Improvement of disk cutters performance in the excavation of small tunnels

A.BORTOLUSSI*, R. CICCU**, B. GROSSO**, C. LODDO**, S. PISTIS** and J. VAŠEK***

* Institute of Environmental Geology and Geo-engineering,
National Research Council, Italy
** Department of Geoengineering and Environmental Technologies,
University of Cagliari, Italy
*** Institute Geonics, Czech Academy of Sciences, Ostrava, Czech Republic

The problems arising in tunnel excavation into hard rocks with the use of mechanical tools consist chiefly in a slow advance rate accompanied by an intensive wear due to the toughness and abrasiveness of the rock. In order to allow the further extension of mechanical excavation beyond the limits of the presently available technology, the assistance of waterjet aiming at improving the performance of the equipment while reducing the wear rate of the tools has been recognised as one of the most interesting technical solutions. The paper illustrates the results obtained at the Waterjet Laboratory of the University of Cagliari on a medium-hard rock using a carrousel-type testing machine capable of reproducing the conditions of rock-tool interaction encountered in the industrial practice and discusses the prospects of the technological advances under development. The results are interpreted on the basis of a numerical model capable of describing the interactions involved.

Keywords: Rocks, Mechanical excavation, Disks cutters, Waterjet

1. FOREWORD

In most methods of full-face mechanical excavation, the rock is removed by contiguous grooves as the result of the action of suitable tools by means if which a stress leading to rock disintegration is applied at contact points moving along circular trajectories. The width of the groves should be large enough as to achieve a good coverage of the face area.

Concerning the velocity at which the load is applied, it can be said that the tools used in current machines practically operate under quasi-static conditions.

As for the forces exerted by the tools on the rock, a distinction should be made between *rolling tools* like disk cutters used in hard rock tunnelling, for which the total force is directed almost perpendicular to the face, from *drag tools* like picks or blades used in softer rocks, for which the cutting force parallel to the rock face is of the same order of magnitude as the normal thrust.

The mechanism of rock excavation for both kinds of tool seems essentially based on tensile failure, although with some differences concerning the initiation and propagation of fractures (Takaoka et al., 1968). With particular reference to the disk cutters, much higher normal forces must be applied in order to achieve a significant penetration resulting in an intensive crushing beneath the tool: it is assumed that tensile stresses are generated in the surrounding intact rock due to bulging of plasticized material (Hood and Alehossein, 2000) thus producing a pattern of fractures ending at the free face.

The technological developments in the construction of machines and tools enable now mechanical excavation to compete with traditional explosive-based methods. Further research is being carried out in order to extend the application even in the case of very hard rocks.

Among the possible advances, the assistance provided by high velocity waterjet is considered very promising owing to the features of this technology that is capable of carrying a considerable power in a very small volume. Moreover waterjet is a no-contact cold tool that can prove very helpful in the case of abrasive rocks.

A long-term research programme has been undertaken at the University of Cagliari aiming at developing a hybrid system based on the synergetic action of mechanical excavation tools with high-velocity waterjet.

2. THEORETHICAL MODELS

According to the model of Roxboroug and Philips (Roxboroug and Philips 2000) a cutter disk having a tip angle "ϕ" and a diameter "D", is penetrated into the rock at a depth "p" under a force "F_n" as shown in figure 1.

As p increases with F_n, the length of the contact arc, coarsely represented by the chord $L = 2(Dp-p^2)^{1/2}$ also increases and the contact area becomes approximately:

$A = 2\, p\, L \tan(\phi/2)$.

Accordingly, the force necessary for achieving a penetration p is given by:

$F_n = 4\, \sigma \tan(\phi/2)\, (Dp^3-p^4)^{1/2}$

where σ is the uniaxial compressive strength of the rock.

If the disk is assumed to revolve freely in absence of friction subject to the loading force F_n and the cutting force F_r; then the resulting force F passes through the centre "o" at the midpoint "c" of the contact arc a-b; the condition of rotational equilibrium entails that:

$F_r \cdot of = F_n \cdot oe$ and thence: $F_n / F_r = \cot\psi$.

Moreover $og/oa = ((D/2)-p)/ (D/2) = \cos(2\psi) = (1-\tan^2\psi)/ (1+\tan^2\psi)$

and thus: $F_n / F_r = ((D-p)/p)^{1/2}$

An expression of F_r as a function of p can be obtained by a suitable combination of the above equations: $F_r = 4\sigma\, p^2 \tan(\phi/2)$.

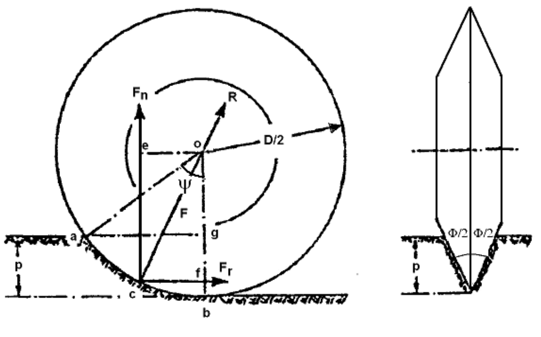

Figure 1. Sketch of a disk cutter

Some experimental data on the performance of disk cutters in the excavation of a coarse-grained sandstone with medium compressive strength aimed at confirming these equations are provided by Bringiotti (Bringiotti 1996) and represented by the curves of figure 2.

