AITES-ITA 2001 World Tunnel Congress

ASSOCIATION INTERNATIONALE DES TRAVAUX EN SOUTERRAIN
AITES

ITA
INTERNATIONAL TUNNELLING ASSOCIATION

PROGRESS IN TUNNELLING AFTER 2000

***Milano*, June 10 - 13, 2001**

REPRINTS

Società Italiana Gallerie

Swiss Tunnelling Society

PÀTRON EDITORE
BOLOGNA

A COMPARISON BETWEEN TBM ADVANCEMENTS IN HORIZONTAL AND UP-HILL TUNNELS

S. FUOCO
Soil Water Structures, Eng. Services, Trento, Italy

P. ORESTE
Technical University of Turin, Italy

ABSTRACT: Nowadays high levels of experience have been acquired in the excavation of horizontal tunnels using TBM, especially as far as tunnels with small diameters (about 4 m wide) are concerned. Less experience has been acquired in the excavation of tunnels under difficult alignment conditions, as in the case of steeply inclined excavations (up-hill tunnels). This paper presents the results of studies which compare the production data collected for tunnels excavated with TBM in "normal" conditions (horizontal tunnel), with those derived from steeply inclined excavations (up-hill tunnels).

1. INTRODUCTION

As known, the productivity of an excavation system with full section machines, called Tunnel Boring Machines (TBM), is conditioned by a series of factors that reduce, sometimes quite drastically, the potentiality of the system itself. The majority of these factors affect the theoretically obtainable productivity of the system in a much more pronounced manner if the altimetric trend of the tunnel that has to be excavated exceeds such inclinations that it is necessary to request the use of auxiliary equipment that allows operation under safe conditions or where it is necessary to back-install a precasted lining that acts as a contrast element and this occurs when one proceeds in the so-called up-hill excavation.

This work illustrates the results of a comparative analysis between the productions of tunnels excavated with TBMs with sub-horizontal axis and those obtained in the case of up-hill tunnels. The purpose of this comparison is that of supplying indications on the real productivity of the excavation system using TBMs for altimetric situations similar to those that have been examined.

2. FACTORS THAT INFLUENCE THE POTENTIAL PRODUCTIVITY

The mean speed of advancement of a TBM is remarkably lower than the net advancement speed that the machine presents during the excavation stage. The first is usually measured in m/days and from necessity takes into consideration the stopping times of the machine due to the installation of the supports, maintenance, the change of tools, the change of shifts and the waiting times associated to the transport system of the mucked material.

In short, the factors that can influence the productivity of an excavation system can be grouped into the following three groups:

- TBM characteristics and its back-up system;
- problems connected to the characteristics of the rock mass which has to be excavated;
- problems connected to the site organisation.

The drops in productivity due to the *regripping* that is necessary with the advancement of the machines and the back-up can be included within the group inherent to the TBM characteristics and its back-up system, as can those due to the *normal and extraordinary maintenance* of the system and those due to an inadequate *"power" of the excavation machine* for the mechanical strength parameters of the rock mass. For each type of rock there is in fact a critical thrust force on the tool and an optimal force connected to the lowest waste of specific energy (fig.1): the thrust force should fall between these two values otherwise the head will work in anomalous conditions that could cause damage to the tools and slow down the advancement. In the group relative to the problems arising from the geological and geomechanical structure, the problems connected to the *installation of a support system of the tunnel* can be considered as can those relative to the *exchange of the cutters* caused by the wear or support breakage, to the local *alteration and fracturing degree* of the rock mass and to the *existing hydrogeological structure.* Finally the problems deriving from the adopted *mucking system*, the *shift changes of the workers* and of the *impositions of a contractual nature*, as for example, the carrying out of investigations at the face during advancement, can all be included in the group relative to the lowering of productivity connected to the site organisation.

The set of these factors, some of which are inevitable in that they are intrinsically necessary to the TBM advancement, can reduce the time potentially dedicated to excavation to a great extent and therefore also the efficiency of the system.

