INFRASTRUTTURE VIARIE IN SOTTERRANEO

EXCAVATION METHODS

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SCELTA DEL METODO DI SCAVO

Si intende per **metodo di scavo** l'insieme e successione delle operazioni atte a creare il vuoto corrispondente alla galleria.

Esso si distingue dal **metodo di costruzione** in quanto questo comprende anche le altre operazioni successive allo scavo.
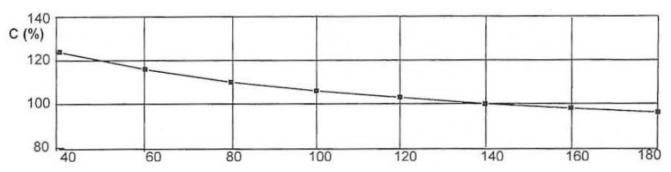
Fondamentalmente per le grandi gallerie la scelta si restringe a decidere se l'abbattimento è eseguito su sezione completa o per fasi (detto questo anche: abbattimento su sezione parzializzata).

La scelta è funzione delle previsioni relative alla stabilità della galleria: a seguito degli studi preliminari, suddivisa la galleria in zone "uniformi" od "omogenee" dal punto di vista geoapplicativo, (per es. in base alle classificazioni) è possibile decidere per lo scavo a sezione piena o per fasi.

Il secondo passo del procedimento consiste nella scelta del metodo in funzione delle condizioni operative riguardanti i mezzi usati per l'abbattimento.

Mentre in passato la scarsa operatività' dei mezzi consigliava spesso l'adozione dello scavo per fasi anche indipendentemente dalle considerazioni di stabilità, oggi la tendenza è di procedere allo scavo su sezione completa quando le condizioni di stabilità lo permettono. Solo al di là di certi valori della superficie trasversale, considerazioni di ordine economico suggeriscono la scelta dell'abbattimento su sezione parzializzata. Anche particolari condizioni operative all'interno di una impresa possono indicare come vantaggioso in determinati casi la scelta dello scavo per fasi.
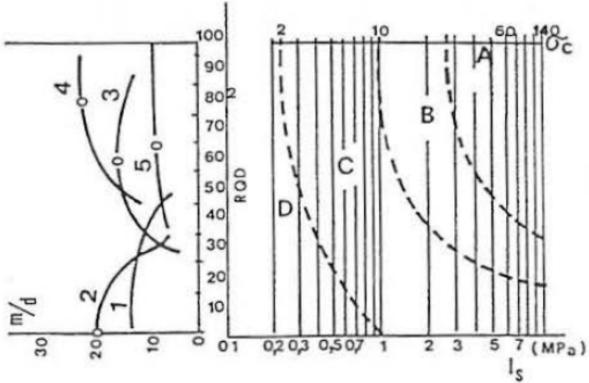
La figura di seguito riportata presenta il costo di scavo in funzione dell'area della superficie trasversale nello scavo per fasi (costo reso eguale a cento nello scavo a piena sezione)

Costo di scavo in funzione dell'area della sezione trasversale di una galleria nello scavo per fasi e nello scavo a piena sezione

Il passo successivo riguarda la scelta dei mezzi. Attualmente sono possibili nello scavo d rocce "dure"' due alternative: lo scavo con l'esplosivo e lo scavo con macchine (frese a attacco localizzato, frese a piena sezione, abbattimento con demolitori ad alta energia d'urto)

A questo proposito è necessario conoscere le caratteristiche di scavabilità della roccia. Nella figura sottoriportata si osservano due diagrammi che indicano i vari campi ai utilizzo dei diversi mezzi di abbattimento e scavo in funzione delle caratteristiche geotecniche della roccia (indicate rispettivamente per mezzo di RQD, Indice di Franklin, resistenza a compressione uniassiale).

Classificazione geotecnica ai fini dello scavo e prestazioni medie dei mezzi di abbattimento.
A destra (da Louis, 1974, modificato):
A: abbattimento con esplosivo e frese piena sezione;
B: frese a piena sezione e frese ad attacco localizzato;
C: frese ad attacco localizzato, demolitori idraulici, pale caricatrici;
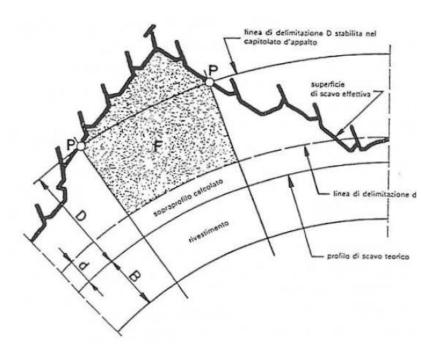D: pale caricatrici.

