Türkiye 15 Madencilik Kongresi / 75'* Muıııtj *Congress of Turkey,* Güyagülcr,Ersayuı,Bılgen(eds)© 1997, ISBN 975-395-216-3

UNDERGROUND EXCAVATION USING ADVANCED CUTTING TECHNOLOGIES

A Bortolussı
Mineral Science Study Centre of C N R .Caghan, Italy

R Ciccu
University of Caghan, Department of Geo-engmeenng and Environmental Technologies, Caghan, Italy

B Grosso
University of Caghan, Department of Geo-engineenng and Environmental Technologies, Caghan, Italy

PP Manca
University of Caghan, Department of Geo-engmeenng and Environmental Technologies, Caghan, Italy

ABSTRACT The paper illustrates the most recent achievements regarding the use of advanced rock cutting technologies in stone quarrying and descnbes a possible tunnelling method based on their application Predictable cost figures are given and future prospects outlined with particular reference to tunnelling and cavern excavation m urban environment

1 FOREWORD

Underground excavation for mining or cıvıl engineering works is generally camed out using conventional methods by which the rock is disintegrated into small fragments This concept, although easy to apply, entails however some drawbacks such as a poorly efficient use of energy since part of it is wasted for unwanted fragmentation In addition, the method making use of explosives produces some ımdesıred side effects like vibration, back-break phenomena and unhealthy working environment

On the other side, mechanical excavation can be economically burdensome, especially in the case of hard rocks, due to the high specific energy involved and to the accelerated wear of cutting tools
A new concept based on the removal of the rock in the form of large blocks isolated from the face by means *of* suitably directed cuts can represent an alternative solution capable of overcoming some of the above inconveniences and limitations (Summers, 1985)

The technologies at hand for the practical application of this concept are derived from the experience gained in ornamental stone quarrying (Anonym, 1988, Ciccu, 1994) Sawing with di<imond-based tools is widely used especially for marble and limestone (Pinzan, 1989, I ornaro. 1992), but diamond wire is also suitable for igneous rocks (Bortolussı, 1989), while waterjet slotting is interesting in the case of heterogeneous granular rocks like granite and sandstone (Agus, 1993)

2 OVERVIEW OF PRESENT EXCAVATION TECHNOLOGY

Underground openings for mining or cıvıl engıneenng purposes are created either by explosive blasting or mechanical excavation The choice between the two methods is chiefly dictated by the characteristics of the rock, by the size, shape and depth of the planned space as well as by the location of the work

It is generally retained that rocks are amenable to mechanical excavation if compressive strength is lower than 100-150 MPa pıovıded that abıasıvıty is relatively low (shales, poorly cemented carbonale sandstones, weak or weathered igneous rooks intensively jointed formations) Beyond this hmil explosive blasting remains the only option available
Whole mechanical excavation using road-hcMclus oi full-face boring machines can In. heller cained out il the shape of the tunnel is uttular in cross section <ind its size does not exceed 6 m in diameter In İhı casi. of large caverns, problems arc encountered duc lu a certain rigidity ol both the method and llic equipment

Some adverse conditions may anse as depth below surface increases, eventually causing a slow-down of excavation rate due to rock stressing (Bortolussi, 1996) and putting additional problems of roof support which must closely follow the advancing face

On the other hand, dnll-and-bfast methods are generally more flexible and they can be applied in a wide variety of conditions regarding the kind of rock, as well as the geometry and the depth of the space underground

However the use of explosive should be limited if the work is located in an urban environment or when the rock is too weak and sensitive to back-break phenomena, that would aggravate the problem of roof support

Therefore the most favourable field of application for mechanical excavation is that of medium/small-size tunnels into weak or poorly abrasive rocks in areas sensitive to adverse side effects, whereas blasting is favoured as rock strength increases, becoming mandatory beyond 150 MPa.

In the case of large tunnels or caverns, excavation is carried out in sections starting from a pilot tunnel which is enlarged to include the surrounding compartments, generally using blasting methods.

The fields of application of the two methods are summarised m Table 1.

