Enhancement of tool performance in mechanical excavation with waterjet assistance

R. Ciccu, B. Grosso, C. Loddo
Department of Geo-engineering and Environmental Technologies of the University of Cagliari, Italy
A. Bortolussi
Institute of Environmental Geology and Geo-engineering, National Research Council of Italy

ABSTRACT: The benefit of assisting a mechanical tool with a high-velocity waterjet has been already demonstrated by the results of the ongoing research being carried out at the DIGITA's Laboratories both on drag picks and on disk cutters. It has been shown that specific material removal and excavation rate can be increased by the synergetic action of the jet resulting also in a slow-down of tool wear and a significant reduction of mechanical specific energy, although total energy is considerably higher due to the hydraulic power demanded for the generation of the jet.
In order to clarify the mechanisms involved in the rock-tool-waterjet interaction aiming at achieving a better knowledge useful for the development of the technology up to a commercial scale, further tests have been made aiming at 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.
A discussion follows and some preliminary conclusions are drawn about the prospects of industrial application of the technology.

1 INTRODUCTION

At present, the technological development concerning the mechanical excavation of rocks aims at:

1. Increasing the performance of the tools in terms of volume removed per unit length of travel;
2. Extending the field of application of mechanised excavation also to hard and abrasive rocks.

The strategies followed for achieving the two goals consist in the use of new materials for the production of more resistant and efficient tools, as well as in the development of suitable systems for the assistance of mechanical instruments, allowing improved operation, reduced wear rate (with consequent extension of the technical life) and superior capability of breaking tougher materials.
For these purposes, one of the most promising way consists in the combined action of a mechanical tool assisted by high-velocity waterjet.
The most interesting findings reported in the scientific literature produced during the last years starting from the early nineties can be summarized as follows:

- with the jet in front and behind the pick, a considerable reduction (at least 30%) of the applied forces can be obtained at low displacement velocity, whereas it becomes insignificant for the highest values typical of industrial practice (2-3 m/s);
- the amplitude of oscillations of the forces around the average value is reduced, resulting in a lower chance of ruptures of the picks;
- less mechanical energy is consumed, although the total energy (mechanical plus hydraulic) employed in the excavation can be considerably higher;
- wear rate is substantially lowered entailing a longer duration of the technical life of the tool;
- reduction of the sparkling is observed enabling safer operations in coal mining.

Within this frame is the intensive research being carried out at the DIGITA's Waterjet Laboratory starting from 1997, involving the University of Cagliari, the CNR and the Academy of Sciences of the Czech Republic.
Among the different research lines, one of the tasks pursued concerns the development of non conventional high performance tools, the industrial utilisation of which could be rendered economically advantageous through the concept of waterjet assistance.
In particular, the tool under investigation consists of a tough pick, whose flat tip is coated by a thin layer of polycrystalline diamond (PCD) having a very high resistance to wear, making it suitable for the excavation of abrasive rocks. However, the material is fragile and thence it is exposed to local ruptures from incurred impacts and may suffer the high temperatures such as those generated at the tool-rock contact point.
The assistance provided by a high-velocity jet of water appears to be a decisive factor for the applicability of this kind of tool in the excavation of hard and abrasive rocks as well as for improving the performance in weaker rocks compared with that attainable with traditional instruments.

2 EXPERIMENAL SYSTEM

2.1 Equipment

The rock cutting tests have been carried out using an apparatus installed at the DIGITA's laboratories reproducing the tool/rock interaction in the case of tunnel boring machines, where a continuous contact with constant penetration takes place under a steady normal force along circular paths with variable radius.
However instead of moving the tool (either a pick, a disc or a roller) against a fixed workpiece, the relative motion is obtained by rotating a cylindrical sample of rock and pushing the tool onto its upper planar surface. The drag force is determined by the torque applied to the shaft of the supporting platform.
The rotation power is supplied by means of an electric motor provided with an adjustable mechanical gearbox, while the vertical load applied by means of a hydraulic piston actuated by a pump through an accurate control system (oil pressure and flow rate).
The variation of the vertical load and of the drag force around the average values set by the oil pressure through an arrangement of electronically controlled valves (10) and by the torque applied to the rotating platform are directly measured by means of two piezoelectric transducers.

