Improved excavation performance of waterjet-assisted mechanical tools

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ABSTRACT: In this paper, after a discussion of the main issues regarding the assistance of mechanical excavation with water jet, the results of an experimental work carried out at the University of Cagliari are illustrated and discussed. The research was aimed both at studying the processes by which mechanical excavation can be improved by using water jets and at quantifying the increase in excavation performance parameters.
In particular, the mechanisms involved in the rock-tool-waterjet interaction have been studied aiming at putting into evidence the contribution of the hydraulic power both as a way to weaken the rock and to increase the stress leading to scale formation. The better knowledge achieved will be useful for the development of the technology up to a commercial scale.

KEYWORDS: Drag tool, disc cutter, water jet assistance, rock excavation, bit wear

1. INTRODUCTION

The possibility of increasing the performance of mechanical tools with the assistance provided by high-velocity water jets has been explored in the last twenty years. The results of past research have often been controversial and found to vary within a wide range, mainly due to the different experimental conditions adopted. A number of hypotheses have been advanced to explain the variability of the results as well as to disclose the mechanism of water jet assistance.

The research concerning the mechanical excavation of rocks is mainly addressed at:

- Improving the performance of mechanical tools in terms of material removal rate (i.e. increasing the excavated volume per unit length of pick trajectory);
- Extending the mechanical excavation to hard and abrasive rocks.

The “water jet assisted excavation” appears to be one of the most promising method for achieving both the stated objectives. It consists in integrating the mechanical tool action, that remains the prevalent one, with that of a high velocity water jet.

Since the years 70s the studies aimed at the development of a commercially feasible “water jet assisted” concept have been firstly addressed at discovering whether and under what conditions the jet is capable of producing an effective increment of the overall performance of the mechanical tool. At the same time, efforts have been aimed at clarifying the mechanism underlying the contribution of water jet to the improvement of the mechanical tool performance.

The outcome of the investigations and the conclusions drawn by the various Authors appear often controversial due to the great variability of the experimental conditions involving a large number of parameters, often difficult-to-control [1], [2].

A first aspect stands in the type of equipment used for the tests, with particular reference to the force application system. Another important feature of the experimental apparatus is represented by the geometric configurations of the assistance system:

- jet directed just ahead of the mechanical tool tip;
- jet impinging in the clearance zone of the tool
- jet through a nozzle located near the tool’s tip, right where the scale forming fracture should originate

- jet impacting at the mechanical tool side, as in the case of disc cutters.

A further element of distinction related to the experimental conditions, concerns the velocity of the tool along the cutting trajectory: many experiments carried out in the years 80s have put into evidence that the benefits of waterjet assistance (increase in the rock volume removed, reduction of applied interaction forces, cooling effects etc.) fade away progressively as long as the tool is moved faster along the path, until becoming negligible at a velocity around 2 – 3 m/s. [4].

It is reasonable to assume that the contribution of water jet may become again significant even at higher velocities provided that the power of the jet is increased so that the energy per unit length remains constant.

Based on the results of the research carried out over the last 30 years concerning the assistance provided by water jets to mechanical tools, the following benefits can be claimed (Ropchan et al. 1980, Dubugnon 1981, Ciccu et al. 1999, Ciccu et al. 2004):

- reduced tool-rock interaction forces;
- less thermal stress of the bits (Ciccu et al. 2004);
- slower wear rate and rarer rupture occurrences of the mechanical tools, whose technical life is thus substantially increased;
- a smaller amount of dust generated during the rock disintegration process;
- increased depth and width of the grooves produced by the traversing tool, resulting in a larger removed volume per unit length of the tool's path across the rock face (Ciccu and Grosso, 2009).
- Reduced sparks generation during excavation resulting in safer working conditions especially in coal mining

Parallel to the progress of the experimental research aimed at quantifying the expected benefits offered by water jet assistance, a broad discussion has been developed among the scientific community concerning the mechanisms of water jet assistance and the models able to describe the tool-jet-rock interaction [7], [8].

Among the different research lines, one concerns the development of non conventional high performance picks, the industrial utilisation of which could be rendered economically advantageous through the concept of water jet assistance with the nozzle ahead of the pick [10], [11]; the other relates to the assessment of the excavation performance of waterjet assisted disc cutters.

Both the research lines have been developed with reference to a medium hard rock with the aim of evaluating the increment of the excavation velocity (depth of cut and volume removed per unit length) rather than testing the possibility of extending the mechanical excavation to the very hard and abrasive rocks.

Further experiments have been devoted to the study of some particular aspects of the excavation mechanisms both for transversal and rotating tools. For the firsts the importance of the contemporaneity of the tool and the jet actions has been investigated, for the seconds the results have been critically analysed with reference to the tool - jet position.

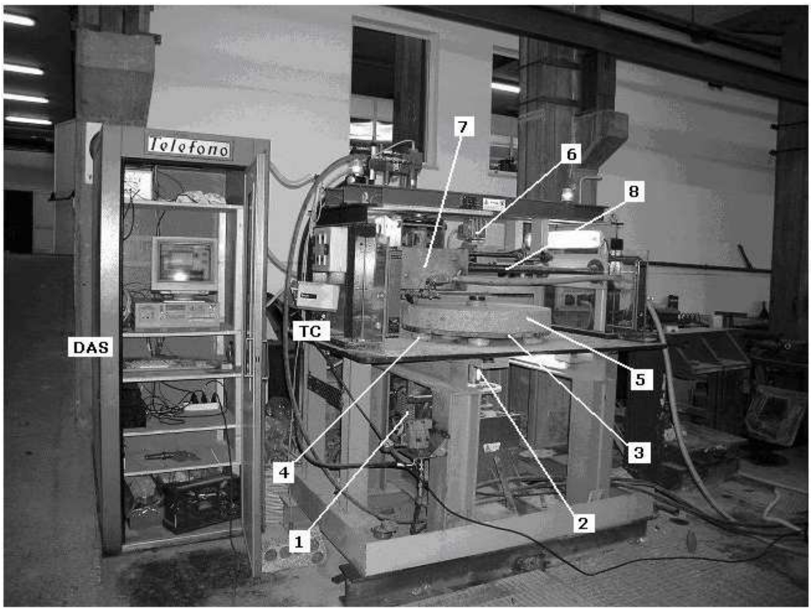
1 GENERAL EQUIPMENT

The experimental apparatus (Figure 1) was designed so as to replicate the typical tool/rock interaction mechanism of tunnel boring machines, where a continuous contact takes place under a steady normal force along circular paths with variable radius.