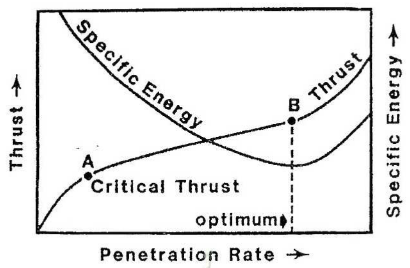


Figure 1. Ratio between the thrust force at the head or the specific excavation energy and the net velocity of advancement of the TBM.

3. PRINCIPAL DIFFERENCES BETWEEN HORIZONTAL EXCAVATION AND UP-HILL EXCAVATION

In "normal" altimetric conditions the cycle that characterises the mechanised excavation with TBMs basically consists of two stages: the real excavation, which is possible up to the end of the jack length, and the recall of the machine head support elements and of the back-up (regripping) during which the excavation operations are interrupted. An exception to this is represented by the double shield machines for which, if the installation of supports behind the machine is associated to the excavation operation, the excavation phase can occur continuously without the regripping operations influencing the production to any great extent.

When up-hill excavating, in the case of open TBMs, it is necessary to equip the excavation system with means that allows regripping of the machines in safe conditions. This can be obtained by arranging a double system of grippers. The added grippers, which make up the "fall preventer device" (figure 2), support the entire weight of the machine and allow the excavation to be performed in safe conditions. Their action allow the TBM grippers to act as exclusive contrast for the advancement, as happens for TBMs in excavation operations with horizontal altimetric axis (figure 2).

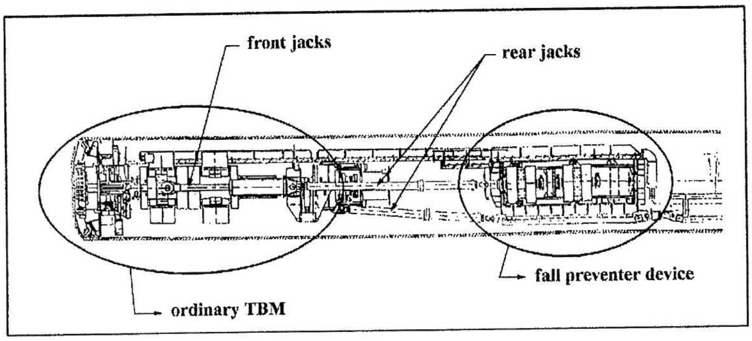


Figure 2. Typical configuration of open TBMs equipped for up-hill excavation.

A remarkable force should be applied overall from the grippers of the fall preventer device on the tunnel walls to contrast the weight of the machine. In some cases, when the rock mass appears fractured with low persistence discontinuities, problems can occur due to the detachment of rock blocks from the walls (figure 3).

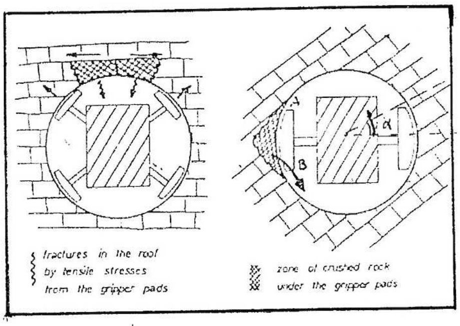


Figure 3. Problems relative to the application of remarkable contrast forces on the tunnel wall, by the fall preventer gripper device.

Another significant difference from the horizontal excavation system is constituted by the movement of personnel and supply materials. In up-hill excavation the system is endowed with winches and cable hauling bogies which are much slower than the vehicles used in horizontal excavation. On the other hand, the mucking can occur more quickly as it is possible to arrange the site for the gravity dumping of the excavated materials in the case of up-hill excavation.

When a collapse occurs, due to the presence of an unforeseen fault of material of poor geotechnical characteristics, which involves the area close to the excavation face, the lateral grippers are also given the task of supporting the weight of the portion of collapsed rock, and the operations of re-establishing stability in the area are more difficult and longer (figure 4) (Bethaz et al., 2000).