A sinistra (da Rose, 1985, modificato):
1- pale caricatrici e scudo di protezione;
2- scudo meccanizzato;
3- frese ad attacco localizzato;
4- frese a piena sezione;
5- esplosivo

Un problema particolare è posto nello scavo con esplosivo dall'**extra-profilo**, sempre presente. Questo, che è definito come lo scarto tra la dimensione nominale di scavo e la dimensione reale, è dovuto da un lato al modo di procedere nell'esecuzione dei fori di mina, che comporta per i fori al contorno una certa deviazione dalla direzione longitudinale; dall'altro all'effetto dinamico dell'esplosivo che frattura la roccia al contorno. Tale effetto è di solito maggiore per le rocce naturalmente fratturate o stratificate rispetto a quelle omogenee ed isotrope e di buona qualità geomeccanica.

La figura sotto riportata mostra l'andamento dell'extra-profilo al contorno di una galleria: restando inteso che il profilo interno della galleria è un dato legato alla fruizione dell'opera, che quindi deve essere rispettato nei suoi elementi di progetto, il profilo di scavo può variare tra una posizione limite interna, al di là della quale nessuno spuntone di roccia può sporgere, ad una posizione più esterna, al di là della quale non devono esistere vuoti. I due profili estremi sono determinati in sede di aggiudicazione dei lavori in comune accordo tra il Committente e l'Impresa costruttrice, in rapporto alla qualità della roccia nelle varie zone. Al di fuori dei valori concordati, l'Impresa si impegna a riempire, a proprie spese, i vuoti con materiale appropriato, nel caso di sovra-profilo, oppure a demolire gli spuntoni di roccia interni, nel caso di sotto-profilo. Alcune normative limitano i valori di extra-profilo: per es. la Società Ingegneri ed Architetti Svizzeri fornisce un valore limite di extra-profilo pari a $0,07\sqrt{S}$, ove S è l'area della sezione trasversale, con un valore massimo che in ogni caso non può superare 0,4 m. Per il caso di abbattimento con fresa ad attacco localizzato od in materiale sciolto, lo stesso Ente fornisce un limite di $0,05\sqrt{S}$.

Extra-profilo: B spessore teorico del rivestimento; F superficie determinante per indennizzare il sovra-profilo determinato dalle condizioni geologiche.

L'extra-profilo è funzione del modo di lavorare dell'esplosivo, della precisione della perforazione, della qualità geomeccanica della roccia. L'attuale tecnica di tiro a contorno liscio (*smooth blasting*) è in grado di ridurre la fratturazione indotta al contorno dei fori più periferici; le perforatrici a controllo automatico immesse recentemente sul mercato sono in grado di dar luogo a schemi di tiro assai precisi e pari a quelli di progetto. La qualità della roccia, se scadente, annulla però i vantaggi connessi con ambedue le citate pratiche operative.

La tabella riportata indica schematicamente i requisiti di ciascun mezzo di scavo in rapporto ai fattori del progetto. Per lo scavo con esplosivo si rileva:

1. per quanto riguarda la forma della sezione non vi sono vincoli, ma è generalmente preferibile una forma non circolare;
2. per quanto riguarda l'area non vi sono limiti, se non quelli dettati eventualmente dai problemi geotecnici;
3. non vi sono vincoli in rapporto al tracciato (curve, pendenze) né, alla possibile eterogeneità della roccia lungo il tracciato o del fronte di scavo;
4. non esistono vincoli per quanto riguarda l'adozione dell'avanzamento a piena sezione o per fasi;
5. per quanto riguarda i sostegni, essi sono generalmente richiesti in maggior quantità rispetto allo scavo meccanizzato, ma per contro, possono essere messi a ridosso del fronte;
6. I sicurezza dei cantieri e l'ambiente di lavoro sono talvolta peggiori rispetto allo scavo meccanizzato (rumori, fumi, vibrazioni, polveri);
7. la flessibilità del metodo di scavo con esplosivo risulta elevata, nel senso che si possono cambiare velocemente le condizioni tecnico-organizzative (per es. cambiamento della sezione, passaggio dall'avanzamento sezione completa a quello per fasi etc.);
8. riguardo ai costi, sono ridotti quelli di investimento rispetto allo scavo meccanizzato