Table 1 Fields of application of excavation technologies

Technology	EXPLOSIVE BLASTING						MECHANICAL EXCAVATION					
Environment	Urban			Free			Urban			Free		
Rock	S	M	T	S	M	T	S	M	T	S	M	T
Civil engineering												
- *Tunnels*												
Small		x	xx	xx	xx	xxx	xxx	xx	x	xx	x	
Medium		x	xxx	xx	xxx	xxx	xxx	xx		x		
Large	x	xx	xxx	x	xxx	xx	x	x		x		
- Caverns	xx	xx	xxx	x	x	x				x		
Mining												
- Development		x	x	x	xx	xxx	xxx	xx		xxx	x	
- *Production*		x		x	xxx	xxx	xxx	x		xxx	x	

Kind of rock	Tunnel size	Application
S = Soft (σ_c< 80 Mpa)	Small. < 10 m^2	xxx Frequent
M = Medium (σ_c=80-150 Mpa)	Medium 10 to 30 m^2	xx Possible
T = Tough (σ_c>150 Mpa)	Large > 30 m^2	x Rare

At the present state of the art il appears that explosive blasting has no competitor in the case of tough and haid rocks, especially in areas free from constraints

However in urban environment, blasting poses severe problems (vibrations, air blast) especially in the excavation of large openings and therefore alternative technologies would be required A trend is the development of special cutting tools coaled with poly crystalline diamond capable of winning harder and abrasive racks applying larger forces but the search of synergistic effects is also being explored. such as in waterjet-assisted mechanical disintegration (Bortolussi, 1997).

A possible alternative is offered by the novel approach proposed in this paper

3. PROSPECTS OF THE NEW CONCEPT

3 I Outline of the method

Instead of disintegrating the rock into fragments using explosive or mechanical instruments, the new excavation concept consists in the extraction of individual blocks isolated by means of cuts using suitable technologies according to the characteristics of the rock at hand (Ciccu, 1996)

- diamond tools (rock cutter or diamond wire) in the case of medium-soft rocks
- waterjet supported by diamond wire or wedging tools in the case of eruptive rocks like granite or hard sedimentary rocks like tough silica sandstone, for instance

The innovative method can be applied for a variety of tasks, like excavation of tunnels, opening of caverns, dimensional stone quarrying and, in general, digging of a space underground, especially in urban environment where cautious techniques should be employed for avoiding nuisances and damage to the existing structures.

The interest in the method is chiefly in the case of tunnelling operations for which the advantages over traditional methods may be prominent.

From the advancing free face a number of vertical and horizontal slots suitably spaced apart are made into the rock Then the blocks are freed using either diamond wire or wedging devices for the back cut Finally individual blocks are extracted by means of fork lifts or other pulling outfits

The concept applied to the excavation of a tunnel into a granite or limestone rock is illustrated in Figure 1.
All "blind" slots at the face can be opened according to a regular grid, whose geometry is dictated by the size of the blocks to be extracted

The hidden back face parallel to the front can be redeemed either by using flat hydraulic jacks-introduced into the slot or by cutting with diamond wire with the machine placed at one side of the drift as shown in Figure 1, cutting starts from the opposite side until the first vertical row of blocks is extracted, then room is created for placing the idle pulleys sideways, thus allowing the DW cut to be completed. Field experience has shown that granite can be slotted with waterjet at a rate of 2.5 m^2/h using a pump of adequate power (100 kW), pressure being around 220 MPa and flowrate 18 1/min.