It substantially consists of a robust steel frame hosting the cylindrical rock sample, about 15 cm thick and 80 cm in diameter, placed onto a circular platform rotating around a vertical axis. The tool is pushed against the upper planar surface of the rotating sample where a circular groove is created.

The rotation power is supplied by an electric motor provided with an adjustable mechanical gearbox, while the vertical load is applied by means of a hydraulic piston actuated by a pump through an accurate control system (oil pressure and flow rate).

During the tests, vertical and drag forces are measured by means of two piezoelectric transducers and their values are stored in the hard disk of a computer through a data acquisition system working at 1000 Hz of frequency.



1. Electric motor with a nominal power of 7.5 kW;
2. vertical shaft rigidly connecting the motor with the sample platform;
3. 80 cm diameter sample platform;
4. spherical bearers supporting the sample platform;
5. cylindrical sample of rock;
6. secondary motor for setting the position of the tool along the platform diameter;
7. cutting head;
8. horizontal rods guiding the cutting head.

DAS: Data Acquisition System

TC: Tempertaure sensitive Camera

Figure 1: Experimental apparatus

The material used for the experiments is a local medium-hard volcanic rock classified as rhyolite or dacite. Its texture is characterised by a fine grained matrix which embeds plagioclase, biotite and amphigene phenocrysts. Its unit weight is 22.7 kN/m^3.

The following Mohr-Coulomb strength parameters have been obtained by interpreting a series of triaxial tests:

- uniaxial compressive strength; 44 MPa;
- tensile strength: 6.7 MPa; cohesion: 11.5 MPa;
- friction angle: 56°..

2 TESTS WITH DRAG BITS

The tool used for the tests is a conical drag bit having a flat tip entirely covered with a 0.8 mm thick layer of polycrystalline diamond (PCD). The very sharp cutting edge has a semicircular profile with a diameter of 12 mm, resulting in a high penetration capability of the tool.

On the other side, since the sharp profile constitutes a mechanical weakness point, the contour of the tool’s rim is progressively modified by the local ruptures caused by incurred impacts and by the high temperatures, resulting in a gradual loss in tool performance.

The upper and the lower picture of the figure 2 represent a new and a worn pick respectively, whereas on the right side of the grooves excavated by the two picks are shown to highlight the decrease of the depth of cut related to the wear process. The importance of keeping the tool at its original geometry is clearly evident.

The assistance provided by the high-velocity water jet appears to be a decisive factor for reducing the number and the intensity of the impacts as well as the temperature of the tool’s tip allowing the utilization of this kind of tool in the excavation of hard and abrasive rocks.

Figure 2. Grooves with new (top) and worn bit (bottom)

The mechanical tool is assisted by a jet of water issued at high velocity placed in front of the pick and fastened to the pick holder sleeve through a supporting arm.

The configuration of the excavation system is schematically represented in Figure 3. The rake and the clearance angles are 20 and 12 degrees, respectively. The water jet is generated at a pressure of 150 MPa through a 0.4 mm nozzle. The flow rate and the hydraulic power of the jet are 2.5 l/min and 6250 W, respectively. The stand-off distance is 40 mm.

The jet is directed so as to impinge on the rock sample with a forward angle of 70° at a point 2 cm away from the tip. This distance has been chosen since it roughly corresponds to the average length of the scales generated during the cutting process without waterjet assistance.

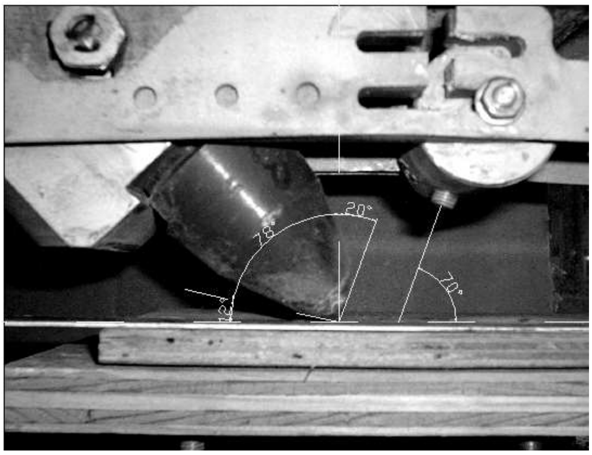


Figure 3: Assistance system geometry

2.1 *Experimental Tests*

Three series of tests have been performed: in the first one the mechanical tool operated without water jet assistance (dry tests); in the second series, the tool was assisted by a jet issued from a nozzle placed ahead of the tip; In the third series the mechanical tool worked along trajectories previously trailed by the jet

Three circular trajectories were explored with radius 150, 250 e 350 mm, respectively and each test was repeated at least three times. At the end, the depth of cut was measured every 15° along the circular trajectory while the excavated volume was evaluated for the entire trajectory by filling the groove with a fine granular material of known apparent density and then weighting it.

2.2 Results

The improvement of the cutting performance has been analysed by comparing the depth of groove and the removed volume per unit length of travel achieved in case of water jet assistance (second series of tests) with those obtained in the "dry excavation" (first series of tests).

The experimental plan included 9 valid dry tests (2 along inner trajectories, 3 along intermediate trajectories and 4 along outer trajectories) and 8 valid waterjet assisted tests (2 along inner trajectories, 4 along intermediate trajectories and 2 along outer trajectories).

As an example of the results achieved, the values of the depth of groove measured every 15° along the circular path, are reported in figure 4 (dry tests and waterjet assisted tests) for the outer trajectories, giving a total of 24 points.

Although the depth of cut appears considerably variable along the trajectories in both the two series of tests, it can be observed that it falls within the range 0.5 – 3.5 mm for the dry tests, and within 2 - 4.5 mm for the waterjet assisted tests.

Similar conclusions can be drawn analysing the graphs regarding the intermediate and the inner trajectories: a shift towards higher limits of the variability range is always observed in case of waterjet assistance.

To carry out a quantitative analysis of the experimental data, they have been grouped according to the radius of the trajectory. The mean value of depth of groove has been then calculated over the entire population of data for the inner, intermediate and outer trajectories separately for the cases of dry and water jet assisted tests (Table 1.)