FORMA SEZIONE	SCUDO MECCANIZZATO (S.M.).	FRESA P.S.	FRESA A.L. (SENZA SCUDO)	FRESA A.L. (CON SCUDO)	DEMOLITORE IDRAULICO	ESPLOSIVO
Circolare	si	si				Possibile
Non circolare			si	in alcuni casi	si	Si
AREA SEZIONE						Tutte
Piccola	Minitunnel	Si	S>10 m²	Si		Si
Media	Si	Si	si; S<25 m²	Si	Si: >50 m²	Si
Grande	Si	Si	Per fasi	Si: più bracci	Si: per fasi	Si
LUNGHEZZA						
< 1000 m	Si	Con riserva	Si	Si con riserva	Si	Si
> 1000 m	Si	Si	Si	Si	Si	Si
ETEROGENEITÀ' LONGITUD.	Con riserva: scudo a lame; uso piccole cariche esplosivo	Si: fresa scudata	Si: con riserva di potenza e peso	Si: con riserva	Si : con riserva di uso esplosivo	Si.
ETEROGEN. FRONTE		Si (usura utensili)	Si : con riserva (usura utensili)	Come Fresa a.l.	Si: con riserva	Si.
TRACCIATO						
Curve	Grandi raggi	Come S.M.	Si	Come S.M.	Tutte le condizioni	Si
Pendenza	Piccola	Sino a 45° in risalita;sino a 15° in discesa	Sino a 15 ° in salita; con riserva in discesa	Come S.M.	Tutte le condizioni	Si

FORMA SEZIONE	SCUDO MECCANIZZATO (S.M.).	FRESA P.S.	FRESA A.L. (SENZA SCUDO)	FRESA A.L. (CON SCUDO)	DEMOLITORE IDRAULICO	ESPLOSIVO
METODO DI SCAVO						
Sez. completa	Si	Si	si (< 25 m^2)	Più frese	Si (per gallerie medie)	Si (secondo le condiz. statiche)
Per fasi	No	No	Si	No	Si	Si
SOVRAPROFILO	Basso	Basso	Sensibile	Come S.M.	Paragonabile ad esplosivo	Medio-alto
SOSTEGNI	Continui	Ridotti	Ridotti	Come S.M.	Ridotti ma in funzione sovraprofilo	Secondo le condiz. statiche
Posizione Installazione	Entro la macchina	10 m dietro la macchina	A ridosso del fronte	Come S.M.	A ridosso del fronte	A ridosso del fronte

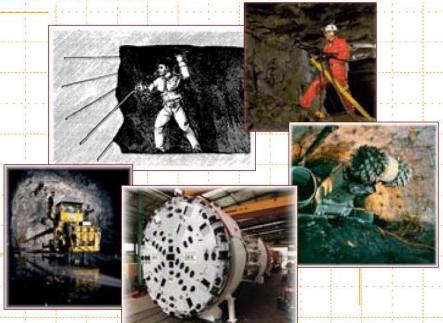|	SCUDO MECCANIZZATO (S.M.).	FRESA P.S.	FRESA A.L. (SENZA SCUDO)	FRESA A.L. (CON SCUDO)	DEMOLITORE IDRAULICO	ESPLOSIVO
Sicurezza dei cantieri	Buone	Secondo le condiz. statiche, con macchina scudata: buone (Temperatura)	Secondo le condiz. statiche; polveri	Polveri e rumori		Media (vibrazioni, polveri, rumori)
TEMPI DI CONSEGNA	9-10 mesi	Come S.M.	2-3 mesi	Come S.M.	Vari	
Montaggio e smontaggio	1 mese (in dipendenza diametro)	1-2 mesi (su piazzale o camera di lancio in sotterraneo)	2 settimane	Come S.M.	Piccolo	
Costo Investimento	Elevato	Elevato	Medio	Da medio ad elevato (secondo Diametro)	Piccolo	Ridotto
Costo Utilizzo	Medio	Medio	Piccolo	Come Fresa a.l.	piccolo	Medio (costo del personale)

The Excavation Process

It is instructive to consider the fundamental objective of the excavation process – which is to remove rock material (either to create an opening or to obtain material for its inherent value). In order to remove part of a rock mass, it is necessary to induce additional fracturing and fragmentation of the rock.
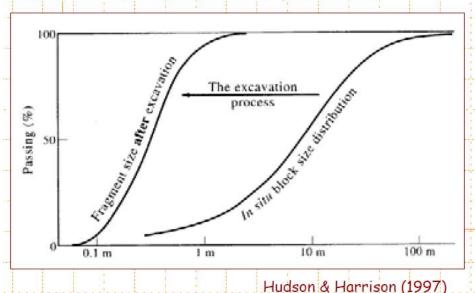
This introduces three critical aspects of excavation:

→ The peak strength of the rock must be exceeded.

→ The *in situ* block size distribution must be changed to the required fragment size distribution.

→ By what means should the required energy be introduced into the rock?