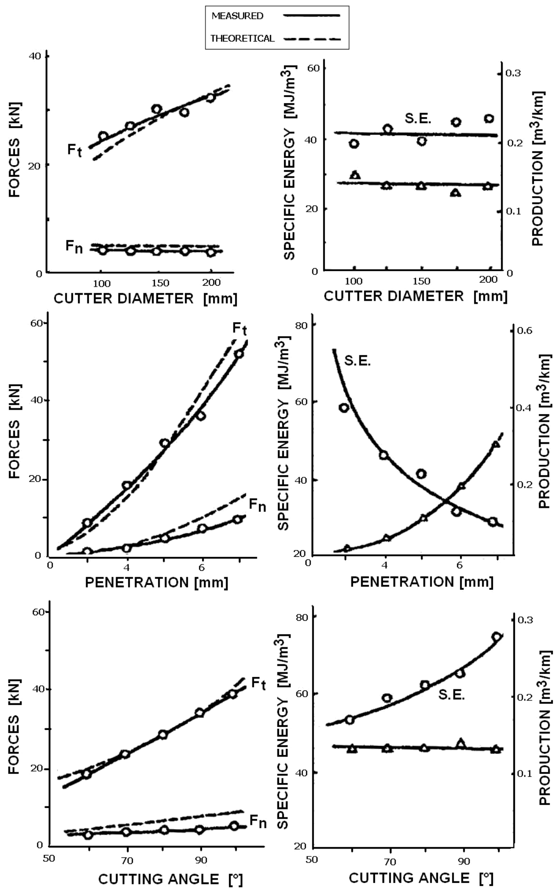

Figure 2. Influence of variables on the performance of disk cutters.

The following aspects can be underlined concerning the influence of the chief variables:

- *Disk diameter*. As the diameter increases the thrust force must be increased while the cutting force remains substantially constant together with the specific energy.
- *Effect of the tip angle.* At increasing tip angle ϕ both the thrust and cutting forces increase, although this latter with a smaller gradient. Specific energy is greatly affected whereas no significant effects are observed on material fragmentation.
- *Effect of cutting velocity.* At a cutting velocity of about 200 mm/s no significant changes are observed in the forces nor in the specific energy and in fragmentation degree.
- *Effect of disk spacing***.** This parameter has a relevant importance for a good coverage of the excavation area leading to the optimisation of the operation’s efficiency. This implies that the thrust force must be high enough in order that the average length of removed cuttings will equal half the disk spacing.

The size of the cuttings can be evaluated through an ultra-simplified two-dimensional model for an ideal flat tool having a linear tip of undefined length, as sketched in figure 3.

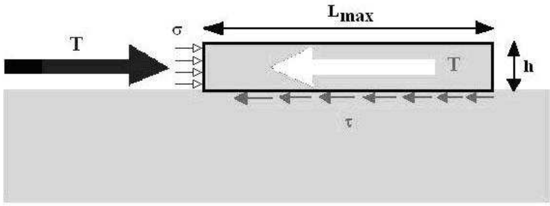

Figura 3. Simplified model for scale formation.

The ratio between the length and the thickness of a detached scale of rock assumed to have a rectangular cross section and a width equal to 1 can be calculated considering that the maximum pushing force applicable tangentially is given by:

$T = \sigma_{rc} h$ where σ_{rc} is the compressive stress leading to plasticization and "h" is the thickness of the scale, while the maximum tangential resistance opposed by the rock is:

$T = \tau_r L_{max}$ where τ_r is the shear strength and "L_{max}" is the maximum length of the scale.

Consequently the ratio h/L_{max} is equal to τ_r / σ_{rc} which is typical of a given rock, varying generally between 1/5 and 1/8.

In the case of a hydrostatic pressure at a rock-tool contact area, the horizontal component of the force acting on the rock eventually leading to the formation of a scale would simply be equal to half the applied thrust.

The length of the rock/tool contact arc is roughly: $l_c = (2Rp-p^2)^{1/2}$.

If the thrust P is considered to be uniformly distributed along l_c, one obtains:

$(P/2)/l_c = p\ \sigma_{rc}$ or else:

$P = 2\ (l_c\ \sigma_{rc}\ p) = 2(2Rp- p^2)^{1/2}\ p\ \sigma_{rc} = 2\ (2Rp- p^2)^{1/2}(i\tau_r)/2$

that represents the optimum thrust as a function of disk radius R, depth of groove p, track spacing "i" and strength features of the rock, the link between the last two being:

$p = (i\tau_r)/(2\ \sigma_{rc})$

As for the force F_r required for the rolling action (on which the power consumed for sustaining the excavation rate directly depends together with the tangential velocity), it can be obtained through the equation:

$F_r = P(l_c/2R) = P(2Rp- p^2)^{1/2}/2R$

that roughly equals the torque of F_r and P with respect to the extreme point "b" of the contact arc.