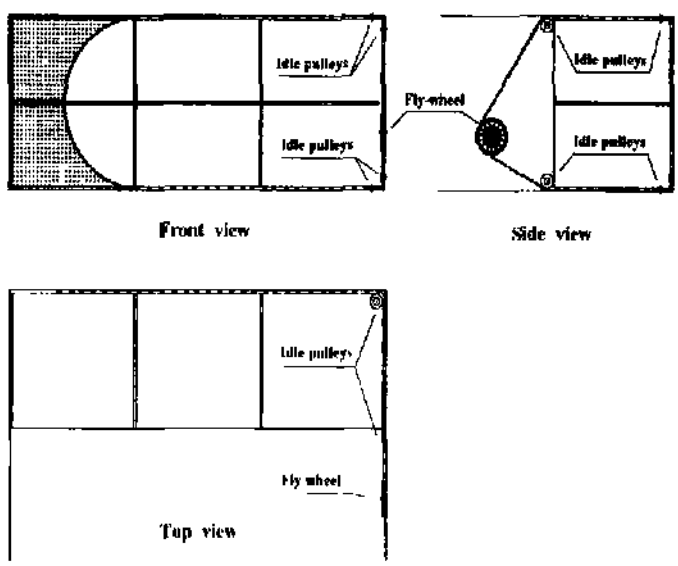

Figure 1 Face slots with waterjel and rear cut with diamond wire sin[1], (granite) w wiib md uilln (Itiiu'.ioitc) in underground tunnelling operation

4 PERFORMANCE OF ADVANCED CUTTING TECHNOLOGIES

4 ! Diamond tools

Today, diamond-based technologies (diamond wire and rock cutter) are extensively used in marble quarrying

Owing to the efTorts devoted to the improvement of the active tool and to the development of the driving equipment, backed by a better scientific knowledge of the cutting mechanism, considerable performance levels are now currently achieved with diamond wire cutting rates as high as 15 m^2/h with tool productivity of the order of 30 m^2/m are now customary with marble in most favourable cases
Being granite rather hard and abrasive, technical results are considerably inferior to those obtained with marble In fact, cutting rate must be limited in order to save the tool, since wear represents a major item in the cutting cost splitting (Bortolussi, 1992)

At the present state of art, wire productivity around 4-6 m^2/m can be attained in granite, provided that cutting rate does not exceed 3-2 m^2/h Results are generally better as quartz content decreases Modern equipment is characterised by high power, up to 60-80 kW

The rock cutter, derived from the machine used in coal and salt mines for face undercutting, provides an efficient technological solution in combination with diamond wire, amenable to a variety of excavation methods, face geometry and quarry configuration, including underground operations Unfortunately, this kind of equipment is not yet suitable for tough and abrasive rocks
Also the rock cutter underwent major developments regarding the structure of the system and the nature of the active elements

Recently, a novel solution has been proposed wherein the carbide-bit chain fitting the swinging-arm hydraulic machine is replaced by a diamond-tipped beli sliding on plastic skids, driven by an electric motor, cooling and lubrication at the contact points ait; suitably assured by water injection through a number of nozzles along the aim periphery This whole-electric, machine is simpler and less expensive due to the absence of hydraulic components but seems lcs>* flexible than the conventional hydraulic counterpart

4 2 Waterjet

Waterjet slotting technology is based on the erosive action of high velocity water jets, generated by means of high pressure pumps
For deep slotting m the quarry, plain waterjet represents the best solution, while waiting for further development of abrasive jets

Different systems have been proposed by a number of American and European manufacturers traversing lances of special design provided with one or more nozzles, either swinging, rotating or oscillating, are used in order to obtain a slot wide enough for further penetration of the cutting head down to the intended kerf bottom

Their efficiency has been tested in the field with very encouraging results to the extent that equipment is now commercially available

Technical results achievable on optimum setting of operational vanables (traverse velocity, rotation speed or oscillation frequency, stand-off distance) are directly related to the hydraulic power (pressure and flowrate) and depend on nozzle configuration

Recent systematic studies using twin oscillating jets have shown that a specific energy m the range of 200-400 MJ/m^2 is required for granite slotting, therefore an input power of at least 120-240 kW would be necessary for achieving a slotting rate of 2 m7h, adequate for the industrial acceptability of the technology

From the economical point of view, the incidence of energy on running cost is predominant, whereas no??le wear is subordinate Waterjet has the potential to compete economically against traditional technologies in granite quarrying, especially flame loi clung and conlinuous dulling, ptovided that specific erieigy is reasonably low