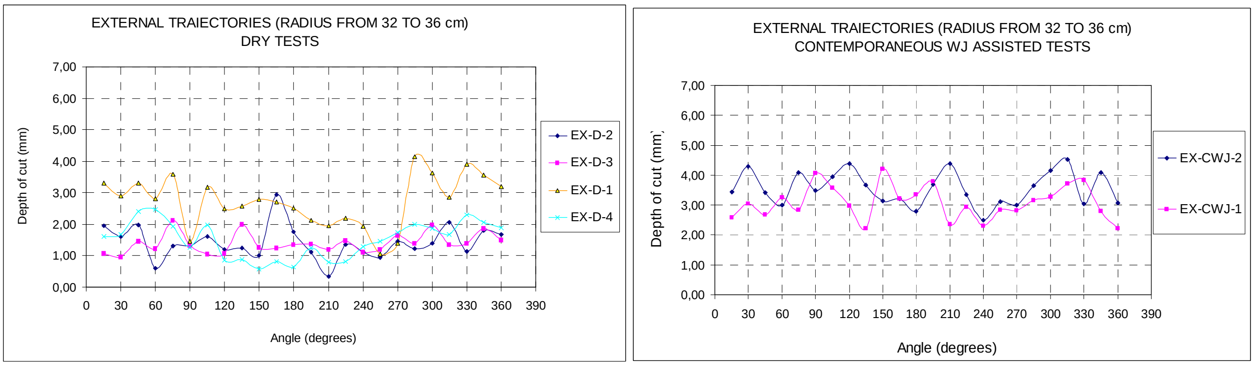


Figure 4. Depth of groove along the trajectories (measurement points every 15° at the centre of the sample)

Table 1. Mean values of the depth of cut

Experimental conditions		**Average depth of cut [mm]**	**Increment [%]**
Outer trajectories	Dry Tests	1.8	
	S-WJ Tests	3.3	88
Intermediate trajectories	Dry Tests	2.0	
	S-WJ Tests	3.6	80
Inner trajectories	Dry Tests	2.4	
	S-WJ Tests	4.6	97

The results shown in Table 1 clearly highlight that the water jet assistance produces a substantial increase (always higher than 80%) in the mean value of the depth of groove even for the less favoured trajectories (the outer ones along which the jet moves faster).

To complete the analysis of the tests results, the excavated volume per unit length of groove (average area of the groove's cross section) has been calculated over the entire length of the trajectories of similar radius and it is given in Table 2 (ratio of the overall volume removed to the total length of the trajectories of similar radius).

Table 2. Average volume per unit length obtained at different trajectories

Experimental conditions		**Average volume per unit length [cm^3/cm]**	**Increment [%]**
Outer trajectories	Dry Tests	0.11	
	S-WJ Tests	0.28	162
Intermediate trajectories	Dry Tests	0.12	
	S-WJ Tests	0.38	210
Inner trajectories	Dry Tests	0.33	
	S-WJ Tests	0.65	95

These data confirm what was already observed concerning the depth of groove: the benefit of water jet assistance is substantiated by a relevant increase of the specific volume of removed rock by 95% - 210%, according to the radius of the circular groove, the higher values holding for the intermediate trajectories.

This outcome can be explained taking into consideration that the volume removed in the dry tests increases considerably as the radius of the trajectory decreases, as mentioned before, and thus the relative contribution of water jet appears, in this case, less evident.

Normal and cutting forces were recorded during the tests, with a sampling rate of 1000 Hz. Their typical behavior is illustrated in figure 5. Some meaningful indexes have been used to synthesize the recorded data:

CF/NF:	ratio between mean value of the cutting force and mean value of the normal force;
SD_{CF}/M_{CF}:	ratio of cutting force standard deviation to mean value;
$N_{1.5}$:	number of values higher than 1.5 $M_{CF:}$ it quantifies the occurrence of force peaks the tool undergoes during the trajectory causing fatigue stressing.

The analysis of the above parameters, reported in Table 3, highlights that:

1. the mean values of the cutting force, measured in the wj assisted tests, are higher than those obtained in the dry tests regardless of the trajectories.
2. the ratio between standard deviation and mean value of the cutting force (SD_{CF}/M_{CF}) is higher in water jet assisted than in dry tests.
3. the number of force peaks, synthesized by parameter $N_{1,5}$, increases in case of water jet assistance.

Table 3: Interaction forces analysis

		CF/NF	**SD/M**	**N1.5**
Outer trajectories	Dry Tests	0.24	0.37	32.33
	S-WJ Tests	0.33	0.36	30.33
Intermediate trajectories	Dry Tests	0.38	0.38	17.33
	S-WJ Tests	0.55	0.57	34.00
Inner trajectories	Dry Tests	0.38	0.41	30.00
	S-WJ Tests	0.77	0.74	39.00

The increment of the cutting force is in accordance with the results obtained for the depth of cut and the excavation rate. In fact, for the same value of the normal force, water jet assistance determines a deeper penetration of the tool and thence a larger cross section of the groove which is associated an increase in the cutting force. The increment of the depth of cut is also the cause of the higher oscillation amplitude of the cutting force and the greater number of force peaks.

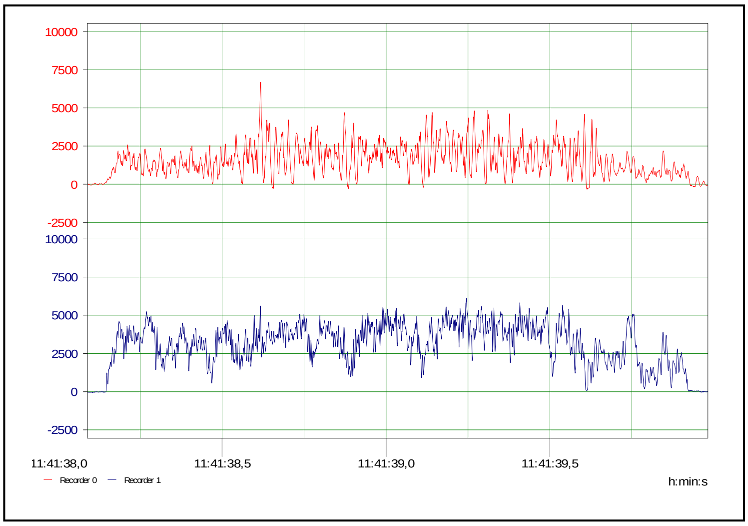


Figure 5. Typical trend of normal (lower graph) and cutting (higher graph) forces.