A satisfactory qualitative agreement has been found between the predicion of the model and the performance of industrial machines working under optimum conditions, that however are not always attainable since "i" ed "R" are not adjustable and σ_{rc} e τ_r can not be changed at all.

Farmer and Glossop (Farmer & Glossop 1980) have tried to compare the cutting mechanism of the disks with the penetration of an indenter into a brittle rock. Accordingly, a main vertical "median vent" is assumed to form starting from a "crushing zone" around the edge of the tool as the result of the applied load, accompanied by a set of parallel fractures that are further propagated downwards as the load increases. As the tool moves forward thus unloading the rock behind, the median vent tends to close and some lateral vents start to form terminating at the free face of the rock.

Comparative tests with and without the application of a water jet showed that the length of the median vent was somewhat longer in the case of dry tests, whereas no difference was found concerning the lateral vents. This is an advantage since less energy is consumed for the formation of the vertical vent that does not provide any important contribution to the cutting process.

A good description of the phenomenon is offered by Savadis (Savadis, 1982) according to which the wedge of crushed material formed below the disk under the compressive load behaves as a secondary tool transferring the stress to the surrounding intact rock into which some fractures are originated (figure 4). As the disk moves forwards, the material expands due to the displacement of the load and a state of stress is originated inside the adjacent rock, starting the process of scale formation due to fracture initiation and propagation. As the rock is broken, the stress is suddenly released and a new cycle begins.

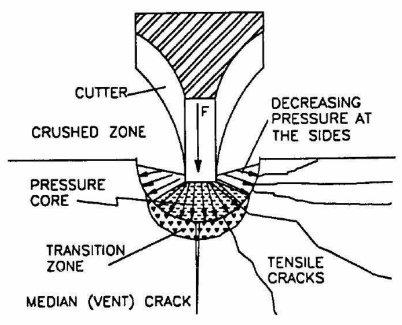

Figure 4. Scheme of indenter penetration

Attention has been paid to whether the mechanism of formation of lateral scales is dominated by shear (Roxborugh & Phillips, 1975, and Ozdemir et al., 1977) or tensile stresses, as claimed by Lindqvist (Lindqvist, 1981). Tests made with visual control by means of a high definition camera put into light a behaviour characterised by upwards projection of the scales typical of traction forces and not by rotation as it would be in the case of shear (Fenn, 1985).

An ideal tool for rock cutting should be cheap, highly efficient, resistant to wear and fatigue, capable of penetrating deeply into the rock with little dust generation, small friction and low specific energy consumption. It should not accumulate excessive heat in its body so as to maintain a suitable temperature in order to limit the wear rate.

The tools can be put out of service either by rupture caused by excessive mechanical stress or by wear due to thermal overload (Alehossein and Hood, 1999). Wear problems can be solved by developing new constituent materials or by suitable thermal treatments of the metal alloys, that however can be detrimental to mechanical strength (Bringiotti 1996).

During the last ten years attempts have been made to improve the tool performance by:

- Studying special material technologies;
- Applying internal and external cooling actions;
- Resorting to the assistance of a water jet.

3. ROCK EXCAVATION WITH WATERJET-ASSISTED ROLLING TOOLS

Some results of previous research carried out at various scientific institutions and industries are briefly resumed in the following (Handewith et al., 1985; Momber, 1998).

3.1. Rand Afrikans University

The machine used for linear tests can apply a vertical load of up to 900 kN to the cutting head fitted with disks having different shape (either sharp-edged, flat or fitted with peripheral buttons), beneath which the rock sample carrier can travel at a maximum velocity of 1 m/s. A 55 kW pump can issue one or more jets of water under a pressure of 45 MPa and a flowrate of 82 l/min. In a particular configuration, two Leach and Walker 1.2 mm nozzles are placed at both sides of the disk.

Tests have been made with each type of disk with or without waterjet assistance (figure 5), in single or multiple passes, on a homogeneous rock (norite having a compressive strength of 250 MPa and high abrasivity).

The main result using the sharp-edged disk was a considerable decrease in vertical and horizontal forces with the application of water jets, but the effect faded gradually at increasing spacing from the disk as well as at increasing depth of slot due to the limited reach of the jet, suggesting that an increase in jet-forming pressure could be beneficial. A certain reduction in specific energy was achieved owing to the smaller horizontal force involved, although the volume removal rate was not affected. The vertical force F_v resulted to be smaller at increasing water pressure until 40 MPa, whereas for the horizontal force F_r no effect was found beyond 5 MPa.

In the case of flat (or worn) disks an important reduction in the vertical force was observed (-26%) independent of spacing and of penetration depth, whereas the horizontal force was not influenced. Again insignificant effects were observed concerning the volume removed per unit length (i.e. the cross section of the excavation groove). The performance of waterjet-assisted worn disks were similar to those of new sharp disks without assistance.

Finally in the case of button-tipped disks a reduction in the vertical force was attained (-23%) with only a slight effect on F_r (Fenn et al., 1985).