5 ECONOMIC ASSESSMENT

As shown above, explosive billing predominates in the excavation of tunnels into hard and ablative rocks exceeding 150 MI'a in compressive strength Only the new concept illustrated line tan be in the future a possible alternative to it, unless further progress is made concerning the development of new high-peiforiiidiice tools loi mechanical excavation On the olhei hand the slot and draw method tan compete with both explosive blasting and mechanical excavation in the case of medium-soft rocks also from the economic point of view

Being it difficult to assess the tunnelling cost with mechanical excavation, which depends very much on the kind of machine used as well as on operating conditions, the viability of the new option is here discussed with reference to explosive blasting only

Based on performance data and cost figures offered by the stone quarrying experience the two methods are compared on technical and economic grounds with reference to the case of a tunnel excavation into granite and limestone

5 1 Case study

The case taken into consideration is the excavation of a tunnel having a 36 m* square cross section Comparison is made on the basis of the time needed and to the cost per unit length Results of the analysis are illustrated here below

5 I 1 Explosive blasting

Drilling and blasting have been designed on the basis of field data according to the most recent experience of tunnel excavation in modern mines

The main parameters of the round are given here below

- Drilling machine Twin-boom hydraulic jumbo
- Blast-hole diameter 48 mm
- Number of holes per blast 76
- Specific drilling 2 ! m/rn'
- Kind oi explosive dynamite profil X
  Charge per hole 1 9 kg 1 I kg
- I otal *chdrgc* 84 kg 36 kg
- Yield per blast hole I 42 m'
  Specific charging 1 1 kg/m

") 1 2 Block removal method (slot-and-draw)

The basic concept has already been described in paragraph 1 I

Il ıs clear that consideiable advantages can bt ddiuvtd in terms of lime and cost bv increasing I he size of individual blocks and thence reducing the number of slots However bigger blocks pose increasing problems of extraction and transportation It is assumed that common high-power machines (front loader equipped with fork lift) are able to handle blocks up to 2S tonnes by weight ı e 2 0 x I 5 x 3 0 m* by volume

Since there is interest in making the slots as deep as possible in order to increase the advance rate by reducing the overall idle time, the blocks should be positioned with their longer edge perpendicular to the face

Accordingly the geometric features of the slotting work are the following

- Inclination of the top slot +5 %
- Inclination of the base slot -10%
- Overall length of the slots at the face *>4 m
- Average slotting depth 3 m
- Total cut surface area 162 m^2
- Average slot width S cm
- Number of blocks extracted 12

5 2 Technical achievements

Of course, results depend chiefly on drilling and slotting rate achievable which in turn is influenced by the kind of rock at hand Drilling and slotting rates also depend on the type and power of the equipment Basic assumptions for calculations, derived from the field experience, are reported in Table 2,3,4, and 5

6 DISCUSSION

6 1 Technical comparison

I rum the technical point or view it is cleai that traditional method is *faster and* simpler In fact *a* full round can be carried out in one shift since drilling and blasting takes about 4 hours leaving enough time loi hımes exhaust with forced ventilation and foi rubble mucking using a front end loader

II root support is not necessary this means an advance laie ol 6 m per day with a 2 shift per day working schedule

Table 2 Basic cost figures for slotting [USÎ/h]

ROCK	Limestone					Granite				
COST ITEMS	MP	En	Co	De.	Total	MP	En	Co	be	Total
Diamond wire	10 29*	1175	99 71	6 25	128 00	10 29*	12 35	85 9	6 25	114 5
Rock cutter	20.58	14.10	63 60	7 87	106 15					
Waterjet(lOOkW)			'			10.29*	28 20	15 75	37 50	91,74
Watenet (200 kWl						10 29*	56 40	23 63	45 00	135 34

* Attendance time shared with other operations (50%)

Table 3 Slotting rate [rrr/h] and unit cost figures [US$/m²] assumed for calculations

ROCK	Slotting rate Limestone	Slotting rate Granite	Unit cost Limestone	P5.'lcost_ Granite
Diamond wire	100	25	128	45 8
Rock cutter	80		13 3	
Waterjet (100 kW)		2 1		43.7
Watenet (200 kW)		42		32.2