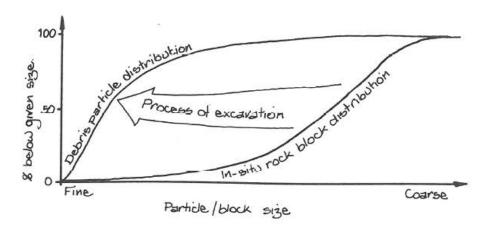# *In Situ* Block and Fragmentation Distribution

Rock is naturally fractured and consists of rock blocks of certain sizes. The fracturing of rock during excavation changes this natural block size distribution to the fragment size distribution. The engineer can consider how best to move from one curve to the other in the excavation process.
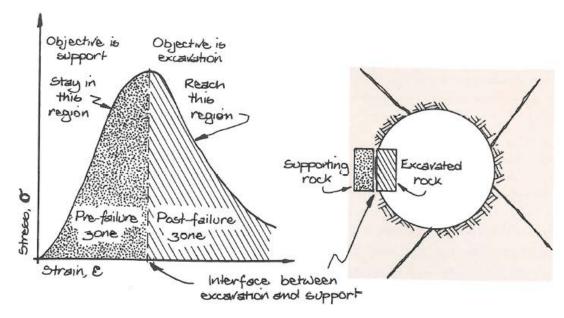
Civil Engineering	Mining Engineering	Petroleum Engineering
Objective: Creation of underground space	Objective: Obtaining the excavated rock	Objective: Transporting oil
Tunnel	Mine stope	Borehole
Geometry specified by engineering function and location with emphasis on integrity of remaining rock. Limited scope for design.	Mine geometry specified by orebody, with emphasis on excavated rock - but many mining methods possible. Large scope for design.	Borehole cross-section dictated by rotary drilling; depth and orientation determined by oilfield access and production strategy. Limited scope for design

Hudson & Harrison (1997)

At its most fundamental level, rock excavation is achieved by increasing the number of fractures and thus changing the size distribution from rock blocks to rock debris; see diagram below.
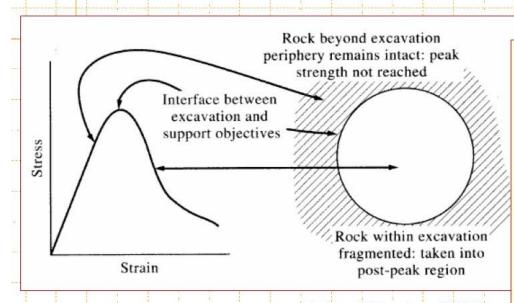

Therefore, on the stress/strain diagram illustrated, it is necessary to reach the post-failure zone in order to carry out the excavation. Once the excavation is complete, however, most of the rock surrounding it is in the pre-failure zone. Thus the rock defining the excavation is at the interface between the two major objectives of rock engineering, i.e. causing failure and avoiding failure respectively.

Energy and Excavation Process

Although the objective during excavation is large-scale fragmentation, at the same time we wish to minimize any damage to the wall rock as this would work towards weakening the rock mass which may result in ground control problems. Fragmentation and rock mass damage are both related to the amount of energy used and whether its applied instantaneously or continuously.

Rock beyond excavation periphery remains intact: peak strength not reached

Interface between excavation and support objectives

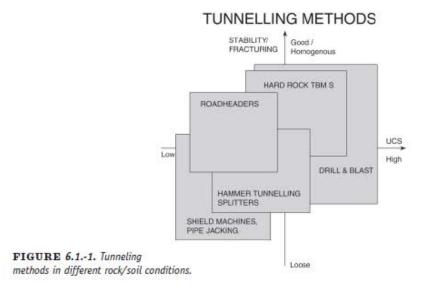Rock within excavation fragmented: taken into post-peak region

Stress

Strain

Hudson & Harrison (1997)

Because the tensile strength of rock is about $1/10^{th}$ the compressive strength and the energy beneath the stress-strain curve is roughly its square, breaking the rock in tension requires only $1/100^{th}$ of the energy as that in compression. Thus, considerable advantages can be gained by carefully considering how to use the energy in an optimal way.

In modern tunnel and underground cavern excavation, it is possible to select from many different methods. The following factors should be taken into consideration when selecting the method:

- Tunnel dimensions
- Tunnel geometry
- Length of tunnel, total volume to be excavated
- Geological and rock mechanical conditions
- Ground water level and expected water inflow
- Vibration restrictions
- Allowed ground settlements

The methods can be divided into drill & blast, and mechanical excavation. Mechanical methods can be split further to partial face (e.g. roadheaders, hammers, excavators) or full face (TBM, shield, pipe jacking, micro tunneling).

TUNNELLING METHODS

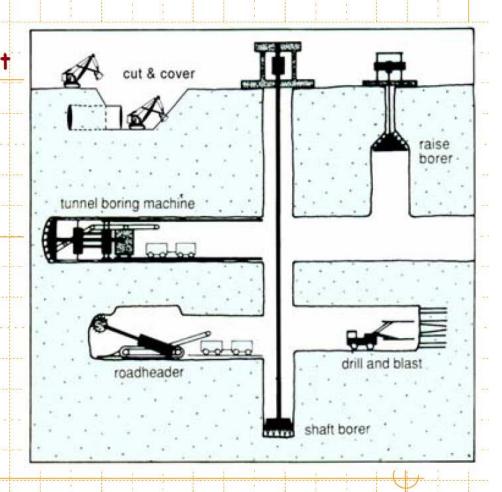**FIGURE 6.1.-1.** *Tunneling methods in different rock/soil conditions.*

The drill & blast method is still the most typical method for medium to hard rock conditions. It can be applied to a wide range of rock conditions. Some of its features include versatile equipment, fast start-up and relatively low capital cost tied to the equipment. On the other hand, the cyclic nature of the drill & blast method requires good work site organization. Blast vibrations and noise also restrict the use of drill & blast in urban areas.