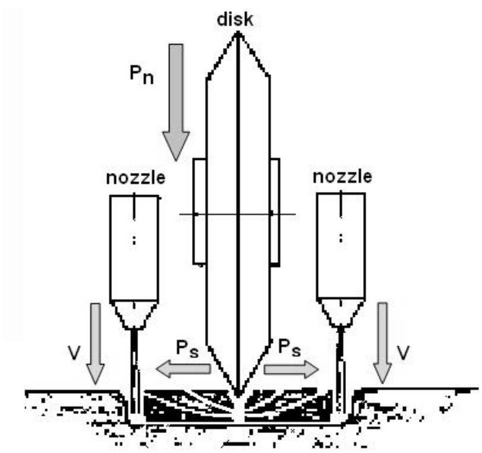

Figure 5. The concept of waterjet assistance

3.2. Colorado School of Mines

At the Colorado School of Mines a big equipment capable of reproducing the underground mechanical excavation at an industrial scale by means of full-face cutting heads up to 2.5 m in diameter fitted with 14 disk cutters can be used. A 32 channels data acquisition system allows a real-time monitoring and control of the process variables. Low and high-pressure water jets can be applied to the tools.

A thrust of 3.6 kN to the cutting head is supplied by means of four hydraulic cylinders, while the rotation is assured by two hydraulic motors with a variable speed fro 0 to 32 rpm and a maximum torque of 135.6 kNm.

The test samples were made of concrete with aggregates of variable size and features similar to those of rocks. A number of tests have been carried out varying the load and the rotation speed with or without waterjet assistance. High values of the forces characterised by a considerable fluctuation have been recorded for peripheral disks. Results with high-pressure waterjet are not yet available (Ozdemir et al., 1983).

3.3. Wirt Maschinen Und Bohrgerate Fabrik GmbH

Deep tests using cutting tools assisted by waterjet have been carried out at the face of a sandstone quarry by Bergbau-Forschung GmbH, in co-operation with the some German mining industries with the financial support of the Ministry of Ecomony of the Land North Rhine Westphalia. The equipment consisted of a tunnel boring machine with a diameter of 2.6 m.

The results of the tests show a 50% reduction of the thrust forces with waterjet assistance which is a great advantage since lighter and cheaper machines can be built. Important benefits concerning the wear rate of the tools and the generation of dust have also been demonstrated (Knickmeyer and Baumann, 1983).

3.4. Skochinsky Institute of Mining

The research carried out concerns the process of hard coal breakage in underground mines using water jets in assistance to revolving tools, with the purpose of creating slots at both sides of the disk cutter. Different configurations have been studied including the position of the jet and the type of tool employed.

It has been observed that deeper slots decrease the strength of the coal and thence produce a higher reduction in the forces and in the specific mechanical energy. In particular, the rolling force and the thrust force resulted to be about 1.5-2 times and 1,2-1,4 times lower, respectively, while a 99.75 abatement of the dust was achieved (Kouzmich and Merzlyakov, 1983).

3.5 Institute of Geonics

A waterjet assisted cutting equipment have been used to test rock materials as hard as granites and sandstones. The experimental apparatus consisted in a linear cutting device, capable of a maximum linear velocity of 0.25 m/s, with three component force transducers, pick holder and water jet nozzle.

The experiments revealed (Vašek 1995) that the use of water jets can considerably reduce cutting forces, tools temperature, dust production.

One of the main goals of the research team has been to improve the effect of the high pressure waterjet at the place of the cutting tool-rock interaction.

3.6. DIGITA University of Cagliari

Previous research at the DIGITA's Waterjet Laboratories concerning the synergetic action of mechanical instruments and jets of water was firstly focussed on drag tools using the "through-the-pick" and the "front-of-pick" configurations.

Results show that an increase in cutting rate (around 30%) can be achieved with waterjet assistance with a certain reduction of the forces at equal performance level. Waterjet also proved to be and efficient cooling system enabling to reduce considerably the wear rate (Ciccu et al. 1999, 2004, 2004).

Experiments with cutting disks have been started using a carrousel-type testing equipment. The main results achieved with dry tests can be summarised as follows:

- The volume excavated per unit length directly depends on the applied vertical load and varies according to the tangential velocity of the tool on the rock as well as to the radius of the circular trajectory.
- Specific Energy decreases at increasing vertical load and peripheral velocity and at decreasing radius of curvature of the circular path.

4. NEW DEVELOPMENTS

In order to demonstrate the feasibility of waterjet assistance to rolling tools, tests have been carried out using the apparatus shown in figure 6.

