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Improvement of the Excavation Performance of PCD Drag Tools by Water Jet Assistance

Raimondo Ciccu · Battista Grosso

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Abstract The possibility of increasing the performance of mechanical tools with the assistance provided by a high-velocity water jet has been explored in the last 20 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. Number of hypotheses have been advanced to explain the variability of the results as well as to disclose the mechanism of water jet assistance. 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 is improved and at quantifying the increment of the excavation performance parameters with water jet. In particular, the mechanisms involved in the rock–tool–water jet interaction have been studied with the goal of putting into evidence the contribution of the jet both as a way to weaken the rock and to increase the stress leading to scale formation. Better knowledge achieved will be useful for the development of the technology up to a commercial scale.

Keywords Drag tool · Water jet assistance · Rock excavation · Bit wear

1 Introduction

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

- Improving the performance of mechanical drag 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 strategy followed in the past was mainly focussed on the development of new materials for the production of stronger tools able to apply greater actions to the rock and so to achieve the above mentioned objectives.

At present, a new concept is under development consisting in the mechanical tools assistance. It includes all suitable methods and techniques aimed at:

- reducing the rock–tool interaction forces;
- decreasing the number and the intensity of the impacts suffered by the tool;
- decreasing the working temperature of the tool tip;

The implementation of a proper system for assisting the cutting tools gives a greater flexibility to the operation of the excavation machines, enabling them to win rock masses characterised by a variable strength, while increasing the technical and economic results. Some additional advantages can be pursued in particular situations such as the reduction of spark generation in coal mines (or in gaseous environments).

One of the most promising assistance methods is the "water jet assisted excavation" that consists in integrating the mechanical tool action, that remains the prevalent one, with that of a high-velocity water jet.

Since the 1970s the studies aimed at the development of a commercially feasible "water jet assisted" concept have

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R. Ciccu (✉) · B. Grosso
Department of Geo-engineering and Environmental Technologies of the University of Cagliari, Cagliari, Italy
e-mail: ciccu@unica.it

been first 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 various authors appear often controversial due to the great variability of the experimental conditions involving a large number of parameters, often difficult-to-control (Hood et al. 1992; Handewith et al. 1985). A first aspect stands in the type of equipment used for the tests, with particular reference to the force application system. Basically, two different types of apparatus have been used:

- in the first type of machine, the penetration of the tool into the rock sample is set up as operative parameter for each test: the depth of the resulting groove and the excavated volume per unit length are pre-defined and the benefit of the water jet assistance can be evaluated only in terms of interaction forces reduction;
- in the second type of testing machine, the tool is pushed against the rock sample under a constant normal force. In this case, the advantage of water jet assistance can be measured by the increase of both the tool penetration and the volume of rock removed per unit length of groove.

Another important feature of the experimental apparatus is represented by the geometric configurations of the assistance system. In this regard, three basic solutions have been studied:

- jet directed to hit the rock just ahead of the mechanical tool tip;
- nozzle behind the tool allowing the jet to impinge on the clearance zone of the tool;
- jet through a nozzle located near the tool's tip right where the scale forming fracture should originate.

Typically, it has been observed that, for chisel-type tools, a better efficiency is achieved when the jet impact point is 1–2 mm ahead of the tip, whereas for point-attack tools the most advantageous position seems to be behind the pick.

In case of jet ahead of the pick, Ozdemir and Evans 1983 put into evidence the importance of the distance between the tool's tip and the jet impingement point: the best results of a series of tests carried out at distances of 3, 6 and 12 mm have been achieved when the jet was closest to the tool. It has been observed by Hood (Hood et al. 1992) that the improvement would have been even higher for distances lower than 3 mm. In this position, according to the author, the jet is capable of removing more efficiently the volume of plasticized material near the tip, thus allowing higher penetration and thence a leading to better performance. It should be borne in mind that the plasticization pressure is a limiting value for the drag force leading to the scale formation mechanism.

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 1980s 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 (Bortolussi et al. (1997). In this regard, it has been observed (Hood) that, in most tests, while the tool velocity was changed, the hydraulic energy of the water jet was kept constant. In these conditions, as the traverse velocity of the cutting tool increases together with that of the nozzle tightly fastened to it, the energy of the impacting jet per unit length of groove (J/m) linearly decreases, thus making the water jet assistance less and less important.

