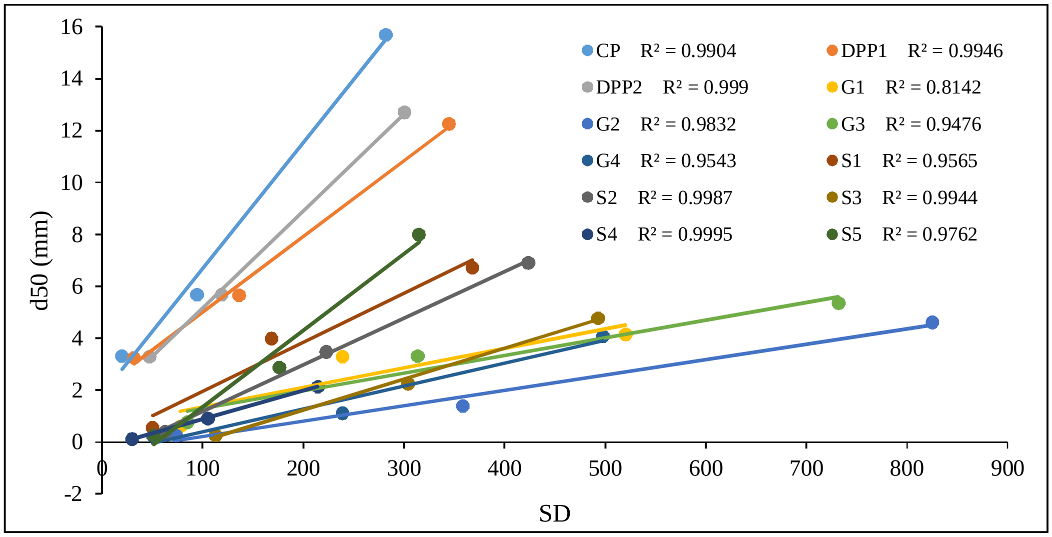


(c)

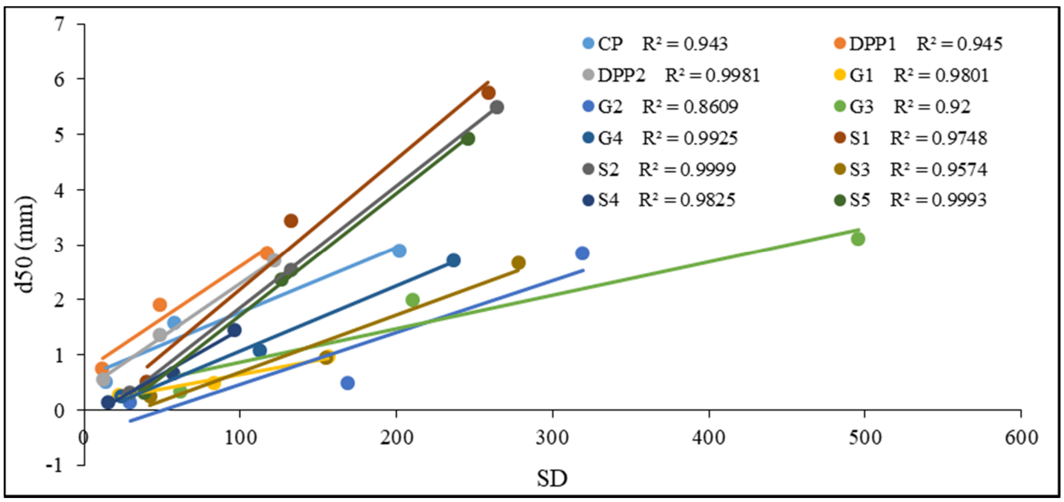
Figure 15. Result of rock cutting test in DPP1 synthetic sample; d = 3 mm; a- Lateral breakage after cutting test in dry conditions, b- Lateral breakage after cutting test in saturated conditions; c) fluctuations of cutting force versus time in dry and saturated conditions.

6.4. Specific energy in dry and saturated rock samples

In a given rock, the lower value of the specific energy is evaluated as the more efficient measure of the cutting system. The values of specific energy in the dry and saturated cutting modes for all rock samples in the cutting depth of 1, 3, and 5 mm are shown in Figure 17. As it can be seen, the specific energy variations in saturated cutting compared to dry cutting in a given sample, and the same cutting depth is different in natural and synthetic rock samples. In natural rock samples, specific energy in saturated cutting is lower than in dry cutting under the same conditions. However, in synthetic rock samples, the specific energy in the saturated rock sample is more than in the dry rock sample. The reason for the increase in specific energy for saturated synthetic rock samples compared to dry rock samples is related to the increase in the mean cutting force, while the mean cutting force decreased in saturated natural rock samples compared to dry cutting conditions.



(a)



(b)

Figure 16. Median size of rock debris versus standard deviation values for all rock samples; a- Dry cuts, b- Saturated cuts.