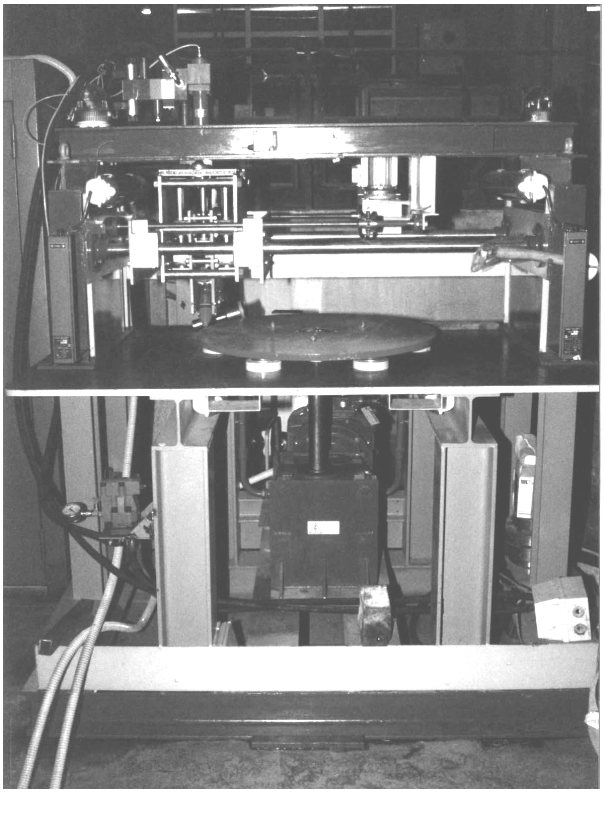

Figure 6. Experimental apparatus at DIGITA's Waterjet Laboratories

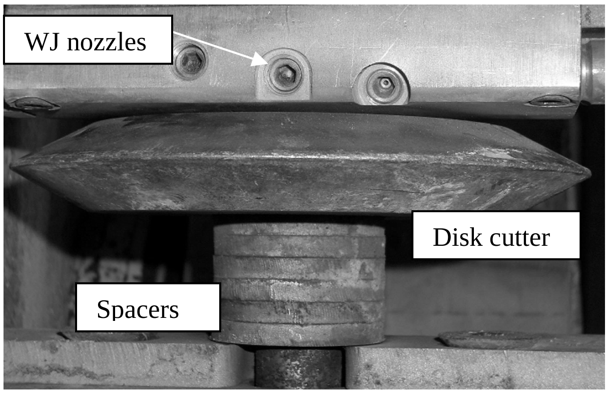

Figure 7. Detail of the cutting head as seen from below

The cutting head is fitted with a 10 cm diameter disk having a 60° tip angle to the side of which the nozzles are placed (figure 7).

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 (σ_c variable up to 80 MPa). The cylindrical rock samples, 10 cm thick with a diameter of 80 cm, have been obtained from sawn slabs using abrasive waterjet for contour cutting.

The parameters kept constant for all he tests were:

- 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°;
- Distance of the jet impingement point from the disk tip: 2 cm;
- Stand-off distance of the nozzle: 3 cm.

The variables explored were:

- Radius of the circular path of the tool on the rock: 0.34 m, 0.26 m and 0.15 m for dry tests and 0.29 m, 0.22 m and 0.11 m for waterjet-assisted tests.
- Rotation speed: 30.30 rpm and 60.60 rpm corresponding to 50% and 100% of the maximum value allowed by the gear device.

Therefore the experimental plan consisted of 24 tests (12 dry and 12 with waterjet assistance) divided into two series at different rotation speed (6+6 tests at ω = 30.30 rpm and 6+6 tests at ω = 60.60 rpm). In each series the radius of curvature was changed and each test was repeated on a different sample for confirmation (the average value was eventually taken after excluding few anomalous results).

Once started, each test proceeds automatically, being the system driven by a computer programme that includes 6 idle rotations of the sample until reaching a steady velocity, after which the tool is pushed down with a hydraulic piston at the set load, while the jet impinges the rock upon opening the cut off shutter; after the active rotation the tool is raised and the jet stopped again (figure 8).

Experimental results have been studied by considering the following features:

- Volume removed per unit length [cm^3/m]
- Excavation rate [cm^3/s]
- Specific Energy [J/cm^3]

- Average depth of groove [mm]
- Average width of groove [mm]

During each test the relevant parameters and variables have been recorded through an automatic data acquisition system.

Tool performance has been evaluated in terms of specific volume (volume removed per unit length) that represents the average cross section of the groove. The results have also been interpreted in terms of excavation rate (removed volume per unit time), i.e. specific volume time’s peripheral velocity of the tool onto the rock sample.

The grooves showed irregular borders due to the variable size of the scales arising from the discontinuous process of cutting. Especially in the case of smaller trajectory radius the detachment of scales occurred more frequently at the inner side of the circular groove. In most tests the waterjet kerfs did not overlap completely with the groove produced by the disk, as it appears in figure 9.