Table 4 Basic cost figures for drilling (including explosive charge) [US$/m]

COST FIGURES	UNIT COSTS	AMOUNT		OVERALL COSTS PER ROUND (USS/round)		OVERALL COSTS PER METRE OF TUNNEL (USS/m)	
		Granite	Limestone	Granite	Limestone	Granite	Limestone
Depreciation	94 117 USS/li	1 7 h/vol	I 4 h/vol	16(1 00	H I 76	5111	4.192
Man Power	2J529US$/h*	1 mcn-4 2 11	3 men-1 9 h	296 47	275 29	98 82	9176
Energy. (1 2%)				24 69		8.2.1	7 19
Cons. (10,1%)				211.77		77 92	68 08
Mai nie nan (16 5%)				127 10		42 41	17 07
Fxplosive 1	2 65 USS/kg	«4kn	84 kg	222 1$!	222 15	74 12	74.12
Explosive *2*	5 29 USS/kg	¥,kj.	If, kg	190 59	190 59	61 51	61 51
Dcioiiaior	I 18USS	76	76	89 41	X9 41	29 Sil	29 8(1
Overall Cost				1144 12	1246 46	448 2 i	41S 48

Table 5 Cycle time per 3 m advance (including 25% idle time) and overall cost figures (US$ per rm-tri' of tunnel) with the two alternative technologies Block removal and mucking are not considered

ROCK	Limestone	Limestone	Giamte	Granite
METHOD	TIME|h|	COS'I [USS/m]	.....riMi-[M	COST[US$/rn|
Dnll-and-blast	39	41 S 48	42	448 21
Slot-and-draw	25.2 + 4 5 - 29 7	718 t 160 - 878	48 2 M8 0 66 2	1.739 4 549 - 2.288

Ott the other hand, shear-and-draw method is much slower even in the case of limestone, due >o the amount of slotting work required On the other hand, block removal by means of a fork lift machine may be somewhat faster than mucking the blasted material More than three shifts would be necessary for achieving an elementary advance of 3 m in limestone and as much as 8 shifts tn granite

This time can be reduced if blocks are cleared by shearing their back face by means of hydraulic jacks introduced into the slots at the face, instead of using diamond wire

6 2 Economic comparison

Also from the economical point of view, the traditional method appears clearly superior since the excavation cost per metre of advance is lower, although a 20% saving in operational cost can be achieved with the new method sf diamond wire cutting is replaced by jack shearing
However, while in the case of granite the difference remains considerable and cannot be substantially reduced as a result of some expected improvement in the slotting operation, the cost for easier-to-slot limestone is not much higher than that with dnll-and-blast and therefore the new method can become competitive, challenging conventional mechanical excavation for tunnelling into medium-soft rocks
In the economic evaluation of a tunnelling project, it should be taken into account that excavation is a generally a minor part of the total cost, being often overwhelmed by other items such as mucking, roof support, general services, maintenance, ventilation and water drainage, overhead expenses I herefore the higher buiden of pure excavation is considerably diluted m the overall economy of the proiect, giving relevance (o other advantages that may become prominent in particular situations

6 1 Advantages of the new method

In spite of the fact thai tradılıonaJ method predominates in normal situations, there may he mslances where restrictions must be applied to the use of rude methods of excavation, as in uilun environment or in presence of particularly sensitive rocks

In ilwse cases the advantages of using (.aillions methods may even outweigh the mue uoııomu aspects

Among the advantages offered by the new method, the following are worth mentioning

- Absence of vibrations that can endanger the structures within the area of influence of the blast,
- reduced roof support requirements due to the lack of back-break phenomena,
- better surface smoothness of the tunnel walls
possibility of using the blocks as a building material

fcxeept for the last one, the above advantages can also be attained with the concept of a mixed method of excavation by which slotting technologies (rock cutter for limestone and waterjet for granite and similar rocks) are used for driving a relief slot at the tunnel contour, while the mass of rock is blasted according to the conventional method