2.2 Tool

The tool employed in the tests is a drag bit having the shape of a conventional conical tool but with a flat tip so that its cutting edge is semicircular with a diameter of 12 mm, entirely covered with a 0.8 mm thick layer of polycrystalline diamond (Figure 1). On the left side a new (upper) and a worn (lower) PCD pick are shown, while the corresponding excavation grooves are reported in the right side. Cutting performance of the new tool is clearly better, underlining the importance to keep the tools at their original geometry by reducing the wear rate, especially by decreasing the thermal stresses.
In the cross section through the tool's axis, the curvature at the attack point is very sharp, providing a high penetration capability into the rock for a given normal load.
On the other side, since the singularity in the profile represents a mechanical weakness point, the contour of the tool's rim is roughly rounded by a chipping process, resulting in a gradual loss in performance.

2.3 Test material

The material used for the experiments is a volcanic rock classified as rhyolite or dacite outcropping in Sardinia near the village of Serrenti from which it takes the name. It is a medium-hard rock characterised by: unit weight 22,7 kN/m^3, uniaxial compressive strength 37 up to about 80 MPa, tensile strength: 6.7 MPa, cohesion: 11.5 MPa, friction angle: 56°.

Figure 1. Grooves with new (top) and worn bit (bottom)

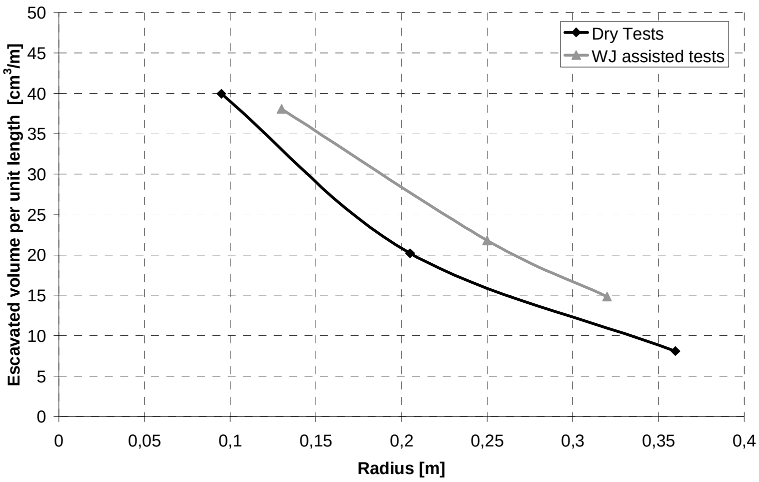


Figure 2. Excavated volume per unit length for dry and waterjet-assisted tests as a function of the path radius. (Normal load: 3.2 kN - Rotation speed:42.42 rpm)

3 AVAILABLE KNOWLEDGE

3.1 Previous results

The results of a first series of tests carried out in 2004 are in part summarised in the diagram of Figure 2 where the excavated volume for unit length is given as a function of the radius of circular travel of the tool against the rock in the case of dry and jet-assisted tests.

The positive effect of the waterjet in increasing in tool performance is clear: in fact the specific volume removed per unit length (and thence the excavation rate), is 20-25 % higher in the case of waterjet assistance for all trajectories.

Concerning the temperature, waterjet application provided a significant reduction in the thermal level reached during the test.

However, the above results did not fully clarify whether any reduction in the oscillation of the rock-tool interaction forces was determined by waterjet assistance.

3.2 New developments of the research

Starting form these results, a new series of tests was realised aimed at verifying the effects of the water jet on mean value and oscillation of rock-tool interaction forces and at better understanding the mechanism by which mechanical tool performance is improved by water jet assistance.

Two simultaneous but distinct mechanisms can be assumed to apply in the assistance of a water jet in rock excavation when the "front-of-peak" configuration in adopted: the first consists in the reduction of the rock strength in the zone around the impact point ahead of the tool; the second is connected to the composition of the stress induced by the water jet with that produced by the mechanical tool, resulting in a greater damage potential to the rock material.

According to the available knowledge, the reduction of the rock strength depends upon the permanence time of the jet on a given point of the rock surface: as the cutting velocity increases the rock weakening effect is likely to become less and less important.