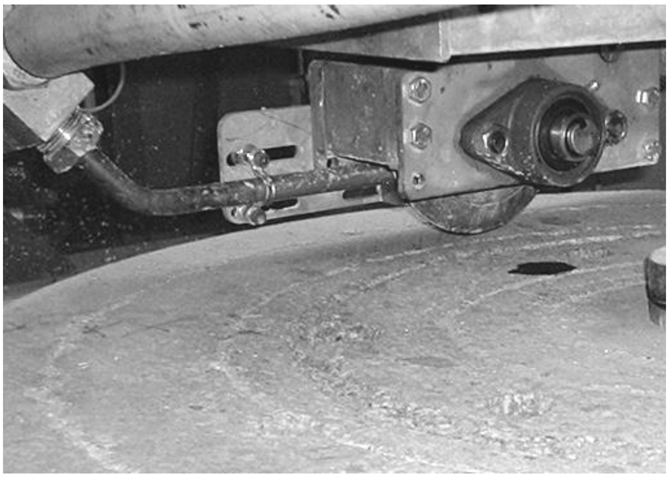

Figure 8. The waterjet-assisted cutting head

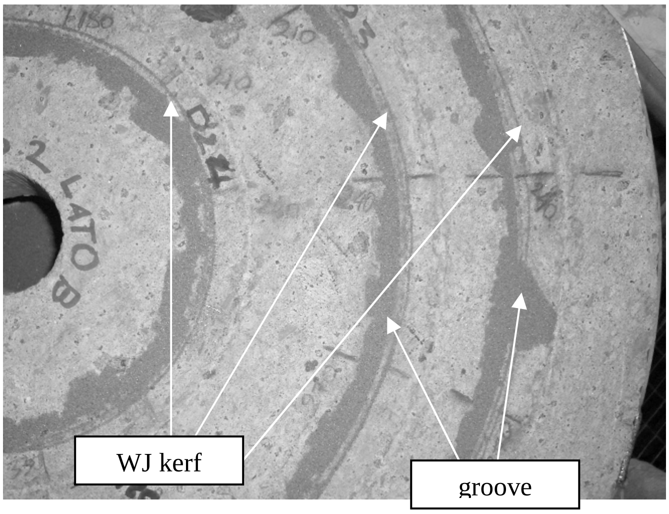

Figure 9. Geometry of the grooves in waterjet-assisted tests

5. RESULTS AND DISCUSSION

5.1. Volume removed per unit length

The experimental results are shown in the curves of figure 10. It appears that:

- the specific volume increases as the radius of the circular path decreases owing to the greater level of stress at the inner side of the groove. The reverse in behaviour with waterjet assistance at the higher rotation speed is difficult-to-explain and may be due to some experimental anomaly, although a similar phenomenon was noticed also in the case of excavation with picks (Ciccu, 2004);
- on doubling the rotation speed (from 30.3 to 60.6 rpm) specific volume is somewhat reduced, as expected;
- the advantage of waterjet assistance, substantiated by an almost threefold increase of specific volume for all the trajectories, is clearly evident. Being the direct contribution of waterjet to material removal quite sensitive to traverse velocity (it drops considerably as velocity increases), the fact that the effect of waterjet assistance is still considerable at the highest traverse velocity within the explored range (0.30 m radius at 60.6 rpm) suggests that the contribution to stress due to the jet impact plays an important role in addition to the weakening of the rock. A flushing action on the plasticized material can also be alleged. Further research is needed in order to confirm this assumption.

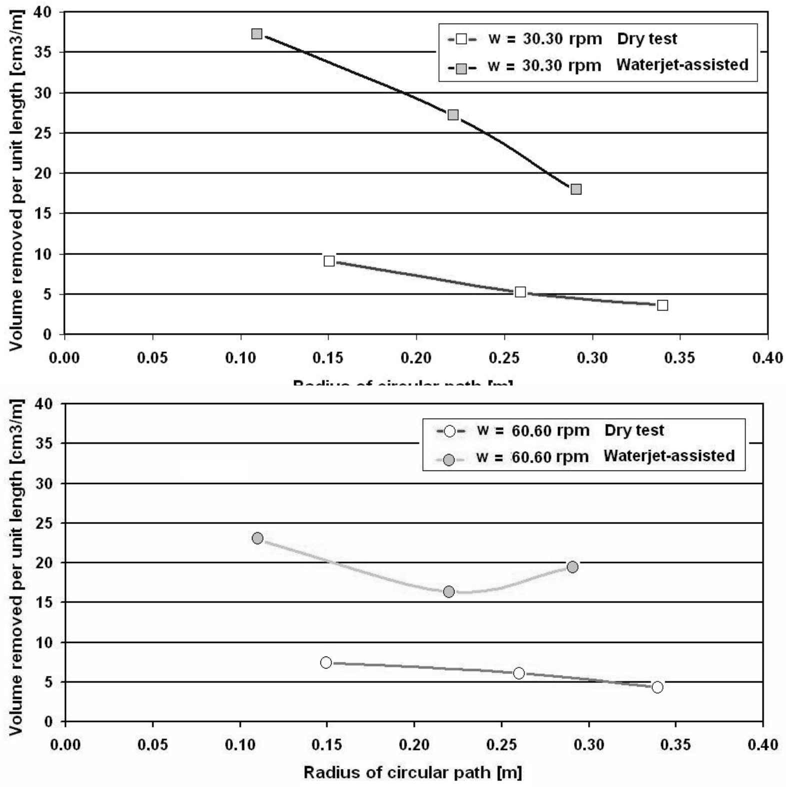

Figure 10. Curves of removed volume per unit length of groove

5.2 Excavation rate

As shown in figure 11, excavation rate is less affected then specific volume by the radius of curvature, owing to the higher peripheral velocity that compensates the fall in specific volume as the radius increases. In the case of waterjet assistance there is even a gain in excavation rate for the larger radius especially for the higher rotation speed.

5.3. Specific Energy

In each test forces have been recorded by means of the data acquisition system enabling to calculate the energy consumed for a full rotation of the sample as the product of the average value of the horizontal force by the length of the groove.