Excavation Methods

Selection of a tunnelling system (i.e. tunnelling method with/without additional measures, e.g. ground conditioning) involves choosing a method that is suitable for and compatible with the given ground and project constraints.

Consideration is generally given to:

- the ground conditions and its variability;
- the geometry, diameter and length of the tunnel;
- the tolerance of nearby structures to ground movement;
- the consequences of ground losses;
- the tunnelling cost;
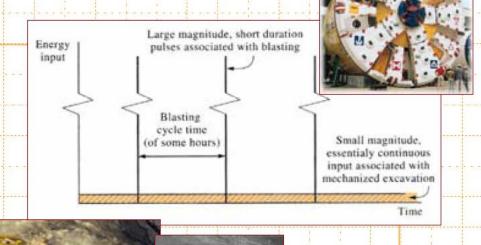- the safety of tunnel workers.

Energy and Excavation Process

One objective in the excavation process may be to optimize the use of energy, i.e. the amount of energy required to remove a unit volume of rock (specific energy = J/m^3). There are two fundamental ways of inputting energy into the rock for excavation:

➡ **Blasting**: Energy is input in large quantities over very short durations (cyclical – drill then blast, drill then blast, etc.).

➡ **Machine Excavation**: Energy is input in smaller quantities continuously.

SCAVO A PIENA SEZIONE IN ROCCE DURE E COERENTI CON ESPLOSIVO

Questo metodo che è anche chiamato "convenzionale", sino ad una trentina di anni or sono era l'unico adatto per lo scavo di gallerie in rocce coerenti dure. Oggi in un certo numero di casi può' essere vantaggiosamente sostituito con i metodi che comportano l'uso di macchine di abbattimento.

Lo scavo con esplosivo comporta alcune fasi fondamentali:

1. *la perforazione* mediante apposite perforatrici di un adatto numero di fori sul fronte della galleria;
2. *il caricamento e brillamento delle mine* con cui si realizza l'abbattimento di una fetta di roccia, il che crea un nuovo fronte; la distanza tra il fronte primitivo ed il nuovo è detto "sfondo";
3. *lo sgombero del materiale abbattuto,* che consiste nel caricamento di questo sui mezzi di trasporto e la successiva asportazione dal fronte.

Ognuna delle fasi principali su descritte può essere a sua volta suddivisa in sotto-fasi che comprendono le preparazioni all'operazione costituente la fase principale. Per esempio la perforazione è preceduta dalla materializzazione sul fronte dei fori da mina, dall'avanzamento vicino al fronte delle perforatrici, dall'allacciamento delle condotte di acqua, aria compressa e linee elettriche etc.

Così anche, per es., il caricamento delle mine è preceduto dall'allontanamento delle perforatrici e del personale non addetto al maneggio degli esplosivi e da altre misure di sicurezza (per es. il sezionamento delle linee elettriche etc.).

Vi sono poi alcune operazioni accessorie ma indispensabili, quale il *disgaggio* delle parti di roccia pericolanti (che è sempre obbligatorio) eseguito dopo lo sparo delle mine.
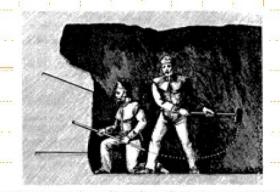
Analogamente lo sparo delle mine è seguito da un periodo di durata varia, (indicativamente 0,5 ore) detto in gergo *sfumo,* durante il quale la ventilazione viene particolarmente forzata per espellere il *tappo* di fumo formatosi al fronte in seguito alla deflagrazione delle mine; alla fine di questo periodo il personale che si era allontanato dal fronte per ovvi motivi idi sicurezza rientra per procedere alle successive operazioni.