As a consequence of the strength reduction, the behaviour of the material can be expected to become more plastic and the excavation mode to shift from an extremely discontinuous process with great variation of the cutting forces, due to chip formation, to a smoother process characterized by smaller oscillations of the forces as well as by a regular and basically constant geometry of the groove. This should ultimately provide a larger excavated volume per unit length of cut.

The effect of stress increase due to waterjet assistance is clearly independent of the cutting velocity but its importance is connected to the relationship between the depth of cut and the distance of the jet impingement point from the pick.

The effect of a more severe state of stress in the rock material should result in smaller size of the chips and thence in a smoothening of the forces behaviour.

Accordingly, a more regular excavation process is to be expected independently of the velocity of the tool.

4 EXPERIMENTAL TESTS

4.1 Experimental plan

Three series of tests have been included in the work plan:

- a first series using a PCD tool without waterjet assistance;
- a second series where the PCD tool was assisted by a high velocity waterjet directed in front of the tool (contemporaneous or synergetic action);
- a third series (in two steps) where the tool was forced to travel along the groove previously made by the jet (non contemporaneous action).

In both cases of waterjet assistance the stand-off distance, the peripheral velocity and all the other parameters were the same.

All the tests have been made on rock samples, the characteristics of which have been described earlier, having a cylindrical shape, 80 cm in diameter and 15 cm thick.

Each series consisted of grooving tests on three circular trajectories having different radius (around 150, 250, 350 mm).

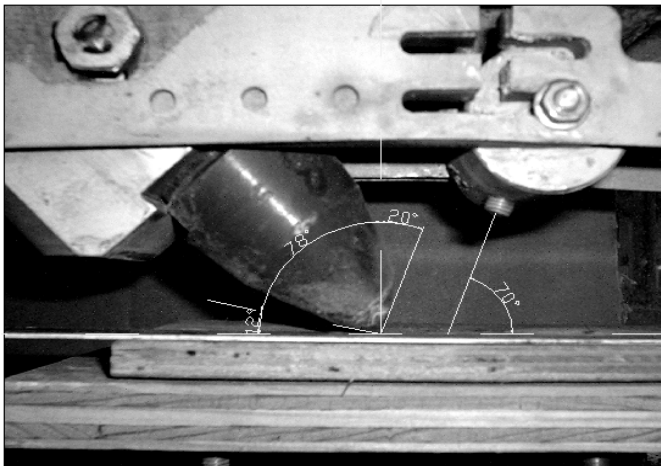
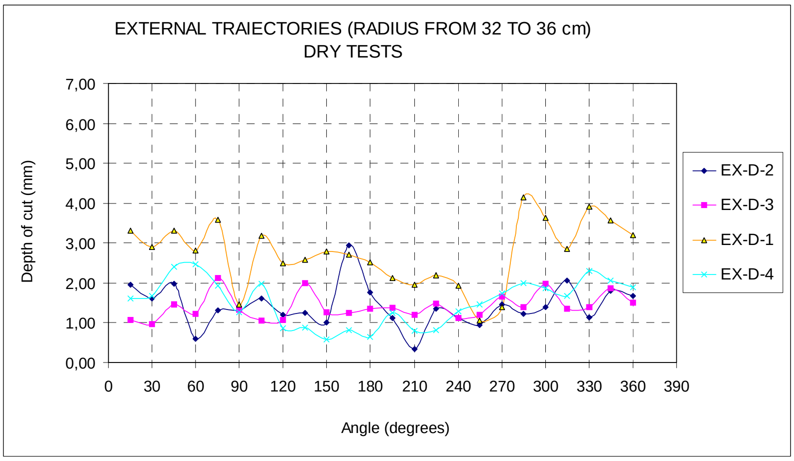