Concerning the energy spent to disintegrate the unit volume of rock, the results shown in Table 4 point out that waterjet assistance reduces considerably the mechanical energy involved in the tool-rock interaction with the consequence that fewer tools are expected to be replaced per unit volume of rock, in spite of a slightly higher fatigue stress.

Table 4. Specific mechanical energy (J/cm3) consumed with and without waterjet assistance

	Outer Trajectories	**Intermed. Trajectories**	**Inner Trajectories**
Dry Tests	65,45	95,00	34,55
S-WJ Tests	35,36	43,42	35,54
NC-WJ Tests	55,71	45,45	37,14

2.3 Analysis of water jet assistance mechanism

The research has been completed with a third series of 14 tests (5 along inner trajectories, 6 along intermediate trajectories and 3 along outer trajectories) carried out in two separated and non contemporaneous phases: in the first one, a circular path was completely described by the jet; in the second, the mechanical tool was forced to follow the same path.

Here, due to the non contemporaneity of the two actions, no interaction takes place between the stress induced by the mechanical tool and that applied by the water jet on the rock surface. On the other hand the reduction of the rock strength is obviously the same as that induced in the contemporaneous tests where the jet acts ahead of the tool.

In Table 5, the mean value of the depth of cut is compared with the corresponding figures calculated in the previous two series of tests, for the inner, intermediate and outer trajectories.

The data clarify that, for all the trajectories, the increment of the depth of cut obtained in non-contemporaneous tests is substantially equal to that achieved in case of contemporaneous water jet assistance. The same can be said with regard to the excavated volume per unit length (Table 6).

Table 5. Mean values of the depth of cut

Experimental conditions		**Average depth of cut [mm]**	**Increment [%]**
Outer trajectories	Dry Tests	1.8	
	S-WJ Tests	3.3	88
	NC-WJ Tests	**3.1**	77
Intermediate trajectories	Dry Tests	2.0	
	S-WJ Tests	3.6	80
	NC-WJ Tests	**3.7**	82
Inner trajectories	Dry Tests	2.4	
	S-WJ Tests	4.6	97
	NC-WJ Tests	**4.8**	103

Table 6. Average volume per unit length obtained at different trajectories

Experimental conditions		**Average volume per unit length [cm^3/cm]**	**Increment [%]**
Outer trajectories	Dry Tests	0.11	
	S-WJ Tests	0.28	162
	NC-WJ Tests	0.28	162
Intermediate trajectories	Dry Tests	0.12	
	S-WJ Tests	0.38	210
	NC-WJ Tests	0.33	167
Inner trajectories	Dry Tests	0.33	
	S-WJ Tests	0.65	95
	NC-WJ Tests	0.63	90

The correspondence between the results obtained operating with non contemporaneous and contemporaneous water jet application, suggests that the improvement in tool performance with respect to “dry” tests, has to be attributed mainly to the reduction of the rock strength operated by water jet; the stress effect, if actually takes place, should be considered negligible.

3 TESTS WITH ROLLING TOOLS

3.1 Apparatus

The experimental apparatus is sketched in Fig. 6. In this case the disc cutting is pushed against the rock by means of a hydraulic cylinder and the nozzle issuing a waterjet located at one side of the disc as shown in Fig. 7.

The disc cutter has a diameter of 100 mm and a cutting angle of 40°. The axis of the nozzle, 0.4 mm in diameter, has an inclination of 70°. The vertical distance the nozzle from the rock is 25 mm.

During the tests both the disc and the nozzle are in a fixed position (except for the vertical displacements), while the rock sample is rotated around the shaft of the supporting platform. Consequently, the tool’s travel on the rock sample’s upper surface is a uniform circular motion with trajectories variable from 500 to 700 mm in diameter according to setting.

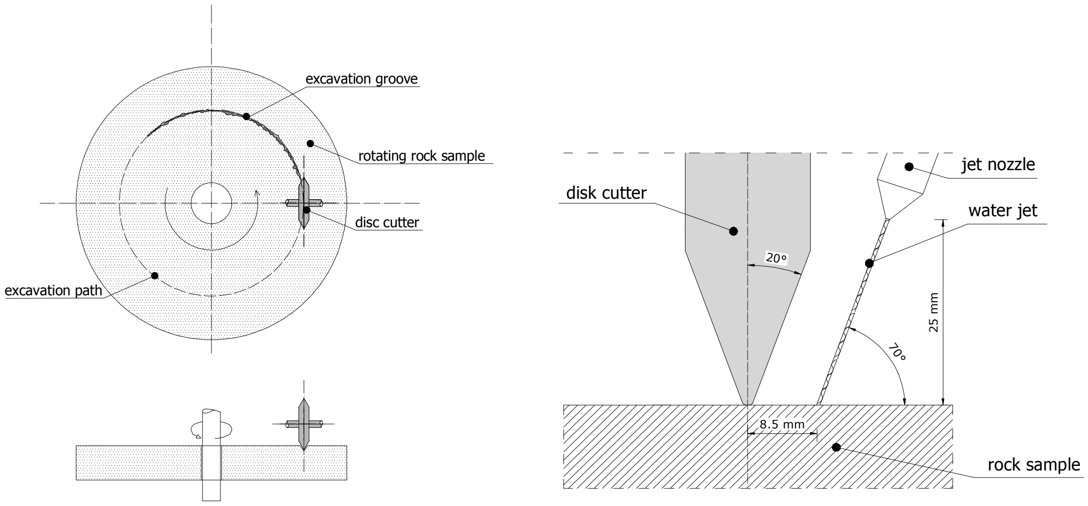


Fig. 6: Experimental apparatus at the DICAAR Waterjet Laboratories

The adopted experimental conditions are given here below:
- Normal load applied to the tool: 10 kN;
- Nozzle diameter: 0,4 mm;
- Jet-forming pressure: 150 MPa;
- Jet inclination from the vertical line: 20°;
- Stand-off distance of the nozzle along the jet: 30 mm.
- Distance of the jet impingement point from the disk tip: 8,5 mm;
- Peripheral velocity: 1 – 2 m/s

Fig. 7: . Detail of the cutting head with three possible nozzle locations as seen from below

3.2 Experimental Plan

The experimental plan comprises 12 excavation tests: 8 performed by the sole mechanical tool and 4 by the waterjet assisted tool. The radius of the dry tests trajectories was in the range 260 – 340 mm while that of the wate jet assisted tests was 290 mm.

3.3 Results

Experimental results have been evaluated with reference to the depth of cut and the volume of rock removed per unit length of groove [cm^3/m].