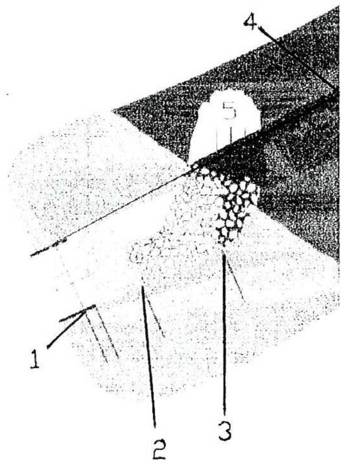


Figure 4. An example of collapse of poor geomechanical quality material ahead of the TBM head: difficult condition for re-establishing stability in the area through remedial works. Key: 1) support panels; 2) cutterhead position during execution of remedial works; 3) cutterhead position during the roof instability; 4) execution of grouted steel bars in the roof area; 5) instability area (Bethaz et al., 2000).

4. DATA RELATIVE TO HORIZONTAL AND UP-HILL EXCAVATIONS

The available data relative to production obtained in the excavation with TBMs of tunnels with diameters between 3.2 and 4.7 m, with sub-horizontal and up-hill axis, are here given.

4.1 Data relative to up-hill excavations

The main characteristics of the examined cases are given in table 1.

It can be seen how the open machines have mainly worked inside massive formations while shielded or double shielded machines were used for relatively worse formations. From the qualitative point of view, with reference to the Bieniaski RMR classification, according to SIA regulations or O-Norm 2203, which was the reference classifications used in the cited cases, it can be indicated that the formations crossed by the open TBMs could be classified as good or very good quality masses (RMR Class I or II and equivalents) for percentages between 70 and 90 %, with uniaxial compression strength of the rock matrixes that vary from a minimum of 50 MPa for the fine schists to a maximum of 300 MPa for the amphiboles. The mean of the later falls between 100 and 120 MPa. In the case of shielded TBMs, no classes of greater reference are available; the uniaxial compression strength of the matrixes involved in the excavation fall around 25 MPa.

The mean production expressed in metres of excavation, referring to daytime production (therefore including all the factors that have constrained the values) are shown in table 2. The trend of advancement obtained for the examined cases are shown in figure 5, when available.

Table1. Main characteristics of the analysed up-hill excavations.

Project	*L (m)*	*P (%)*	*TBM Model*	*D (m)*	*Prevalent rock mass*
Maen	1750	24÷35	Open	4.2	Calceschists; Meta-gabbros; Meta-basites; Serpentinites; Schists
Cogolo	500	42	Open	3.9	Paragneiss; M.pegmatites; Schists; Anphibolites (presence)
Metro Alpine	1580	17÷48	Open	4.2	Serpentinites; Anphibolites; Prasinites e Chloritoschists
Zermatt Sunnegga	1700	36÷63	Open	3.7	Anphibolites; Prasinites; Chloritoschists; Calceschists
Clauson Dixence Tratto F8-F6	1600	68	Double shielded	4.7	Alternance of schists, sandstones and carboniferous slates; Dolomitic limestones
Clauson Dixence Tratto F6-F5	700	15÷64	Double shielded	4.7	Alternance of schists, sandstones and carboniferous slates; Anidrites
Clauson Dixence Tratto F5-Verruccano	450	68	Shielded	4.4	Alternance of quartzites and limestones; carboniferous schists
Silz	1995	80	Open	3.2	Schists, gneiss; mica-schists

Key: L: Tunnel length (approximate); P: Inclination; D: Tunnel diameter

From an examination of the table it can be noticed how there are significantly different efficiencies, while, with the exception of two cases, the mean global production falls around values between 2.5 and 4.9 m/day. It is also possible to notice that the difference between the mean daily productions and the maximum ones are higher for the open machines than for the shielded ones.