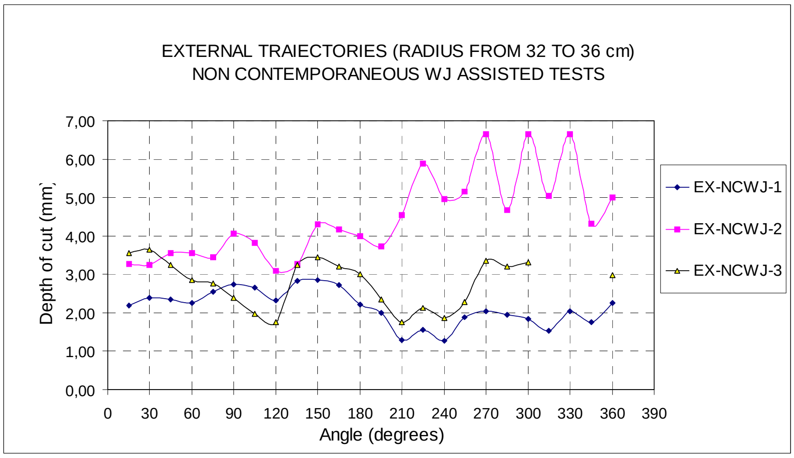
Figure 3. Details of the diamond tipped cutting tool

The results of the first series have been assumed as the reference levels for evaluating the effect of waterjet assistance.
The outcome of the second series (synergetic action) puts into evidence the combined effect of the additional stress and the weakening action induced by the jet, while the third series, because of the delayed passage of the tool, elucidates only the weakening effect of the jet on the rock.
All the tests have been carried out under the same conditions described below.
The bit attack angle was 98 degrees and the tool was set in the holder as shown in Figure 3 so that the rake and the clearance angles were 20 and 12 degrees, respectively.
The pick was assisted by a water jet positioned in front of the tool. The water jet was generated at a pressure of 150 MPa through a 0.4 mm nozzle, the resulting flow rate being 2.5 l/min. The stand-off distance was 40 mm. The jet was directed so as to impinge on the rock sample with a forward angle of 70° at a point 2 cm away from the tip, corresponding to the mean size of the scales detached by the tool in the "dry" tests.
A test begins with 6 idle rotations of the circular sample until reaching a constant value of the rotation speed equal to 42.42 rpm. Then the pick is pushed against the sample with a vertical load of 3 kN. After a complete rotation the pick is automatically raised. During each the test, normal and cutting forces, the vertical position of the pick and the angular velocity were measured with an acquisition frequency of 1 kHz.
In order to evaluate the benefits of waterjet assistance on the excavation results of the mechanical tool, the depth of cut and the excavated volume have been evaluated. The depth of cut was measured every 15° along the trajectory. The excavated volume was evaluated for the entire trajectory using a fine granular material with known specific gravity poured into the groove until filling it completely and then weighted.

4.2 Results

A total of 31 tests have been made following the various trajectories: outer (9 tests), intermediate (13 tests) and inner (again 9 tests) according to the three experimental conditions: dry and with waterjet assistance (synergetic or non contemporaneous).
Results are represented in terms of depth of groove measured along the path, volume removed per unit length and rock-tool interaction force.





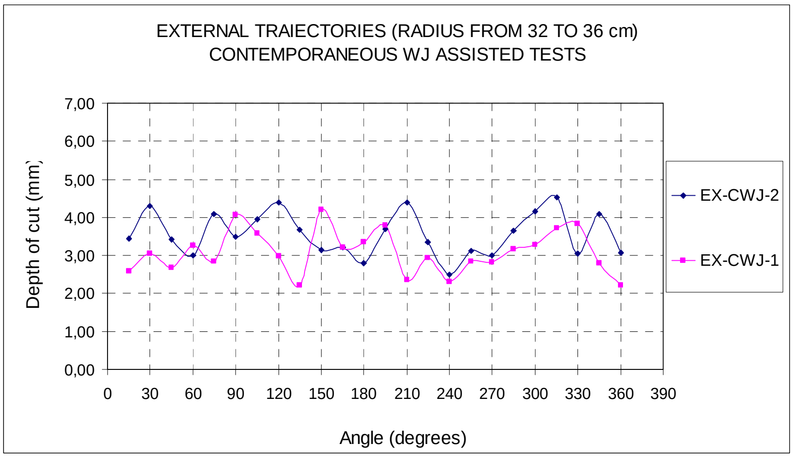


Figure 4. Depth of groove along the trajectories (measure points every 15° at the centre of the sample)

A - Depth of groove and excavation rate.