It is reasonable to presume 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.

Albeit a coherent synthesis aimed at drawing reliable conclusions appears quite difficult on the basis of the experimental data from the various sources, the following interesting results are widely accepted by the scientific community:

- In both configurations with the nozzle placed in front of or behind the tool, the assistance provided by water jet results in a reduction of interaction forces by at least 30% at low traverse velocities (0.25 m/s) working at constant penetration depth. However, this help decreases and eventually disappears for velocities higher than 2 m/s. Actually a reduction in the average values of interaction forces variable from 65 to 80% has been measured by Ropchan and Wang 1980 and Dubugnon 1981, while experiments made by British Coal gave a reduction of 30 and 50% for penetration and cutting forces, respectively.
- Both the amplitude and the frequency of the force oscillations are reduced by water jet assistance.
- The mechanical energy required for the removal of a unit volume of rock is smaller in case of water jet assistance. However, the total energy consumed as the sum of mechanical and hydraulic energy is considerably higher than that consumed by the mechanical tool alone.
- The temperature of the tool tip and the wear rate are considerably reduced by the action of the jet.

- Sparks generation during excavation is better controlled in case of water jet assistance 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 (Hood 1984; Vasek 1992).

According to the assumption agreed upon by most experts, the improvement in excavation performance should be accredited to the flushing of the intensively crushed material operated by the water jet. The elimination of this plasticized zone located around the tool tip would allow the increase of the stress applicable to the rock. As a consequence, a deeper penetration, as well as an increased amount of large scales in the size distribution of rock disintegration cuttings would be achieved, especially in the case of tools with a negative attack angle. Through this model, the better efficiency obtained when reducing the distance between the tool tip and the jet (less than 3 mm), is well interpreted.

An important consequence of this mechanism is that the energy needed for water jet assistance would be relatively low: it would be senseless to work with jet generation pressure above, e.g. 30 MPa (Fowell et al. 1992).

In addition to this, other mechanisms have been proposed in the attempt to explain the advantage of high-pressure water jet assistance with the jet directed in front of the tool (Fig. 1). According to these hypotheses, the improvement of the tool performance can be attributed to:

- The damage induced by the impacting jet on the rock target and the consequent reduction of the resistance opposed by the rock against the tool penetration.
- The increase of the stress in the rock material just ahead of the tip due to the pressure exerted by the impacting jet.

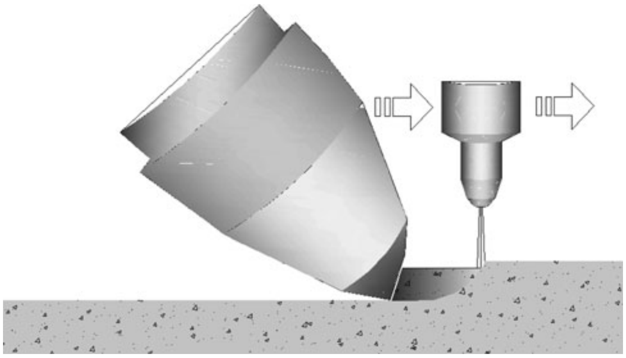

Fig. 1 Water jet assistance with the jet directed in front of the tool

In agreement with the first statement, the rock would be first weakened by the hitting jet before undergoing the action of the mechanical tool, that thence would work more efficiently. As a result, the increase in penetration depth and the improvement in the removed volume per unit length will be obtained. The second statement implies that the additional stress induced by the pressure of the impacting jet ahead of the tool would promote the formation of the scales generated by the mechanical tool. Of course, the two mechanisms can take place simultaneously.

As it is generally accepted in the scientific literature, the weakening effect on the rock produced by a water jet around the impact point, is roughly proportional to the impact time, at least initially, before the increase of stand-off distance and the disturbing interferences between the incoming jet and the exhaust water become effective. This means that the damage produced by the jet can be roughly assumed as inversely proportional to the traverse velocity of the tool, the jet moving with the same speed.