Dopo lo sgombero e se la situazione lo impone anche prima, almeno in modo sommario segue la messa in opera dell'armatura (calcestruzzo proiettato, bulloni, rete, centine etc.).
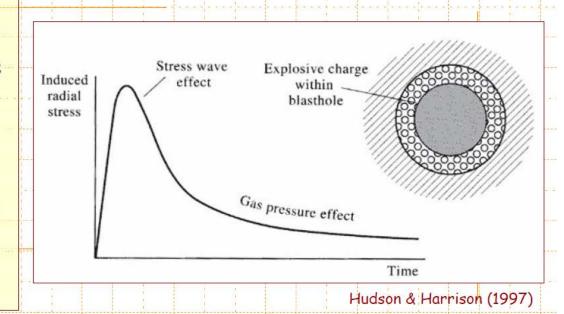
Le fasi ora descritte vengono a costituire un "ciclo", in quanto si tratta di una serie ripetuta di operazioni distinte. Contraddistingue il ciclo la sua durata, la durata delle singole fasi e lo sfondo ottenuto. Nelle tabelle allegate fuori testo vengono forniti esempi di cicli con i valori medi dei parametri (durata e sfondo) in varie differenti situazioni, sia come sezione della galleria, sia come tipo di roccia.
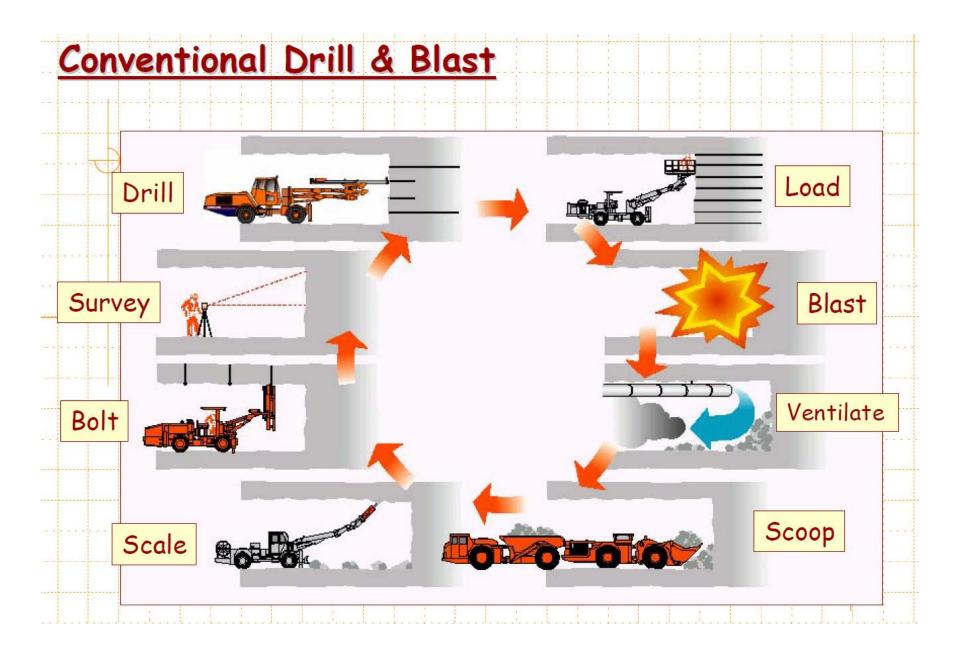
Drill & Blast

The technique of rock breakage using explosives involves drilling blastholes by percussion or rotary-percussive means, loading the boreholes with explosives and then detonating the explosive in each hole in sequence according to the blast design.

The explosion generates a stress wave and significant gas pressure. Following the local fracturing at the blasthole wall and the spalling of the free face, the subsequent gas pressure then provides the necessary energy to disaggregate the broken rock.
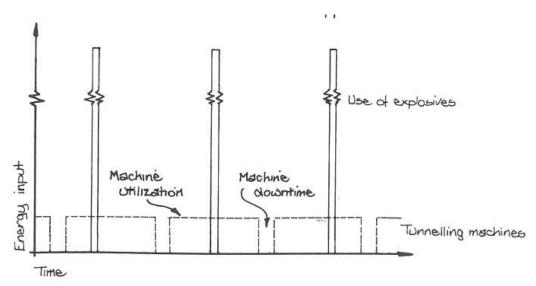

Hudson & Harrison (1997)

Conventional Drill & Blast

Drill

Load

Survey

Blast

Bolt

Ventilate

Scale

Scoop

Drill & Blast - Drilling

Bohrhammer | Bohrgestänge | Bohrkrone

Kabine

Aggregate & Schlauchaspel

Bohrarme & Arbeitsplattform

water flush (chip removal) | rotation | thrust force | percussion hammer

Rock is usually excavated by explosives (large rapid inputs of energy at periodic intervals), or by machines (lower rates of essentially continuous energy). These two extremes of energy are illustrated in the diagram on the right.
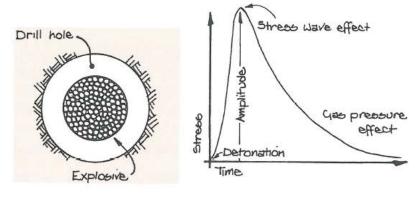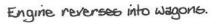