Specific energy was calculated as the ratio of absorbed power (horizontal force F_o·times peripheral velocity V) to the excavation rate:

- Mechanical power $W_m = F_o \cdot V$ [W] or [J/s]
- Excavation rate R_s [cm^3/s]
- Specific Energy (mechanical) $SE_m = W_m / R_s$ [J/cm^3]

To the mechanical energy the hydraulic energy must be added in the case of waterjet assisted tests as follows:

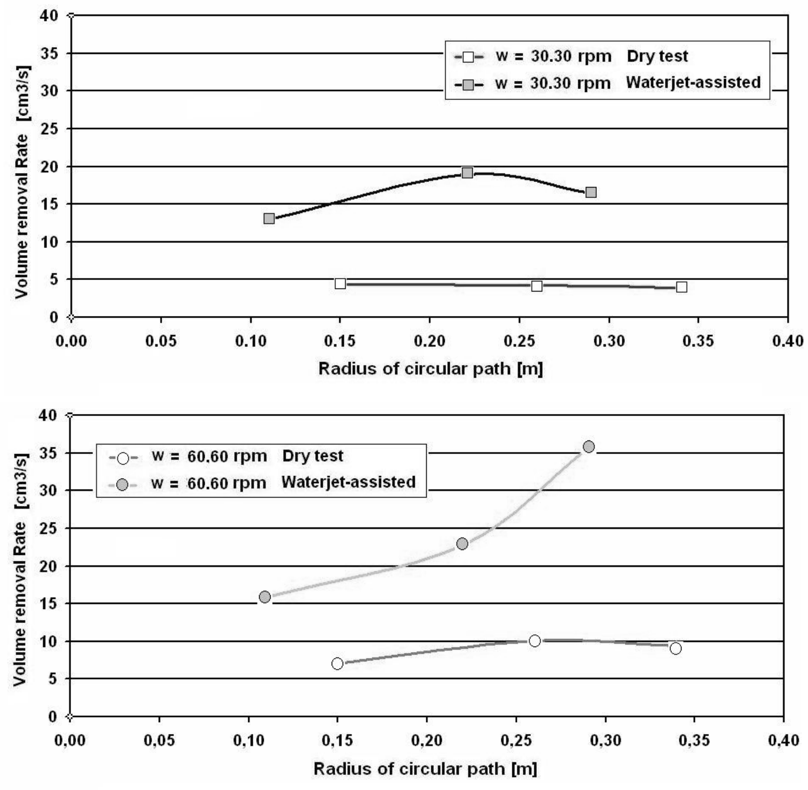

Figure 11.Curves of excavation rate

- Pressure P = 150 MPa
- Water flowrate (for the ϕ = 0.4 mm nozzle used in the tests)
  $Q = 2.6$ l/min $= 0.043 \cdot 10^{-3}$ m^3/s
- Hydraulic power $W_h = Q \cdot P$ = 6,500 W or J/s
- Excavation rate R_s [cm^3/s]
- Specific energy (hydraulic) $SE_h = W_h / R_s$ [J/cm^3]

Specific energy (mechanical and total) is shown in the bar diagrams of figure 12 for the various experimental conditions. Comparing the results of dry and wet tests it appears that, being the force substantially the same in both cases, a considerable reduction of mechanical specific energy with waterjet assisted disks is achieved thanks to the increase in the excavation rate.