Therefore, if the prevailing mechanism was that of reducing the strength of the rock, it should be expected that the efficiency of water jet assistance becomes higher at slow traverse velocities, gradually diminishing as velocity increases. Actually, this outcome has been observed in many experiments. On the other hand, rock weakening does not require the simultaneous action of water jet and mechanical tool and thus it is not affected by the distance between the impact point of the jet and the tool's tip nor from the time lag of the two actions in the same point. Under this assumption, the action of the jet and that of the mechanical tool can be considered as fully independent and they can take place in different times. Consequently, the excavation trajectory can be first followed entirely by the jet, that will produce certain damage to the rock, and then rerun by the mechanical tool that will encounter a material already weakened with respect to the original one. The effect of strength reduction should be accompanied by a modification in the typical features of the material removal process: more explicitly, both the interaction forces and the tool penetration should show a more steady trend with lower frequencies and narrower oscillations around the average values. Also, the geometry of the excavation groove should be characterised by less variability concerning both the depth and the width.

The stress state induced by the jet near the impact point on the rock sample is practically independent from the velocity with which the nozzle is traversed along the path. It only depends on the pressure exerted by the jet as well as on the nozzle diameter. The hydrodynamics of the jet (stationary or pulsating) are also very important although the discussion here developed is restricted to the stationary jets.

For the ideal case of linear trajectory and homogeneous material, the combination of water jet stressing (tensile) with that generated by the mechanical tool (shear) depends chiefly on the geometric relationships concerning the excavation depth and the distance of the jet impact point from the tool's tip. The necessary condition for the synergetic effect is that the two contributions are simultaneously active in the volume of influence. Conversely, there would not be any combined effect if the jet and the tool actions are not coincident in both space and time (not simultaneous).

2 Framework and Aims of the Research

Within this frame an intensive research is being carried out at the DIGITA's Waterjet Laboratory, involving the University of Cagliari, the CNR and the Academy of Sciences of the Czech Republic.

Among the different research lines, one of the pursued tasks concerns the development of nonconventional high-performance tools, the industrial utilisation of which could be rendered economically advantageous through the concept of water jet assistance with the nozzle ahead of the pick (Ciccu et al. 1999, 2004a).

The tool studied 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 hand, 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 pictures of the Fig. 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.

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

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 utilisation of this kind of tool in the excavation of hard and abrasive rocks. Accordingly, a new testing apparatus has been designed and installed at the DIGITA's water jet laboratories with the specific goal of quantifying the improvement of the PCD pick performance as well as of investigating the underlying mechanisms.

3 Equipment

The equipment (Fig. 3) reproduces the typical tool/rock interaction of the 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 1,000 Hz of frequency.

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 Fig. 4. The mechanical tool is held inside a sleeve at the bottom of which a set of disk springs allow the impacts to be dampened thus diminishing the risk of damage of the tool's edge. The rake and the clearance angles are 20° and 12°, 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 6,250 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

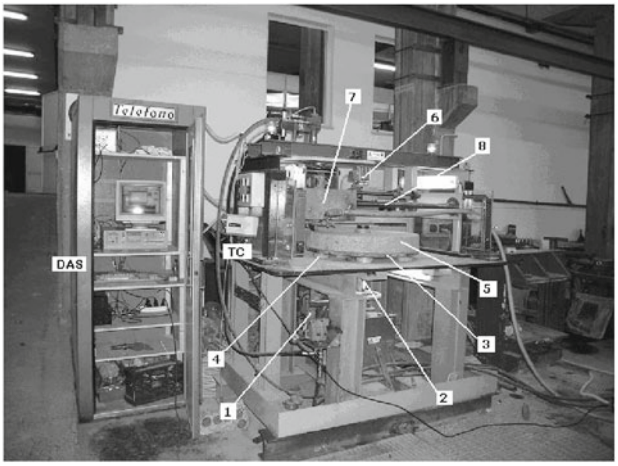

Fig. 3 Experimental apparatus

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

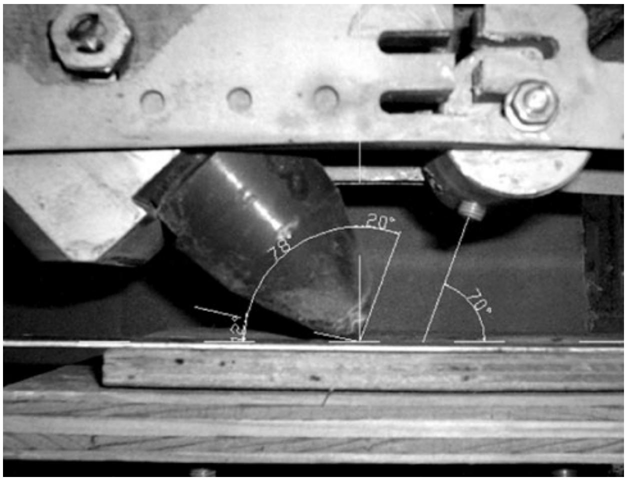

Fig. 4 Assistance system geometry

corresponds to the average length of the scales generated during the cutting process without water jet assistance.