In this way the benefits of cautious excavation can be pursued in most cases without incurring m an intolerable increase in cost

7 CONCLUSIONS

In underground works conventional technologies (dnll-and-blasl in case of medium-hard rocks and mechanical excavation in the case of medium-soft rocks) are capable of solving a large variety of problems commonly encountered in the engineering practice

The study here illustrated shows that the new concept described in the paper, consisting m slotting and block removal, although technically feasible, is not generally applicable due to its inherent limitations making excavation rate too slow and cost considerably high especially for hard rocks

However, there are instances where the method can be take« ml« consideration as an alternative option, whenever cautious excavation is icquired m order to avoid damage ctnd disturbances pioduced by the ruder counterparts

I he new method approaches the cost level of tiadrtion.tl competitor only in the case of soil locks m wlui.li diamond based technologies are highly efficient

\s tor Udlerjet slotfini' in p,m<U* is still too slow and too Lxpensivt al lin. piesenl slate ol art and ils application is piohlalilt <>n)\ for (lirncnsioii.il slont S|UIUV»IIK l U w u tht H i. ,i t ast in vi laken tnio consideration m this paper, where the slot-and-draw method using waterjet can be superior, that of quartz sandstone which can be cut with at particularly high rate (even 15 m^3/h), whereas conventfonal percussion drilling and mechanical excavation can be very expensive due to an exceptionally high tool wear

ACKNOWLEDGEMENTS

The prospects of advanced cutting technologies are here assessed on the basis of the results of ongoing research being carried out at the University of Caglian within the programmes of MURST and CNR, availing of the support of EMSa

REFERENCES

Agus M , Bortolusst A , Ciccu R , Kim W M , Manca P P. 1993 *"The influence of rock properties on waterjet performance"* Proc. 7th American Water Jet Conference, Seattle, pp.427-442

Anonym. 1988, " *Carrière de Rothbach (Bas-Rhin): Découpage du grès avec des jets deau* ", Industrie Minérale-Mines et Carrières, N 10

Bortolussi A, Ciccu R, Manca P P , Bosu M , V.Tgiu A 1996, " *Influence stressing state m rock slt ttmg with waterjet",* Proc. Geomechamcs '96, 0 rava, (m print)

Boıtolussı A, Ciccu R, Manca P P , Massacci G I9( ) *"Simulation and optimization of rock cutting with diamond wire",* Proc 22nd AP Com, Berlin, pp 63-176

Borf ïlussi A., Ciccu R., Manca P P,Massacci G] 9 >2 *"Industrial viability of soft technologies for hard stone quaiiying",* Proc XVth World Mining Congıess, Madrıd.pp S33-542

Ciccu H Manca I' *V,* 1994 " *Energy requirements m mode • slum- ÜI/OSTH-S"' ,* Proc 3rd Jm Symp on M mi; \ *'nmunti una* lquipmenl selection, İstanbul, pp 111-!' -

Ciccu i , I'i am m in glu A 1996 *"Quarrying grumte underg, mud is now feasible with waterjet",* hoc 1 ilh mia national Conference on .Idling *Tcchm»* >#y Caglian, pp 441-453

Pinzan vi I989 *"Ui colUvazıoııe deı taptdei carbonu. ci",* Pioc Conv Int sir Silua/mnc e prospettıve detl'industna lapidea, Caglian, pp 127-145

Fornaro M., Mancmi R, Pelizza S, Stragiotti L 1992, " *Underground production of marble in Italy. Technology, economy and environmental constraints",* Proc XVth World Mining Congress, Madrid, pp 573-582

Summers D.A 1985 *"A review of water jet excavation research",* 26th US Symp on Rock Mechanics, Rapid City, pp 895-903.

Bortolussi A., Ciccu R, Grosso B , Ortu G , Vasek J. 1997 " *Waterjet-assisted hard rock breakage with cutting tools".* Fourth International Symposium on Mine Mechanization and Automation, Brisbane, Australia (rn print)