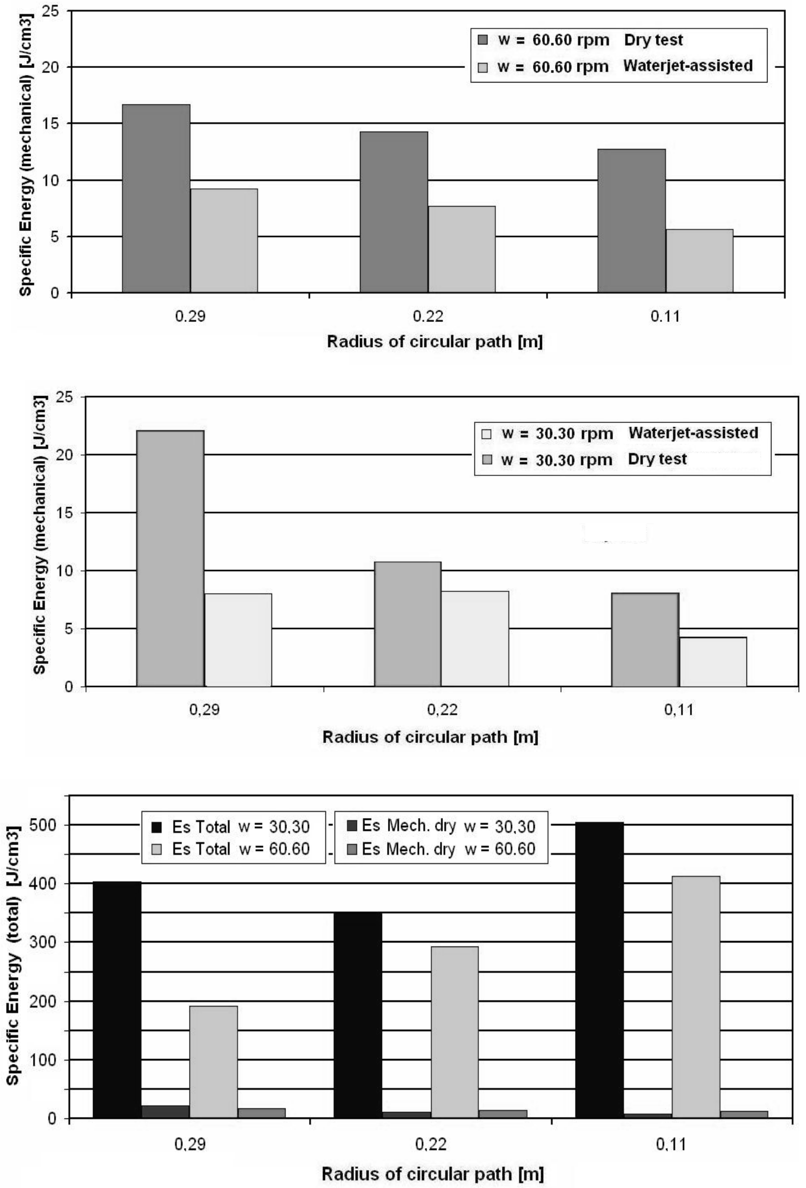

Figure 12. Bar diagrams of specific energy

On the other side, total specific energy is much higher for the wet tests due to the very high power carried by the jet. It is interesting to note that while mechanical energy increases with the radius of curvature, the opposite happens for the total energy at equal rotation speed.

6. CONCLUSIVE REMARKS

It is trivial to say that specific volume depends on penetration depth and on the angle of rupture. Therefore for a given penetration specific volume can be modified only by varying the angle of rupture (geometry of the groove) that however in the case of disks depends chiefly on the strength characteristics of the rock and much less so on penetration. Accordingly, an equal volume of material can be removed through a sequence of small increments or with a single pass reaching the same overall depth.

However the cutting force F_r increases with depth more slowly than specific volume, entailing that specific energy diminishes at increasing penetration. Consequently it is generally more convenient from the point of view of energy consumption to remove the material with a single pass (Roxborough 1985).

It is also worth noting that lifetime of the tools can be correlated to specific energy, making this parameter very important in the economy of mechanical excavation.

The assistance of waterjet provides a very interesting contribution to the solution of the above problem: besides helping in increasing the penetration depth and thence in reducing the mechanical specific energy it provides a considerable cooling action that reduces the wear rate.

The result that waterjet assistance seems to be more efficient for disks than for drag tools is quite intriguing. This may depend on the fact that a jet placed ahead of the pick along the trajectory lays on the same vertical plane as the peripheral velocity and it impinges the rock just at the midpoint of the scale’s front border contributing to the scale formation only at the very moment of detachment.

On the other hand a jet placed at one or both sides of a disk cutter at a distance corresponding to the length of the scale moves along the border of the scale under formation thus contributing to the excavation process almost continuously. Therefore energy is much better exploited in this case.

The application of a high pressure jet of water brings about a considerable increase in total specific energy consumption. However this does not prevent the possibilities of industrial application, since in the overall economic balance of a tunnel excavation energy does not represent a critical issue accounting only for 10 to 20% of total tunnelling cost according to cases.

The possibility of reducing the time needed for completing the work through a faster excavation rate offered by the waterjet assistance is of greater importance since the amount of all fixed cost are proportional to it.

ACKNOWLEDGEMENTS
Work carried out in the frame of a joint research agreement between CNR of Italy and the Academy of Sciences of the Czech Republic.

REFERENCES

Alehossein H and Hood M., *An application of linearised dimensional analysis to rock cutting* in Int J of Rock Mech and Min Sciences 36: 701-709. 1999.

Bringiotti M., *Guida al Tunnelling, L'arte e la tecnica,* ed. PEI, Parma, 1996

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

Fenn O., Brian E., Protheroe And Noel Joughin C., *Enhancement of roller cutting by means of waterjets*. Rapid Tunnelling Conference pag. 341, June 1985.

Farmer, I.W., Glossop, N.H.. *Mechanics of Disc Cutter Penetration,* Tunnels and Tunneling, Vol. 12, No. 622-25, 1980.

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 tunneling tecniques*. 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

Momber A.W., *Waterjet application in costruction engineering,* Balkema, Rotterdam, pp 163-175, 1998.

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.

Ozdemir L., Miller R., Sharp W. *Design and operation of two large scale laboratory rock drilling and boring equipment for water-jet rock cutting reserch*. 2nd U.S. Water Jet Conference, University of Missouri, Rolla,U.S., May 1983.

Roxborough F., Phillips H.R., *Rock Excavation by Disc Cutter,* Int. J. Rock Mechanics & Mining Sciences, Vol. 12, N. 12, 361-366,1975.

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

Savidis G. M., *Fundamental studies on the excavation of rock by button cutter*, ph. D. Thesis of N. S. W., Sydney, Australia, 408. 1982.

Takaoka S., Hayamizu H., Misawa S., *Rock cutting by disc cutters*, Journal of the Mining et metallurgical Institute of Japan, 1968.

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