The material used for the experiments is a medium-hard volcanic rock classified as rhyolite or dacite outcropping in Sardinia near the village of Serrenti from which it takes the name. Its texture, investigated by microscopy analysis on thin sections, is characterised by a fine-grained matrix which embeds plagioclase, biotite and amphigene phenocrysts. The following Mohr–Coulomb strength parameters have been obtained by interpreting a series of triaxial compressive tests: uniaxial compressive strength, 44 MPa; tensile strength, 6.7 MPa; cohesion, 11.5 MPa; friction angle, 56°. Its unit weight is 22.7 kN/m^3.

4 Experimental Tests

Three series of tests have been performed: in the first one the mechanical tool is 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 this case the two actions (mechanical and hydraulic) take place simultaneously and synergetically and the effect of the increased stressing is not discernible from that of the rock weakening.

The difference between the results obtained in the second series of tests and those obtained in the first one enables to quantify the overall contribution to excavation offered by the synergetic assistance of the water jet.

In the third series the mechanical tool worked along trajectories previously trailed by the jet; in this case, the mechanical and hydraulic actions do not take place simultaneously and then are not synergetic. The water jet does not contribute to the rock stressing but only to weakening the rock volume in the immediate surrounding of the impact line.

The comparison between the results obtained in the second with those obtained in the third series of tests allows to separate the effect of increased stressing from that of rock weakening.

The three series of tests have been carried out with fixed apparatus geometry (tool attack angle, stand-off distance, distance between tool tip and water jet impact point, etc.) and constant values of the operational parameters (rotation speed, normal force applied to the mechanical tool and hydraulic power of the jet), whereas three circular trajectories were explored with radius 150, 250, 350 mm, respectively. Each test was repeated at least three times.

All tests were preceded by six idle rotations of the circular sample until reaching a constant value of the rotation speed equal to 42.42 rpm, then the pick was pushed against the sample with a vertical load of 3 kN. After a complete rotation the pick was automatically raised.

During the tests, data of normal and cutting forces, vertical pick position and angular velocity were collected with sampling rate of 1 kHz; 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 weighing it.

5 Results

5.1 Analysis of the Benefits Introduced by the Water Jet Assistance

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 nine valid dry tests (two along inner trajectories, three along intermediate trajectories and four along outer trajectories) and eight valid waterjet assisted tests (two along inner trajectories, four along intermediate trajectories and two 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 Fig. 5 (dry tests and water jet assisted tests) for the outer trajectories, giving a total of 24 points. It is trivial to mention that the line linking the measurement points does not describe the actual value of the depth along the path and it is drawn only for making the figure more legible.

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 water jet 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 water jet 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).

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).

A statistical analysis of the depth values reveals that the dispersion obtained in the water jet assisted tests does not differ very much from that found for dry ones. The excavation process appears to be characterised by a greater variability in the depth of the cut and by the occurrence of a greater number of very large scales as confirmed by the screen size analysis of the collected cuttings (Ciccu et al. 2004a, b). The expected improvement in the regularity of groove geometry (Evans et al. 1984) as a potential benefit of water jet assistance does not appear, therefore, fully confirmed by the experiments.