This aspect should be compared with the influence that the characteristics of the rock mass have on the open machines and on the shielded ones; these last allow productions that are less influenced by the geomechanical characteristics of the rock mass. It should be underlined that in the case of Clauson Dixence, the rock mass appears on average of a lower quality than the mass excavated with open TBMs.

The inclination of the tunnel also appears to play a certain role in the reduction of the net speed of advancement.

4.2 Data relative to horizontal excavations

The main characteristics of the examined cases are given in table 3. These are only limited to tunnel excavation with open TBMs and slopes for which it has not proved necessary to make use of machines equipped with fall preventer systems.

Qualitatively speaking, with reference to the previously mentioned classifications, it can be stated that the formations crossed by the open TBMs can be classified, with the exception of case 2, as masses of discrete-good quality (Classes II or III according to the Bieniawski or equivalent classifications) for overall length percentages of between 60 and 70 %, with uniaxial compression strength of the rock matrixes that vary between a minimum of 20-30 MPa for fine sedimentary rocks to a maximum of 120-130 MPa for metamorphic rocks.

Table 2. Productions obtained for up-hill excavations.

Project	*TBM Model*	*D (m)*	*AGDP (m/g)*	*MDP (m/g)*	*Efficiency (%)*
Maen	Open	4.2	4.2	30.0	16
Cogolo	Open	3.9	3.0	24.0	11
Metro Alpine	Open	4.2	3.1	19.6	33
Zermatt Sunnegga	Aperta	3.7	2.5	18.3	50
Clauson Dixence Tratto F8-F6	Double shielded	4.7	2.7	14.4	7
Clauson Dixence Tratto F6-F5	Double shielded	4.7	7.0	17.2	16
Clauson Dixence Tratto F5-Verruccano	Shielded	4.4	4.9	12.3	23
Silz	Open	3.2	11	-	30÷39 (*)

Key: D: Tunnel diameter; AGDP: Average global daily production; MDP: Maximum daily production; Efficiency: Ratio between real time spent on the excavation and the potential excavation time; (*) as a function of the rock mass type.

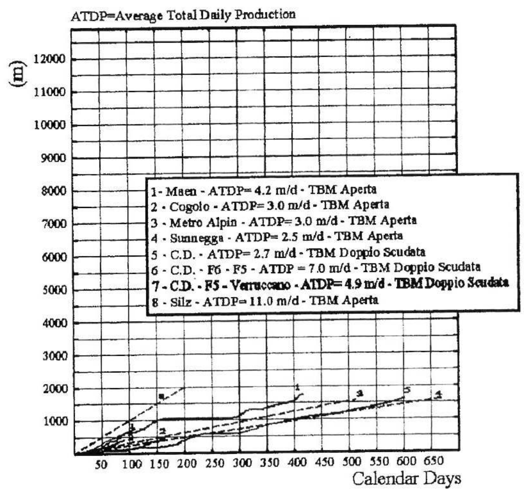


Figure 5. Total productions obtained in the up-hill excavations.

The mean productions expressed in excavation metres per day, referring to daytime production, are given in table 4. The trend of the advancement obtained in the examined cases is given in figure 6a, when available.

The data shown in the table bring to light the extreme variability of the global production. From a first examination of the causes of this variability, a close connection has been deduced between the characteristics of the excavated rock mass and in particular for the geomechanical quality of the rock mass and with the presence of poor rock, from the geomechanical point of view, or of peculiar areas such as, for example, those with the presence of gas.

Table 3. Main characteristics of the analysed horizontal excavations.