The properties of intact rock are important for excavation because the intact rock has to be broken. Conversely, the properties of discontinuities are important for stability because the discontinuities can allow failure to develop at low stress levels. There are cases where the natural discontinuity patterns make excavation and debris removal easier, e.g. when rock ripping.
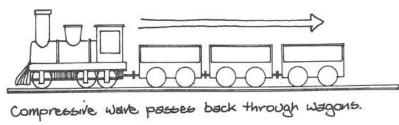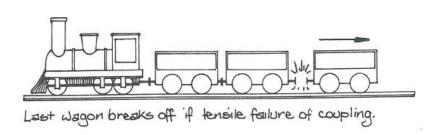
4.1   Blasting

Excavation by blasting involves the detonation of explosive placed in drill holes in the rock mass. Extremely high gas pressures are developed in the drill holes over a very short period, causing a dynamic stress wave to radiate out from the charge at sonic velocities. High gas pressures in the drill hole can be sustained over a relatively long period by continued burning of the explosives.
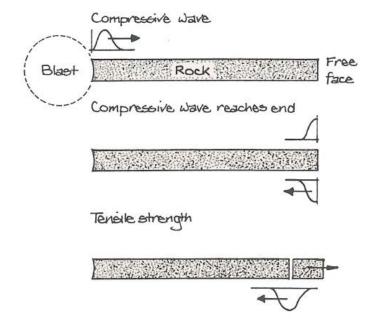
The result is compressive fracturing around the hole, and spalling caused by the compressive wave being reflected from a free face as a tensile wave. This is explained in the diagram and by the analogy of a train coupling failure.
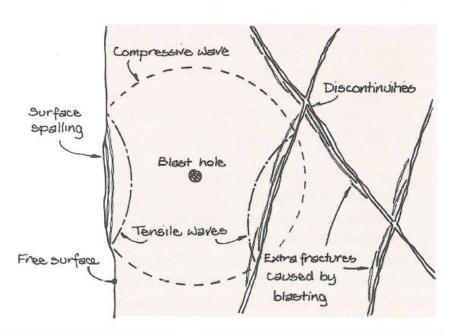
The presence of a free face for the tensile stress wave to develop is therefore one of the keys to successful blasting. For this reason most blasting rounds are designed on the basis of blasting to a free face, which either already exists or is progressively created.

The tensile strength is much less than the compressive strength, so although the rock can sustain a particular compressive stress wave, it may not be able to sustain a reflected tensile stress wave of comparable amplitude.

By the same token, discontinuities can cause problems, both from internal spalling due to reflection at dilated discontinuity surfaces, and from gas pressure effects.

Blasting always causes vibrations. The prediction of these and their effect on structures is clearly explained in Key references 3 and 4.

Key references

1. LANGEFORS, U and KIHLSTROM, B. (1973) The modern technique of rock blasting. John Wiley and Sons (New York)
2. HOEK, E. and BRAY, J. W. (1981) Rock slope engineering. Institution of Mining and Metallurgy, London
3. DOWDING, C. H. (1985) Blast vibration monitoring and control. Prentice Hall (New Jersey)
4. NEW, B. M. (1983) Ground vibration caused by civil engineering works. TRRL RR 53. Transport and Road Research Laboratory, Crowthorne, Berks
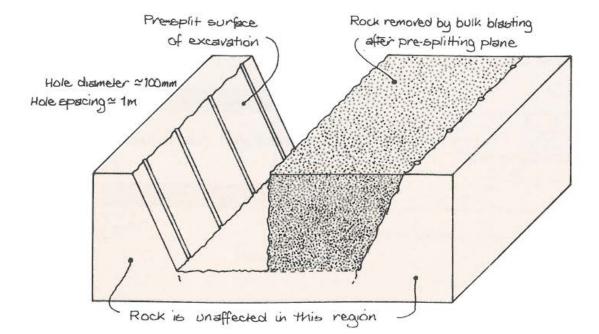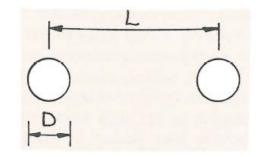
4.2   Pre-splitting

Pre-splitting is a blasting technique by which the final rock slope face is created first, such that subsequent bulk blasts do not damage the rock beyond the excavation boundary. The pre-split plane is created by simultaneous blasting in relatively closely-spaced, usually small-diameter holes, as illustrated in the diagram below.

The most important keys to successful pre-split blasting are:

– drillhole accuracy : parallel holes
– drillhole diameter : must be small
– closely spaced holes (L/D<10)
– decoupled explosives (leaving an air gap between explosive and rock)
– simultaneous detonation

After successful pre-splitting, the 'half drillholes' can usually be seen, as shown in the photograph.