The values of depth of groove have been grouped according to the position of the trajectory and to the kind of waterjet assistance (dry tests or waterjet-assisted tests, either synergetic or non contemporaneous).
Figure 4 shows the depth of groove measured along the outer trajectories. The curves allow to evaluate its variation along the path and to compare the results achieved with or without waterjet assistance.
Of the 9 graphs in figure 4, four represent the tests without waterjet, three the tests with synergetic assistance and two with non contemporaneous assistance.
It can be clearly observed that for each trajectory the values oscillate within a rather ample range due to the local variation of the rock characteristics, with a period probably linked to the stiffness of the testing machine and of the system used for the application of the normal load (a hydraulic piston).
The results of the tests conducted in similar conditions range between 0.5 and 4 mm in the case of dry tests, between 1.5 and 4.5 mm in the case of non contemporaneous waterjet assistance and between 2 and 4.5 mm in the case of synergetic waterjet assistance (excluding the final part of the curve of the test EX-NCWJ2 which is evidently anomalous).

Table 1. Average values and corresponding increments of the depth of cut for different experimental conditions for the outer trajectories

Outer trajectories **Kind of experiment**	**Average depth of cut** **[mm]**	**Increment** **[%]**
Dry Tests	1.8	
NC-WJ Tests	3.1	77
S-WJ Tests	3.3	88

For the outer trajectories, the average values of the depth of the groove with the corresponding percent increment are reported in Table 1. The analysis of those data clearly shows the benefit of waterjet assistance on the excavated depth, with a small difference between the two configurations: synergetic and non contemporaneous. The last observation leads to the conclusion that the main effect of waterjet seems to be related to the induced rock weakening.
The results of the second set of 13 tests are related to the intermediate trajectories again for dry conditions and for synergetic or non contemporaneous waterjet assistance. The influence of the waterjet assistance is confirmed also in this case with a significant increment of the depth of groove for both synergetic and non contemporaneous configurations, as reported in Table 2.

Table 2. Average values and corresponding increments of the depth of cut for different experimental conditions for the intermediate trajectories

Intermediate trajectories **Kind of experiment**	**Average depth of cut** **[mm]**	**Increment** **[%]**
Dry Tests	2.0	
NC-WJ Tests	3.7	82
S-WJ Tests	3.6	80

The results obtained in the third set of 9 tests related to the inner trajectories are reported on Table 3. The data analysis confirm the achievements for the other two trajectories.

Table 3. Average values and corresponding increments of the depth of cut for different experimental conditions for the inner trajectories

Inner trajectories **Kind of experiment**	**Average depth of cut** **[mm]**	**Increment** **[%]**
Dry Tests	2.4	
NC-WJ Tests	4.8	103
S-WJ Tests	4.6	97

Table 4. Average volume per unit length obtained at different trajectories

Average volume per unit length [cm^3/cm]			
Kind of experiment	**Outer Trajectories**	**Intermediate Trajectories**	**Inner Trajectories**
Dry Tests	0.11	0.12	0.33
NC-WJ Tests	0.28 (157%)	0.33 (167%)	0.63 (90%)
S-WJ Tests	0.28 (162%)	0.38 (210%)	0.65 (95%)

The average values confirm that the excavation depth increases with the decrease of the radius of the trajectory, irrespective of the presence and the kind of waterjet assistance.
As reported in Table 4, the measurements of the excavated volume per unit length lead to the same conclusions achieved in the analysis of the depth of groove. In case of waterjet assistance the excavated volume per unit length increases approximately by the same amount for both non contemporaneous and synergetic configurations except for the intermediate trajectories for which better results are achieved with the synergetic action. The influence of the radius of the trajectory is again confirmed.

B - Forces
For each test, the cutting and normal forces have been measured and recorded in order to evaluate the influence of waterjet assistance on the frequency and amplitude of the peaks of force and to quantify the differences between the synergetic and non contemporaneous assistance configurations.
As an example, the graphs of Figure 5 show the typical trend of normal (top) and cutting forces (bottom).
The information contained in the acquired data files has been elaborated for obtaining suitable parameters describing the value and the variability of the forces during the test. The ratio between the cutting and the normal force (CF/NF), the ratio between standard deviation and average value of cutting force (SD/M) and the number of peak values exceeding 1.5 times the average cutting force (N1.5) are of particular interest.