3.3.1 Depth of grove

The depth of the grooves has been measured along the path at sampling points every 30° angular steps (12 points for each path). The measured values for the two series of tests (with and without waterjet assistance) are reported in Fig. 8. The experimental points are connected with a curved lines for better evidence.

Both diagrams put into light a significant variability of the groove depth that can be attributed to the heterogeneity of the rock and in particular to the presence of fenocrysts. In spite of this, it clearly appears that the grooves obtained in the tests with waterjet assistance are significantly deeper that those obtained in “dry” tests.

For the sake of a comprehensive evaluation of the effect of waterjet assistance the data of groove depth have been grouped together independent of the respective trajectories into the two broader classes of “dry” and “wet” tests, the first including 96 measurement points and the second one 48.

The calculated mean values and the corresponding dispersion parameter of the distribution of groove depth for each class of tests are reported in the following 7.

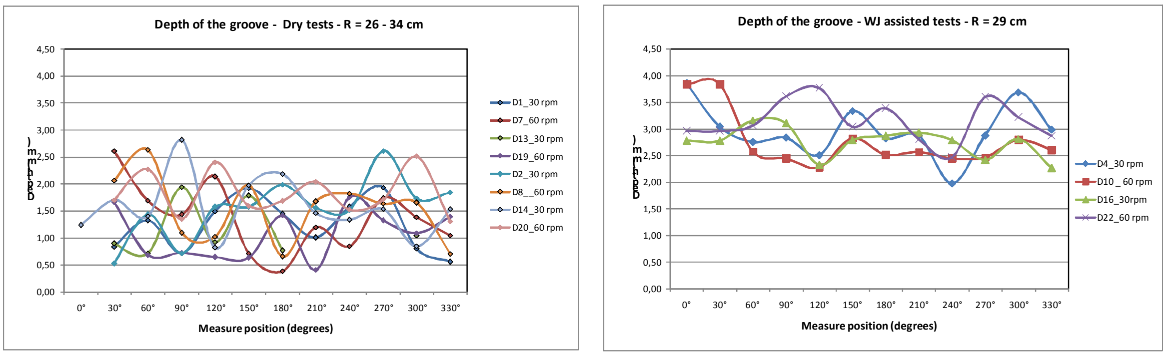


Fig. 8: Depth of the grooves

Table 7. Statistical reference parameters for the depth of groove in “dry” and “wet” tests

	Depth of grooves		
	Mean values (mm)	Standard deviation (mm)	Ratio st. dev./mean value
Dry tests	1.42	0.56	0.40
Waterjet-assisted tests	2.90	0.45	0.16

The comparison of the mean values puts into evidence the significant contribution of waterjet assistance to the excavation results. Concerning the dispersion parameter, a lower value of the standard deviation is observed for waterjet-assisted tests, albeit with poor significance. However if the ratio of the standard deviation to the mean value is considered, the difference becomes much clearer, witnessing that considerably deeper and more regular grooves are obtained with waterjet assistance.

3.3.2 Volume removed per unit length

The removed volume of complete circular grooves have been measured by filling them with a strictly classified sand and the average volume per unit length Vu [cm^3/m] calculated as the ratio of the volume to the groove’s length (cm^3/cm).

The set of data so obtained, consisting of 8 elements for dry tests and 4 elements for wet tests with waterjet assistance, are represented in Fig. 9.

It turned out that the parameter Vu varies from 3.75 to 6.75 cm^3/m (mean value is 4.84 cm^3/m) in case of dry tests and from 13.26 to 22.51 cm^3/m (mean value is 16.61 cm^3/m) for the wet tests. Therefore the unit volume removed per unit length is increased by a factor of 3.8 by waterjet assistance.

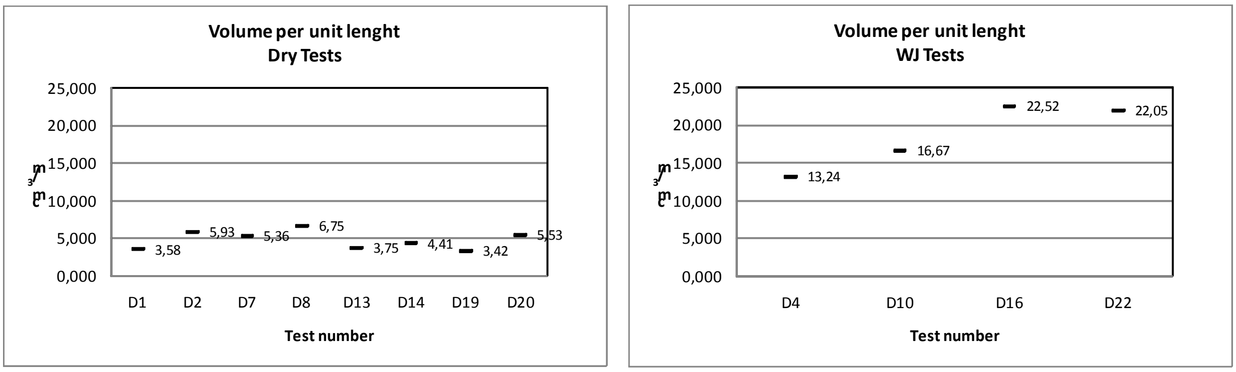


Fig. 9: Volume removed per unit length

The specific mechanical energy (J/cm^3) involved in the excavation has been calculated by combining the data of peripheral velocity of the disc cutter, the measured drag force and the removed volume. The average value for the dry tests resulted to be 21.5 J/cm^3, compared to a much lower value of 8.8 J/cm^3 for waterjet-assisted tests.

This outcome can be attributed to two factors: the first is the considerable increase of the removed volume from 4.84 cm^3/m to 16.6 cm^3/m; the second is a substantial reduction of the drag force whose mean value decreased from 161 kN to 95 kN.

However, an additional energy of more than 300 J/cm^3 is consumed for the generation of the high-velocity waterjet, raising the total to about 313 J/cm^3.

4 ANALYSIS OF THE EXCAVATION MECHANISM

4.1 Geometric characteristics of the grooves

The visual inspection of the samples put into evidence the presence of markedly different features between the grooves made with or without waterjet assistance (Fig. 10). For a quantification of such differences, in addition to depth, also the lateral extent of the groove was measured on either side of the ideal disk trajectory, again every 30° of angular step. The length of the two segments (internal and external span) were summed up for obtaining the groove's width, while their difference (either positive or negative) represented the degree of asymmetry of the groove.