Project		*L (m)*	*D (m)*	*Prevalent rock mass*	*Case No°*
Evinos-Mornos (da 0 a 8090 m)		8090	4.2	Triassic limestone, Flysh (sandstone and siltstone)	1
Evinos-Mornos (da 25262 a 29392 m)		4130	4.2	Flysh (sandstone and siltstone)	2
Alassio		2310	3.6	Clayed and limed mudstone	3
Cardano		3070	3.9	Ignimbrite reolitic	4
Val D'arzino		5660	4.5	Siltstone and mudstone	5
Bleu Montain		5940	3.4	Sandstone	6
Prato Isarco		12500	3.5	Ignimbrite, Tuff, fillades	7
Pre Saint Didier	Left Tube	2145	3.9	Calceschists and schists arenaceous, black schists, sandstones	8
Avise	Left Tube	1285	4.5	Fine gneiss and micaschists	9
	Right Tube	2640	4.5		10
Leverogne	Left Tube	1630	3.9	Calceschists, Fine gneiss and Micaschists	11
	Right Tube	1650	3.9		12
Arvier	Left Tube	2360	3.9	Fine gneiss and Micaschists	13
	Right Tube	2355	3.9		14
Villeneuve	Left Tube	2750	3.9	Formation of calceschists and green rocks (ophicalcites)	15
	Right Tube	570	4.7		16
	Right Tube	2200	3.9		17

Key: L: Length of tunnel (approximate); D: Tunnel diameter

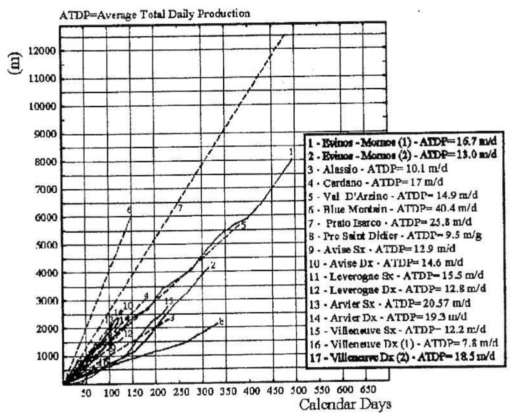
The quality of the rock mass, which conditions the installation of support systems and therefore the consequent stopping times, reduces the productivity of the system in a proportional manner, while the presence of particular areas can lower the global production because of stopping times that are necessary to resolve the problem. It should be underlined that in the examined cases the stops of this kind were always of a modest number (usually one single episode, rarely two). As far as the production is concerned, it has been ascertained that the highest ones correspond to good-very good quality rock masses found in an almost uniform manner along the tract, while the lowest production corresponds to mediocre rock masses associated with one or two stopping episodes to resolve precise cases.

It could be interesting to compare these productions with those obtained in three cases of horizontal excavation carried out using double shielded TBMs, with installation of precasted linings, with comparable diameters. The characteristic data of these 3 cases and the obtained productions are shown in table 5, while the advancement trend is given in figure 6b.

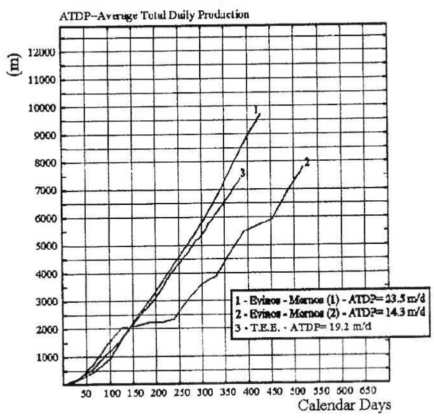
Table 4. Productions obtained for horizontal excavations.

Project		*L (m)*	*D (m)*	*AGDP (m/g)*	*MDP (m/g)*	*Efficiency (%)*
Evinos-Mornos (da 0 a 8090 m)		8090	4.2	16.3	53	28
Evinos-Mornos (da 25262 a 29392 m)		4130	4.2	13.2	42	19
Alassio		2310	3.6	11.7	53	24
Cardano		3070	3.9	17.0	51	43
Val D'arzino		5660	4.5	15.0	90	26
Bleu Montain		5940	3.4	40.4	173	-
Prato Isarco		12500	3.5	25.8	78	-
Pre Saint Didier	Left Tube	2145	3.9	9.50	59	30-40
Avise	Left Tube	1285	4.5	14.6	47	34
	Right Tube	2640	4.5	12.9	66	-
Leverogne	Left Tube	1630	3.9	13.2	62	50-60
	Right Tube	1650	3.9	15.7	55	60
Arvier	Left Tube	2360	3.9	19.1	40	58
	Right Tube	2355	3.9	20.4	49	61
Villeneuve	Left Tube	2750	3.9	7.8	17	30-40
	Right Tube	570	4.7	18.5	53	40-50
	Right Tube	2200	3.9	12.2	59	32