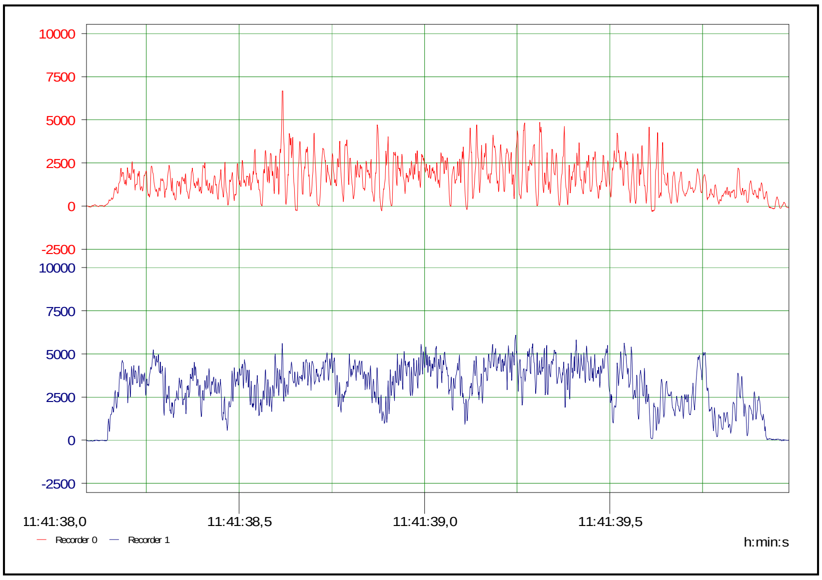


Figure 5. Typical trend of normal (higher graph) and cutting (lower graph) forces.

It is trivial to observe that, although these parameters provide a synthetic picture of the results, they do not completely define all the significant aspects of the process.
The ratio between the cutting and the normal force is proportional to the resistance encountered by the tool during its movement, which is related to the cross section area of the excavation groove. Therefore it

enables to evaluate the increment of depth of groove and thence the gain in efficiency obtained with the assistance of the waterjet at equal normal force.
The ratio between the standard deviation and the average value of the cutting force represents the average value of the amplitude of oscillation, while the number of values exceeding 1.5 times the average value of the cutting force is an indication of the frequency of the force peaks responsible of fatigue stress of the tool.
The results reported in Table 5 show that the cutting force is lower in dry tests than in waterjet-assisted tests for both synergetic and non contemporaneous conditions of waterjet action. The data also confirm the increase in cutting force when the radius of the trajectory decreases. The results are in agreement with the findings ensuing from the analysis of the depth of groove and specific removed volume.
The ratio between the standard deviation and the average value of the cutting force is higher in waterjet-assisted than in dry tests, meaning that the effect of reduction of the force peaks expected in the first case is not always encountered, thus deserving further investigation.
The influence of the radius of the trajectory is confirmed: higher average value and standard deviation of the cutting force are obtained for the inner trajectories.
These achievements are also corroborated by the number of force peaks represented by the parameter N1.5, which is higher in case of waterjet-assisted tests.
The wider oscillation of cutting force obtained in case of waterjet-assisted tests and for the inner trajectories can be explained considering that the excavation mechanism shifts from a predominant shearing action of the tool tip for shallower grooves to a prevalent "wedging" effect of the tool sides leading to the formation of larger scales in case of deeper grooves. In fact, the interaction profile between the tool and the rock increases with the depth of groove, determining the number and the size of the chips produced. While the groove excavated by means of the PCD tool is more regular when the depth is lower than 2-3 mm, for deeper grooves the geometry is irregular as a result of the higher lateral extension of the chips produced. In the last conditions, besides the higher oscillation of the of cutting force, the unsteady excavation process implies an higher average of that parameter.

Table 5. Values of CF/NF, SD/M and N1.5 parameters obtained for different experimental conditions.