The groove's width is bound to the corresponding depth by the mechanism governing the formation of the scales during the excavation process but also to the mechanical characteristics of the rock, natural or modified, at either side of the tool.

The measured values are reported in the diagrams of

Fig. 1 for the cases of dry or wet tests.

It was found that, similarly to what happened for the groove's depth that doubles with the application of a waterjet, also the groove's width considerably increases from an average value of 8 mm up to 13 mm.

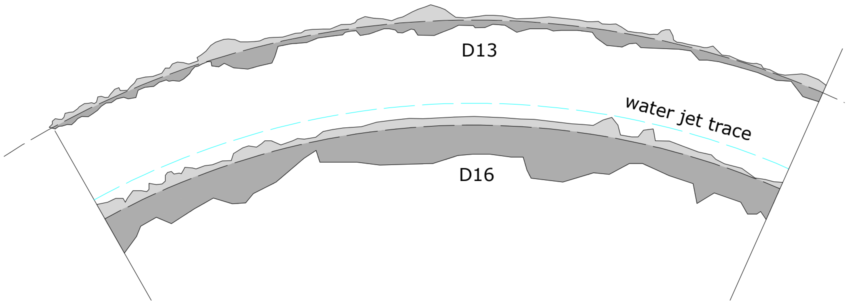


Fig. 10: Typical geometry of the grooves excavated with (D16) and without (D13) waterjet assistance

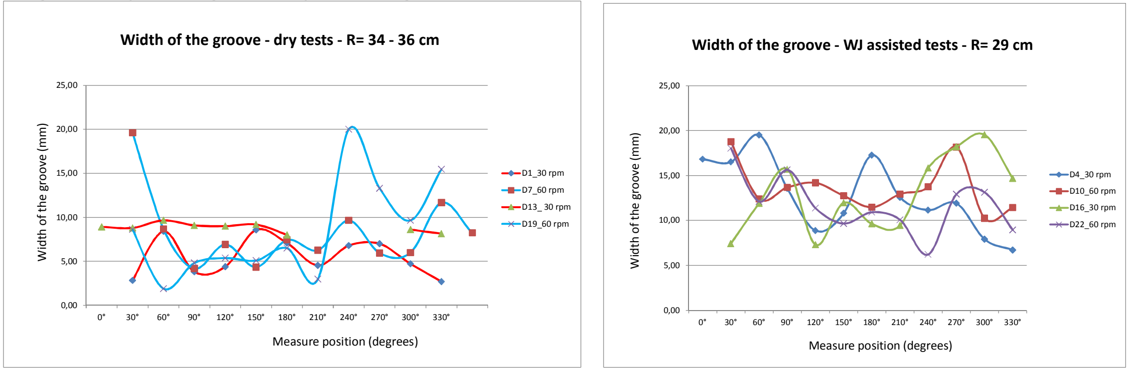


Fig. 1: Width of the groove

Concerning the regularity of the groove, it can be said that the average size of the scales produced by conventional tools at both sides is almost the same so that the resulting grooves are rather regular as shown in

Fig. 2, where the inwards and outwards extent of a typical groove from the trajectory of the tool's tip is reported with a positive or negative sign, respectively. In this case the symmetry is witnessed by the balanced scattering of the points representing the average value of the groove's extent at either side, equal to 4.2 mm.

Quite different outcome is observed in the case of waterjet assistance. In fact, the groove's geometry is markedly asymmetric since the inner extent of the circular groove is considerably larger than the outer span, at the same side of the waterjet kerf. (Fig. 10). Moreover, the outer boundary of the groove appears less erratic and more regular than the inner one.

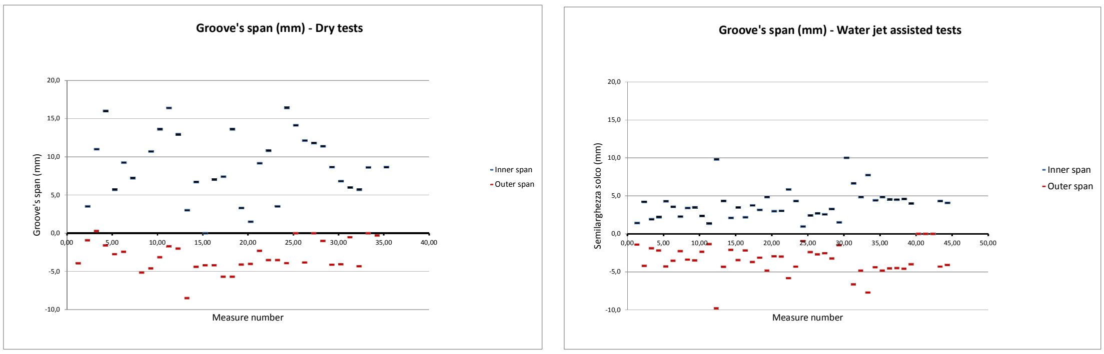


Fig. 2: Groove's span at the inner and outer trajectory side

The distribution of the groove's span at either side (the outer taken with positive sign and vice-versa) shown in the diagram of

Fig. 2, confirms the observation of the visual analysis: the average value of the inner span of the grooves approaches 9 mm whereas that of the outer span is about 4 mm and generally terminates before the waterjet kerf.

The standard deviation is 4.3 mm for the inner span and 2 mm for the outer one, confirming the narrower dispersion of the distribution.

This experimental outcome is contrary to what expected, since the presence of the waterjet kerf representing a free surface should have favoured the formation of the scales, in compliance with the already discussed excavation model.

For better understanding, the typical cross section of the grooves obtained with or without waterjet assistance is depicted in Fig. 3, showing also the average values of depth and width of removed volume. In the case of waterjet assistance, the groove appears deeper, wider and asymmetric due to the fact that larger scales are produced at the inner side, while much smaller particles are formed at the waterjet side.