Key: D: Diameter; L: Length; AGDP: Average global daily production; MDP: Maximum daily production; Efficiency: Ratio between the real time spent for excavation and potential excavation time.



a)



b)

Figure 6. Total production obtained in the horizontal excavations with open TBMs (a) and double shielded TBMs (b).

It should be considered that the Evinos-Mornos project the excavation was performed inside rock masses prevalently between the class III and IV and mean uniaxial compression strength of the intact rock between 60 and 80 MPa, while the T.E.E. project was obtained excavating a tunnel inside a rock mass of prevalently class II and III, with mean uniaxial compression strength of the order of 150 MPa.

Table 5. Main characteristics and productions for three excavation cases using double shielded TBMs.

Project	*L (m)*	*D (m)*	*Prevalent rock masses*	*AGDP (m/g)*	*MDP (m/g)*	*Efficiency (%)*
Evinos-Mornos (da 8090 a 17790m)	9700	4.0	Flysh (sandstone and siltstone)	22.7	60.0	40 (*)
Evinos-Mornos (da 17790 a 25260 m)	7310	4.0	Flysh (sandstone and siltstone), Triassic limestone	13.8	50.0	40 (*)
Tolo Effluent Export (T.E.E.)	7470	3.6	Granite	19.2	43.0	35 (*)
Key: (*) for rock mass classes (Bieniawski classification) from I to III						

5. COMPARISON BETWEEN PRODUCTION OBTAINED IN HORIZONTAL AND UP-HILL EXCAVATIONS AND FINAL CONCLUSIONS

From an examination of the results obtained in the studied cases a net difference appears evident in terms of productivity between horizontal and up-hill excavations. The production fields of variability registered in the examined cases are shown in figure 7. AS foreseen, in the horizontal excavations the variability in the global production is extremely high. In the examined cases it varies between 7.8 m/day and 40.4 m/day and is closely connected to the average geomechanical quality of the rock mass. Only in some cases did the resolving of an incident (that is, concentrated stopping time) lead to an important reduction of the mean global production. In general, the higher limit of this field of variability is correlated to good-optimal quality rock masses; on the other hand, the values close to the lower limit are correlated to rock masses of mediocre quality. Inside this field of variability, the production obtained with double shielded TBMs, supported by the installation of precasted linings, can be found, (at least for the three examined cases) in an intermediate position with global production between 13.8 and 22.7 m/d. This allows one to confirm what has already been indicated by various authors in merit of a lower susceptibility of the advancement of this kind of TBM to the quality of the rock mass involved in the excavation. It should be considered that with the placing of the precast lining behind the machine, the shielded TBM can supply a final lining and therefore, strictly speaking, a comparison with open TBMs should be performed also considering, in the global production, the installation of any final supports.

The analysed cases of up-hill excavation highlight a lower variability of the mean global production. The field of production is limited on the upper side by a mean production equal to 11 m/day and on the lower side by a mean production equal to 2.5 m/day.

Inside this field of variability it is not possible to distinguish the benefit of the double shielded TBM on the excavation if not of the implicit benefit in the case of use of precasted linings.

Such net difference between horizontal and up-hill excavation productions can be attributed to the greater burdens of times necessary for the supply of materials and personnel, the regripping operations with fall preventer systems and, in general, the greater difficulties of carrying out ordinary and extraordinary maintenance of the machines in particularly difficult altrimetric conditions. Any incidents, furthermore, require longer times to resolve, therefore contributing to a further diminishing of the mean advancement velocity.