	Outer Trajectories	**Interm. Trajectories**	**Inner Trajectories**
		CF/NF	
Dry Tests	0.24	0.38	0.38
NC-WJ Tests	0.52	0.50	0.78
S-WJ Tests	0.33	0.55	0.77
		SD/M	
Dry Tests	0.37	0.38	0.41
NC-WJ Tests	0.48	0.48	0.92
S-WJ Tests	0.36	0.57	0.74
		N1.5	
Dry Tests	32.33	17.33	30.00
NC-WJ Tests	44.00	32.00	48.00
S-WJ Tests	30.33	34.00	39.00

5 CONCLUSIONS

The results of the experimental tests basically confirm the findings achieved in previous research work on waterjet-assisted mechanical tools, although with some discrepancies concerning the forces. The main aspects regarding the positive influence of waterjet on tool performance have been fully clarified.
When using PCD picks, the volume excavated per unit length increases with decreasing radius of the circular trajectory in both cases of dry and waterjet-assisted tests.

The depth of groove and the volume removed per unit length increase in case of waterjet-assisted mechanical tool. The increase in depth ranges between 80% and 100%, according to the trajectory radius, while the increase in the excavated volume ranges between 90% and 200%.

Results of force measurement show an increase in the average value and the oscillation of the cutting force in case of waterjet-assisted tests. The reason of this result is most probably related to the increment of the depth of cut which produces a discontinuous cutting mechanism generated by the particular geometrical interaction between the pick tip and the rock, characterised by the formation of larger chips.

Under the experimental conditions, the results obtained suggest that the reduction of the forces pick values is not achievable through the action of waterjet. Consequently the increase of PCD tool technical life due to the reduction of forces picks and frequencies is not realistically to be expected when waterjet is combined with those kind of tools.

A negligible difference is being outlined between the results obtained in the tests with waterjet acting at the same time and in advance respect to the pick. That experimental achievement indicates that the increase of pick performance induced by waterjet is mainly due to the rock weakening rather than to the stresses combination.

However, the results of the experiments confirm that the combination of the two technologies has a positive effect on tool performance even under industrial velocities conditions.

6 ACKNOWLEDGEMENTS

Work carried out in the frame of research projects supported by MURST and CNR. Many thanks to Mr P. Borghero for the precious assistance provided during the tests.

7 REFERENCES

A. Bortolussi, R. Ciccu, B. Grosso, C. Loddo, S. Pistis and J. Vašek: *Improvement of disk cutters performance in the excavation of small tunnels* Proceedings CAMI and MPES2005, Calgary, November 2006 (on CD)

Ciccu R, Grosso B., Ortu G., Agus M., Bortolussi A, Vašek J., Jekl P., *Rock Disintegration using waterjet-assisted Diamond tools,* Proc. 10th AWJC, (Hashish Ed.) WJTA, pp. 465-477, Houston 1999

Ciccu R, Grosso B., Loddo C., Vašek J., Bortolussi A. *Mechanical excavation of hard rocks*. Proceedings MPES 2004, Wroclaw, Poland, September 2004

Ciccu R., Grosso B., Loddo C., Bortolussi A., Vašek J., *Waterjet-assisted drag tools for rock excavation* Proceedings Waterjetting 2004 BHRg Ed, Mainz, Germany, September 2004

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

Hood, M., and Alehossein, H., *A development in rock cutting technology,* Int. J. Rock Mechanics & Mining Sciences. 37, 297-305, 2000

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

Knickmeyer W., Baumann L., *High pressure water-jet assisted tunnelling techniques*. Proc. 2nd U.S. Water Jet Conference, University of Missouri, Rolla,U.S., May 1983

Kouzmich I.A., Merzlyakov V.G. *Schemes of coal massif breakage by disc cutter and high velocity,* Proc. 2nd U.S. Water Jet Conference, University of Missouri, Rolla,U.S., May 1983

Lindqvist P. A., *Energy consumption in disk cutting of hard rock*, Dept. of Mining, Univ. of Lulea, Sweden pp. 189-196, 1981

Ozdemir L., Miller R., Wang F. D., *Mechanical tunnel boring prediction and machine design*. Annual Rept. NSF IRA -770199 Colorado School of Mines, Golden, 1977

Roxborough F. F.: *Research in mechanical rock excavation progress and prospects*. Rapid excavation and tunnelling Conference, pag. 225-242, June 1985

Vašek J., *High Pressure Water Jet Assistance of Hard Rock Cutting Process*, 8th American Water Jet Conference Houston, Texas,1995