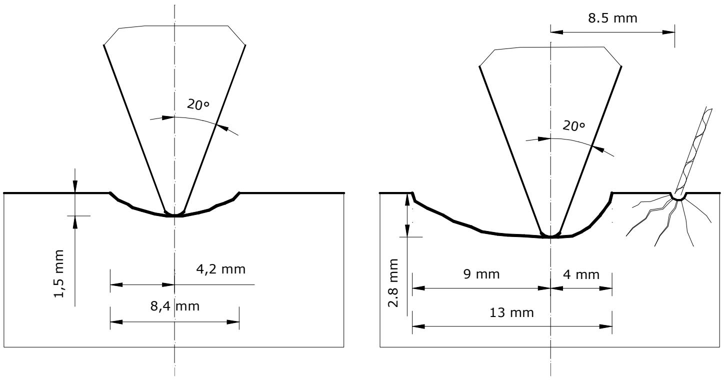


Fig. 3: Typical geometry of the groove for dry (left) and WJ assisted (right) excavation

The scales produced by the mechanical tool alone are characterised by a detachment angle Ψ equal to 18°, whereas those obtained in the case of waterjet assistance show different features according to the side of the groove considered: at the waterjet side (outer band) the scales are formed with Ψ = 35°; at opposite side with Ψ = 24°.

4.2 Interpretation of the experimental results

The main geometric features of the grooves obtained with the experimental tests have been summarized in the following Fig. 4:

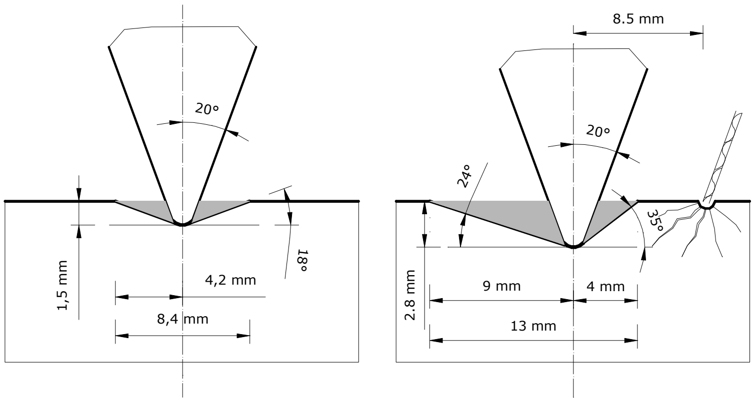


Fig. 4: Schematic geometry of the scales detached in the dry (left) and WJ assisted (right) tests

Groove made with the disc cutter alone:

- Average depth: 1.4 mm
- Span at each side: 4.2 mm
- Angle of scale formation Ψ: 18°

Groove made with waterjet assistance:

- Average depth: 2.8 mm
- Groove's span: 4.0 mm at the waterjet side; 9.0 mm at the inner side
- Angle of scale formation Ψ: 35° at the waterjet side; 24° at the inner side
- Tool's angle: θ=20°

Using the 2D modified model developed by Miller and Sikarskie, the angle ϕ representing the shear strength of the rock, can be obtained once the angle of scale formation ψ has been experimentally determined.

For the groove created by the mechanical tool alone:

ψ=18° $\theta+\phi$=55° ϕ=35° at both sides

For the groove created by the waterjet assistance:

ψ=24° $\theta+\phi$=41° ϕ=21° at the “dry”side

ψ=35° $\theta+\phi$=20° ϕ=0° at the waterjet kerf side

The above analysis clearly discloses that a significant reduction in the shear strength of the rock (ϕ) occurs mainly at the waterjet side of the tool producing an increment of the scale formation angle ψ and a corresponding reduction of the potential groove width. The difference between the values of the span at the inner and at the outer part of the groove is caused by the greater reduction of the rock internal friction near the waterjet impingement points (outer side). The reduction of the groove width has a detrimental effect on the volume excavated per unit length.

On the other hand, the rock weakening extends to the zone of the disk wedge action, resulting in the increase of the groove depth *p* whose magnitude compensates the highlighted detrimental effect and finally results in the overall increase of the volume excavated per unit length of path.

5 CONCLUSIONS

The research concerning the assistance of drag tools by high velocity water jet, was addressed both at quantifying the improvement of the excavation performance and at clarifying the mechanism of tool assistance.

The main outcomes can be summarised as follows:

- The values of the depth of cut recorded along the trajectories trailed by the water jet assisted tool are always higher than those obtained in case of simple mechanical excavation; the average increment has been found in the range 80% - 100%, according to the radius of the circular path.
- The increment of the volume excavated per unit length of groove obtained with the introduction of the water jet assistance has proved to fall between 90% and 200%.
- The analysis of the forces involved revealed an increase of the average value of the cutting force and a corresponding increase of its oscillation in case of water jet assisted tests.
- A negligible difference is being outlined between the results obtained in the tests in which water jet and mechanical tool actions were contemporaneous (synergetic) and those in which the two actions were non contemporaneous (non synergetic). This experimental outcome indicates that the improvement of tool performance induced by water jet assistance is mainly due to the rock weakening rather than to stresses combination.

In synthesis, then, under the specific experimental conditions, the results obtained suggest that water jet assistance is effective in improving the performance of the mechanical tools and this effect is mainly due to the reduction of the rock strength operated by the jet impacting the rock ahead the tool. Furthermore, in the specific experimental condition, the reduction of the force peaks is not achievable through the action of water jet and consequently the increase of PCD tool technical life is not realistically to be expected when water jet assistance is applied to this kind of tools although the effect cannot be quantified.

The reason of this fact is related to the increment of the depth of cut which enhances a discontinuous cutting mechanism characterised by the formation of bigger chips.

However when the average number of tools to be replaced per unit volume of rock is considered instead of the mere time duration the advantage of using water jet assistance can be considerable.

Concerning the tests with the disc cutter, the comparative analysis of the results with or without waterjet assistance evidences an increase both in the groove depth and in the volume removed per unit length respectively by a factor of 2 and 3.8. These data leave no doubts about the contribution of the waterjet to the excavation process effectiveness.

The reliability of these results is corroborated by the fact that, in all the tests, the tool-rock relative velocity was kept between 1 and 2 m/s, i.e. comparable to that typical of the rolling tools in conventional fullfacers. This aspect deserves particular mention since most tests described in the literature have been carried out at much lower velocities (0.1 – 0.5 m/s), beyond which the benefit of waterjet assistance gradually decreases until fading away near 1 m/s (the damage induced by waterjet is strongly time-dependent).

The energy consumed for the generation of the jet is by far higher than that necessary for the functioning of the mechanical tool to the extent that the total energy involved is increased by a factor of 10 confirming that energy consumption is the main obstacle to the diffusion of the waterjet assistance technology. However it must be considered that the excavation rate and thence the completion time is, in most practical cases, a priority often justifying an increase in energy cost.