Table 1 Mean values of the depth of cut

	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

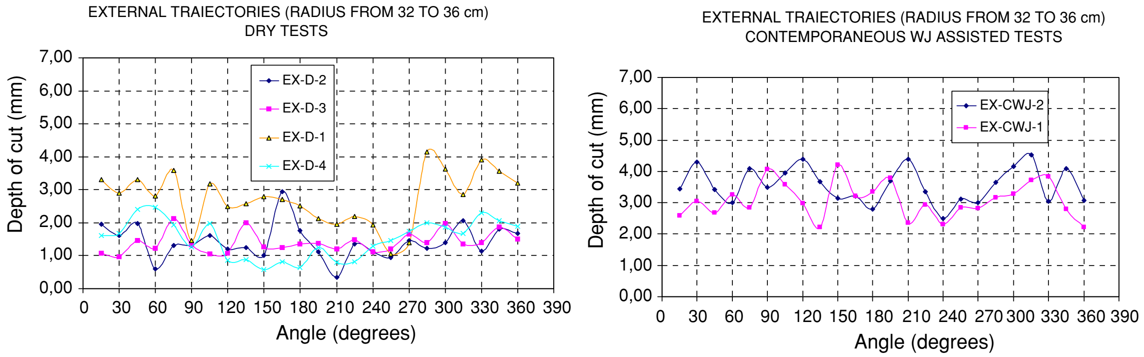

Fig. 5 Depth of groove along the trajectories (measurement points every 15° at the centre of the sample)

However, this result cannot be taken as a general conclusion and it should be referred to the features of the testing apparatus and in particular to the fact that a constant value of the vertical load is applied to the tool while it is free to move along the vertical direction (normal to the sample). Under these conditions the water jet assistance generates an increment of the depth and, consequently, of the width of the groove. It is reasonably likely that a better steadiness of groove geometry can be achieved in tests performed with an apparatus in which the vertical position of the tool is fixed and the depth of cut does not change during the test.

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).

The data depicted in the table 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 decreases considerably as the radius of the trajectory increases, as mentioned before, and thus the relative contribution of water jet appears, in this case, less evident.

5.2 B–Forces

Aimed at studying the modifications introduced in the rock–tool interaction mechanism by water jet assistance, normal and cutting forces were recorded during the tests, with a sampling rate of 1,000 Hz. Their typical behaviour is illustrated in Fig. 6. Some meaningful indexes have been defined to synthesize the recorded data:

CF/NF	ratio between mean value of the cutting force and mean value of the normal force. This parameter is proportional to the resistance encountered by the tool during its movement, which is correlated to the area of the groove's cross section and thus to the tool's penetration depth. For a given value of the normal force it represents a measure of the excavation process efficiency.
SD_{CF}/M_{CF}	is ratio of cutting force standard deviation to mean value. It quantifies the average value of the cutting force oscillation amplitude
$N_{1.5}$	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.

It is worth mentioning that although providing a synthetic overview of the results, those parameters do not completely define all significant aspects of the process.

The analysis of the above parameters, reported in Table 3, highlights some important features of the rock–pick–water jet interaction:

1. The mean values of the cutting force, measured in the water jet 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.
4. A general increasing trend of the force parameters, either in dry and in water jet assisted tests, can be associated at the smaller values of the trajectory radius.

Table 2 Average volume per unit length obtained at different trajectories

	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

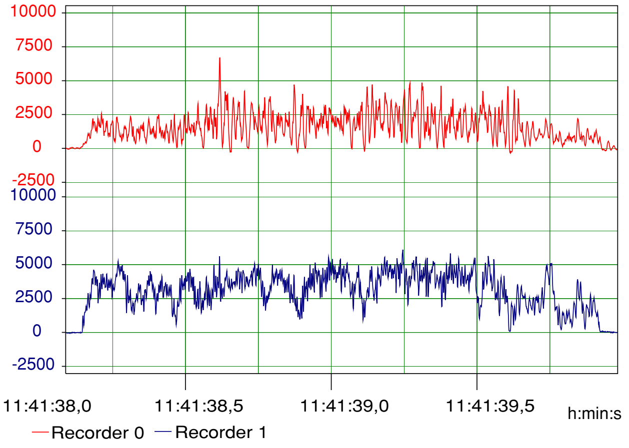

Fig. 6 Typical trend of normal (*lower graph*) and cutting (*upper graph*) forces

Table 3 Interaction forces analysis

	CF/NF	SD/M	$N_{1.5}$
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 the values of which are higher in case of water jet assistance. 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 results pointed out at points 2 and 3 highlight that water jet assisted excavation is characterised by higher oscillation amplitude of the cutting force and greater number of force peaks. This outcome can be explained considering that the excavation mechanisms shifts from a predominant shaving action of the tool tip for lower depths (achieved in the experiments with the tool alone) to a prevalent scaling/wedging effect at both sides ahead of the tool in case of the higher depths obtained with the water jet assistance. In fact, the interaction profile between the tool and the rock becomes larger with the depth of groove, determining the increase in the number and the size of the chips produced. Visual inspection confirmed that, while the groove excavated by means of the PCD tool is regular when the depth is lower than 2–3 mm, it becomes progressively irregular for deeper penetration as a result of the wider lateral extension of the chips produced. In the last conditions, besides the higher oscillation of the of cutting force, the unsteady excavation process implies a higher average value of SD_{CF}/M_{CF} and of $N_{1.5}$.