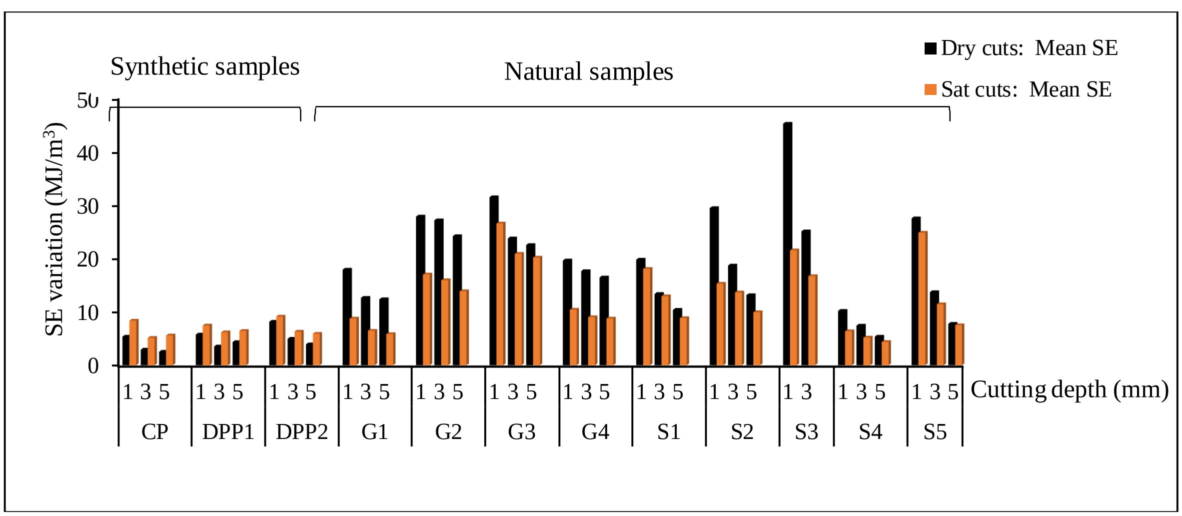


Figure 17. Values of specific energy versus cutting depth in dry and saturated samples.

7. Conclusions

Experimental results of the rock cutting with a chisel pick in dry and water-saturated conditions including peak and mean cutting forces, the amplitude of cutting force fluctuations, and the size of cutting fragments to provide more in-depth insight into the mechanical effect of water saturation on the rock cutting process, were compared and discussed. Twelve low- to medium-strength rock specimens were prepared and subjected to a small-scale linear rock cutting at cutting depths of 1, 3, and 5 mm. Also the size analysis of rock debris collected from the cutting test was carried out by sieving test. The results of experimental studies showed that the PCF and PCF′ values in saturated cutting conditions for all rock samples are reduced compared to dry conditions. Also MCF decreased for the natural rock sample, while it remained unchanged or increased for the synthetic rock sample.

It seems that if the fine material obtained from the rock cutting test in saturated conditions becomes pasty and leads to the clogging of the chisel pick, leading to increase in the mean cutting force of the pick. However, the magnitude of the force at which the chisel pick can break the rock, i.e. PCF decreased under saturated conditions. The ratio of PCF/MCF also decreased in saturated conditions than to dry conditions.

In both dry and saturated cutting conditions, an increase in the cutting depth causes a corresponding increase in the PCF, MCF, and PCF. There was a strong relationship between cutting forces (PCF, PCF, and MCF) and the depth of cut for a given rock sample in both dry and saturated conditions. There was a strong correlation between the standard deviation and size parameters of rock debris for both dry and saturated rock tests, which indicates that the amplitude of the cutting force fluctuations can be used to evaluate the chipping efficiency.

In general, the results of this study in the field of saturated rock cutting showed that water saturation had a significant effect on the rock cutting process (mechanical cutting of rock), so it is suggested that the mechanical effect of water saturation in order to design efficient cutting systems and predict the performance of mechanical cutting machines to be considered.

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مطالعه تجربی اثر اشباع آب روی نیروی برشی سنگ از یک تیغه اسکنه‌ای

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چکیده:

هدف این کار بررسی اثر اشباع آب بر نیروهای برش و راندمان تشکیل تراشه با انجام مجموعه‌ای از آزمایش‌های برش خطی کوچک مقیاس با یک تیغه اسکنه‌ای بر روی دوازده نمونه سنگ با مقاومت کم و متوسط است. نیروی برشی حداکثر و میانگین نیروی برشی وارد بر تیغه اسکنه‌ای تحت شرایط برش خشک و اشباع توسط کرنش‌سنج‌های تعبیه شده در دینامومتر اندازه‌گیری و ثبت می‌شوند. همچنین دامنه نوسانات نیروی برش در شرایط برش خشک و اشباع با اندازه‌گیری انحراف معیار داده‌های نیروی برش مقایسه شده و رابطه آن با اندازه قطعات برش بررسی می‌شود. نتایج به‌دست‌آمده نشان می‌دهد که نیروی برشی حداکثر در شرایط اشباع نسبت به شرایط خشک کاهش می‌یابد. میانگین نیروی برشی در آزمون برش نمونه‌های مصنوعی بدون تغییر یا در برخی موارد افزایش می‌یابد، در حالی که در نمونه‌های طبیعی کاهش می‌یابد. افزایش نسبی در میانگین نیروی برشی در نمونه‌های سنگ مصنوعی به دلیل حالت خمیری مواد ریز تولید شده از برش اشباع و گرفتگی تیغه اسکنه است. یک همبستگی قوی بین انحراف استاندارد داده‌های نیروی برشی و اندازه متوسط خرده‌های برش یافت شده است، که نشان می‌دهد انحراف استاندارد داده‌های نیروی برشی معیار مفیدی برای ارزیابی کارایی برش است. یافته‌های پژوهش حاضر نشان می‌دهد که برای داشتن یک سیستم حفاری کارآمد در عملیات صحرایی، باید در طراحی پارامترهای عملکرد دستگاه برش و پیش‌بینی عملکرد دستگاه حفاری، وجود آب و شرایط اشباع در نظر گرفته شود.

کلمات کلیدی: آزمون برش سنگ، شرایط اشباع، گرفتگی تیغه، تحلیل اندازه ذرات، حفاری مکانیکی.