As a result of the study of groove's features it turns out that the volume removed by the waterjet assisted tool is deeper, wider and with steeper sidewalls compared to the one obtained in the dry tests. Moreover, the geometry is characterized by a marked asymmetry with respect to the disc's plane and in particular by a shorter span and an almost even border at the waterjet side.

The interpretation of the excavation mechanism according to the model developed by Miller and Sikarskie suggests that the steeper inclination of the groove's walls is the consequence of a reduction of the shear strength of the rock resulting from the action of the jet, especially in the surroundings of the impact points. Such a negative effect implies a narrower groove thus impairing the achievement of a larger excavation volume after each revolution of the tool.

On the other side deeper grooves are made in the weakened rock resulting in a positive effect on the specific volume removed, up to 3,8 times higher, as explained earlier.

Finally it is worth mentioning that, at least on rocks of medium strength, the nozzle configuration in lateral position, at one or both sides of the tool, is not fully beneficial since it determines the formation of smaller scales at the waterjet side. Maybe even better results can be achieved by placing the jet right in front of the tool in order to make a rock weakening kerf with the advantage of increasing the groove's depth without limiting the size of the scales.

Furthermore, the results of the experiments confirm that the waterjet assistance has a positive effect on tools performance even at peripheral velocities typical of industrial operations.

REFERENCES

1. Hood M. Knight G.C., Thimons E.D. A review of jet assisted rock cutting transaction of ASME vol 14, may 1992.
2. Handewith, H. J., Evans, R. J., Thimons, E. D. An Overview of Water Jet Assisted Rock Cutting at the Pittsburgh Research Centre. Proceedings of the 3rd U.S. Water Jet Conference, Pittsburgh, PA, 1985
3. Ozdemir, L., and Evans, R.J., 1983, Development of a water jet assisted drag bit cutting head for coal measure rock, Proceeding Rapid excavation and tunnelling Conference, Chicago, IL, June 12-16, Vol. 2 , pp 701-718;
4. Bortolussi A., R. Ciccu, B. Grosso, G. Ortu, J. Vasek: Water jet assisted rock breakage with cutting tools. Proceedings of the IV International Symposium on Mine Mechanization and Automation, (H. Gurgenci, M. Hood Ed.) Cooperative Research Centre for Mining Technology and Equipment Publ., Brisbane, Australia, July 6-9 1997, pp. A4-21- A4-27
5. Ropchan, D., Wang, F. D., and Wolgamott J., 1980, "Application of water jet drag bit and pick cutter for the cutting of coal measure rocks" Final Technical Report to the U.S. Dept. of Energy, Contract N0 ET – 77-a-01-9082, April.

6. Dubugnon, O., 1981, “ An experimental study of water assisted drag bit cutting of rocks,” Proceedings of the 1st U.S. Water jet Symposium, Golden, CO, April, II-41-II-4.11.
7. Hood M. Water jet assisted rock cutting – the present state of the art, Proceedings: Bureau of Mines Open Industry, Meeting, Pittsburg, PA, June 21, 1984
8. Vasek J. Theoretical evaluation of pick tips assisted by high pressare water jet - 11 th Int. conf. on Jet cutting technology – 8 – 10 sept. 1992 St. Andrews, Scotland.
9. Fowell R.J., Gillani S.T., Waggott A. – Water jet assisted rock cutting – the importance of jet position- 11 th Int. conf. on Jet cutting technology – 8 – 10 sept. 1992 St. Andrews, Scotland
10. Ciccu R., B. Grosso, G. Ortu, M. Agus, A. Bortolussi, J. Vasek, P. Jekl: Rock disintegration using waterjet-assisted diamond tools; Proc. 10th American Waterjet Conference, (M. Ashish Ed.) Waterjet Technology Association Pub., Houston, August 14-17, 1999 pp. 465-477
11. R. Ciccu, B. Grosso, C. Loddo, A. Bortolussi, J. Vašek: Waterjet Assisted Drag Tools for Rock Excavation,Proc. of 17th International Conference on Water Jetting “Advances and Future” Mainz, Germany, 7-9 September 2004, Edited by Colin Gee, Published by BHR Group Limited, The Fluid Engineering Centre, Cranfield, UK (C) BHR Group, pp 271-284 ISBN: 1 85598 042 8
12. Ciccu R., Grosso B., Loddo C., Vasek J., Bortolussi A.: Mechanical excavation of hard rocks. Proceeding of the Mine Planning and Equipment Selection 2004. (pp. 189-195). ISBN 04-1535-937-6
13. Evans, R. J., Handewith, H. J., Thimons, E. D. Analysis of mechanical tool force reduction when using water jet assisted cutting. Proceedings: Bureau of Mines Open Industry, Meeting, Pittsburg, PA, June 21, 1984
14. Hood M., G. Knight C., Thimons E.D., A review of jet assisted rock cutting, Washington, D. C. (2401 E St., N. W., Washington 20241): U.S. Department of the Interior, Bureau of Mines, 1990
15. Dubugnon, O., 1981,: An experimental study of water assisted drag bit cutting of rocks,” Proceedings of the 1st U.S. Water jet Symposium, Golden, CO, April, II-41-II-4.11.
16. Fenn O., Protheroe B. E. and Joughin N.C.: Enhancement of roller cutting by means of water jet. In Proc. 7th Rapid Excavation and Tunneling Conf.., New York (Edited by C.D. Mann and M.N. Kelly), Vol. 1 pp.341-356 Soc. Min. Eng. AIME, New York (1985)
17. Hood M., H.Alehossein: A development in rock cutting technology”. International Journal of Rock Mechanics and Mining Sciences. Vol. 37, pp.297-305, 2000.
18. Knickmeyer Wilhelm and Baumann Lothar: Activated roller cutters as a means of rock breakage – initial test results and future applications - SME Rapid Excavation And Tunneling Conference Proceedings – 1981 - Chapter 83 - New Developments in Underground Methods
19. Miller M. H., D. L. Sikarskie: On the Penetration of Rock by Three-Dimensional Indenters”, International Journal of Rock Mechanics and Mining Sciences. Vol. 5, pp. 375-398, 1968.
20. Roxborough F., H.R. Phillips: “Rock Excavation by Disc Cutter”, International Journal of Rock Mechanics. Vol. 12. pp. 361- 366. 1975)
21. Snowden R. A., Ryley M. D. and Temporal J.: A study of disk cutting in selected British rocks. Int. J Rock Mechanics and Mining Science & Geomechanic Abstracts. Vol 19, PP. 107 – 1211, 1982