Finally, the energy spent to disintegrate the unit volume of rock has been calculated.

The results shown in Table 4 point out that waterjet assistance reduces considerably the mechanical energy involved in the tool–rock interaction, especially for intermediate and outer trajectories, 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/cm^3) consumed with and without water jet assistance

	Outer trajectories	Intermediate 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

5.3 Analysis of water jet assistance mechanism (rock–tool–water jet interaction)

Research has been completed with a third series of 14 tests (5 along inner trajectories, 6 along intermediate trajectories and 3 along outer trajectories) aimed at further clarifying the mechanism of the water jet assistance. The tests have been carried out in two separated and noncontemporaneous 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 noncontemporaneity 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.

This series of noncontemporary (nonsynergetic) tests has been carried out under the same experimental conditions (value of normal force, rotation speed, water jet generation pressure) adopted for contemporaneous and synergetic tests (second series).

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 noncontemporaneous tests is substantially equal to that achieved in case of contemporaneous water jet assistance. The same can be

Table 5 Mean values of the depth of cut

	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

said with regard to the excavated volume per unit length (Table 6).

The correspondence between the results obtained operating with noncontemporaneous 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.

Concerning the analysis of rock–tool interaction, Table 7 summarises the value of the force indexes calculated for the three series of tests.

The index cutting force/normal force ratio (CF/NF) obtained in noncontemporaneous tests assumes roughly the same values calculated for contemporaneous assistance: they are practically coincident for the intermediate and the inner trajectories while a significant difference emerges for the outer trajectories. Nevertheless, in both series of water jet assisted tests, cutting force values are higher than those measured in dry tests.

The analysis of the SD/M and $N_{1.5}$ parameters confirms that, like in the case of contemporaneous water jet assistance, noncontemporaneous method causes a higher variability of the interaction forces related to the increase in the depth of cut. On the other hand, no clear differences appears between the feature of the interaction forces in the tests performed with the two assistance methods.

6 Conclusions

The illustrated research, concerning the assistance of mechanical excavation 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.

Three series of tests were carried out using an experimental apparatus in which the applied normal force remains constant during the test and the tool follows circular paths. In the first series, tests were performed without water jet assistance (dry tests); in the second, the assistance of a water jet working ahead of the pick was introduced (synergetic actions) while in the third one the pick was forced to follow the path previously trailed by the water jet (nonsynergetic actions). The mechanical tool was a special conical drag bit having a flat tip entirely covered with a 0.8-mm-thick layer of polycrystalline diamond. The average values of the depth of cut and of the volume excavated per unit length were assumed as indexes for evaluating the excavation performances while parameters CF/NF, SD/M and $N_{1.5}$ were introduced for describing the features of rock–tool interaction. Each test was repeated at least two times.

The main outcomes of the research 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%.
- Forces analysis 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

Table 6 Average volume per unit length obtained at different trajectories

	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

Table 7 Interaction forces analysis

	Outer trajectories	Intermediate trajectories	Inner trajectories
CF/NF			
Dry tests	0.24	0.38	0.38
S-WJ tests	0.33	0.55	0.77
NC-WJ tests	0.52	0.50	0.78
SD/M			
Dry tests	0.37	0.38	0.41
S-WJ tests	0.36	0.57	0.74
NC-WJ tests	0.48	0.48	0.92
$N_{1.5}$			
Dry tests	32.33	17.33	30.00
S-WJ tests	30.33	34.00	39.00
NC-WJ tests	44.00	32.00	48.00

mechanical tool actions were contemporaneous (synergetic) and those in which the two actions were noncontemporaneous (nonsynergetic). 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 performances of the mechanical tool 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, it is not realistic to expect increase in PCD tools' technical life 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.

Furthermore, the results of the experiments confirm that the combination of the two technologies has a positive effect on tools' performance even at peripheral velocities typical of industrial operations.

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