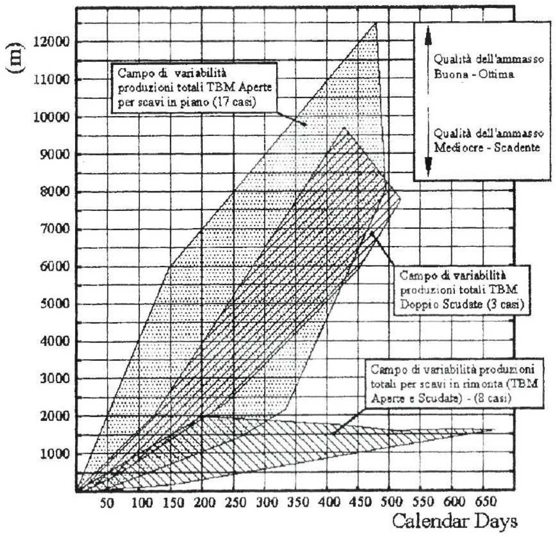


Figure 7. Variability fields of the horizontal and up-hill excavations.

6. REFERENCES

Bethaz E, Fuoco S., Mariani S., Porcari P., Rosazza Bondibene E. (2000). Scavo In Timonta Con Tbm: L'esperienza del cunicolo di Maen, Gallerie e grandi opere sotterranee. N.61, Agosto 2000.

Dolcini G., Fuoco S. & Ribacchi R. (1996) – *Performance of TBMs in complex rock masses.* North American Tunneling '96, Balkema Rotterdam.

Fuoco S.(1994) - *Basi tecniche per la scelta di TBM per ammassi rocciosi collassanti e spingenti* - Master in Ingegneria Ambientale specializzazione in Mechanized Tunneling – (Tesi di Master-non pubblicata).

Grandori R. (1997) – *Progetto Cleuson Dixence – (Svizzera) – Realizzazione di una condotta forzata in galleria di grande lunghezza con pendenza fortemente variabile ed impiego di frese scudate con rivestimenti prefabbricati – confronto produzioni, pregi e difetti dei sistemi adottati.*

Grandori R.(1996) - *La TBM universale alle soglie del 2000. Aspetti tecnici ed imprenditoriali.-Gallerie e grandi opere in sotterraneo-* Novembre 1996 N.50.

Grandori R., Lembo A., Fazio & R. Ribacchi (1994)– Tunneling by double shield TBM in the Hong Kong granite.

Innaurato N., Mancini R. & Peila D. (1996)- *Modello previsionale di comportamento di frese a piena sezione per rocce dure mediante analisi statistica* - Società Italiana Gallerie - 9 febbraio 1996- Giornata di studio.

Innaurato N., Rondena E. Zaninetti A..(1992) Previsioni e riscontri nello scavo con fresa a piena sezione. Quarto ciclo di conferenze di Meccanica ed Ingegneria delle Rocce, Novembre 1992.

Marcheselli P.P. & Morelli S.(1996) - *Nuovi sistemi di meccanizzazione degli scavi in sotterraneo mediante utilizzo di macchine fresatrici a piena sezione* - Società Italiana Gallerie - 9 febbraio 1996- Giornata di studio.

Montanari L.F., Comin C., Nicolini A. Pizzarotti E. M. – *Il cunicolo pilota realizzato con fresa: i suoi riflessi nella progettazione ed esecuzione di gallerie ferroviarie.*

Pignatelli M. (1999) – *Autostrada Montebianco – Aosta. Realizzazione di cunicoli esploratıvi con frese tipo T.B..M. – Potenzialità del mezzo meccanico.* Gallerie e grandi opere sotterranee – n° 57 – Aprile 1999.

Scolari F., Valent G. (1995) - *Criteri di scelta di una fresa per scavo in roccia* - Società Italiana Gallerie - Roma, 22 giugno 1995.