Pre-split surface of excavation

Rock removed by bulk blasting after pre-splitting plane

Hole diameter ≈100mm
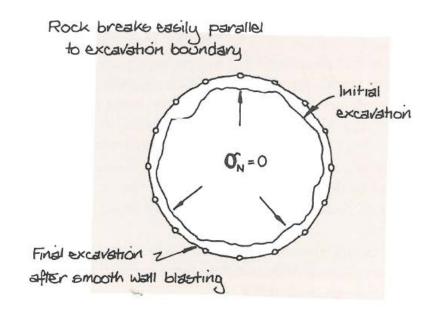Hole spacing ≈ 1m

Rock is unaffected in this region

Parallel drillholes after pre-splitting

The pre-splitting technique is an excellent example of the successful application of rock engineering principles to achieve a specific objective – in this case a smooth final slope, with minimal damage to the rock behind and hence optimal safety (assuming that the slope is carefully designed – see Section 5.2), and minimal long term maintenance.

The technique is thoroughly described in Key reference 1. It can be used successfully in quite fractured and inhomogeneous rock, although it may be necessary to space the holes more closely. The presence of a high *in-situ* stress field could, however, inhibit development of a smooth plane, and smooth-wall blasting may be substituted.

Deep underground, pre-splitting is ineffective because rock breaks perpendicular to the least principal stress. However, once an excavation is formed, one of the principal stresses is perpendicular to the excavation boundary. Smooth-wall blasting afterwards is then very effective; see diagram. For rock surfaces with weakened joints, or where the thickness of rock to be removed is relatively small, smooth-wall blasting can also be effective.

Rock breaks easily parallel to excavation boundary

Initial excavation

$\sigma_N = 0$

Final excavation after smooth wall blasting

LO SCHEMA DI TIRO

Dicesi schema di tiro l'indicazione sommaria della posizione dei fori da mina sulla fronte, la loro direzione, lunghezza e diametro.
I fori da mina comprendono:
  -*fori di intesto;*
  -*fori di scarico;*
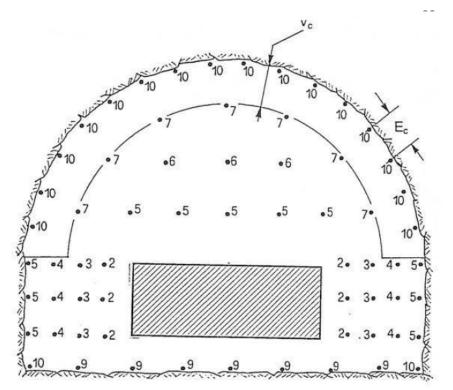 -*fori di contorno (in corona, al piede etc.)*
La figura chiarisce la terminologia adottata.
I fori di intesto possono essere inclinati rispetto all'asse della galleria (schemi a cuneo o piramide, a ventaglio, oppure paralleli all'asse, con fori di scarico non riempiti di esplosivo: variamente denominato, questo schema può' assumere il nome di "canadese", "burn cut" etc..
Questi schemi fondamentali sono riconducibili al modo di lavorare dell'esplosivo: questo per esplicare nel modo migliore la propria azione richiede la presenza di superficie libere preesistenti a più' o meno breve distanza dalla carica. La superficie libera è solitamente costituita dalla stessa fronte della galleria per i fori di intesto; dal cratere creato dall'intesto per le mine di scarico; per le mine a fori paralleli, le superficie libere sono create artificialmente mediante fori non riempiti.

Le mine vengono fatte brillare a gruppi successivi: prima quelle di intesto, il che serve a moltiplicare le superficie libere, poi le altre. Per le mine di intesto solitamente vengono utilizzati i microritardi: ogni mina viene fatta brillare con ritardo, rispetto alla precedente, di centesimi di secondo; i gruppi successivi possono essere fatti brillare ad intervalli di qualche frazione di secondo (0.5 s).
L'uso dei microritardi riduce la pezzatura del materiale abbattuto e le vibrazioni conseguenti all'esplosione, vantaggi questi talvolta molto apprezzati.

Posizione di fori di intesto, di scarico e di contorno nello schema di *volata* in galleria.
- fori di intesto: zona tratteggiata;
- fori di scarico N. 2-3-4-5-6-7;
- fori di contorno in volta N. 10;
- fori di contorno al piedritto N. 5;
- fori di contorno al piede N. 9 e 10).
I numeri indicano la successione temporale dei tiri relativi ai vari gruppi di mine.

Le figure fuori testo mostrano alcuni schemi di tiro relativi a gallerie di media e grande sezione

Schema di volata relativo ad una galleria di circa 90 m2 in calcescisti (Galleria autostradale del Frejus)

Tipo di intesto: a fori inclinati convergenti
Diametro fori: 52 mm
Lunghezza: 3,80 m circa
Numero: 103
Lunghezza perforata: 398 m
Velocità perforazione: 2 m/min
Tempo globale perforazione: 75 min
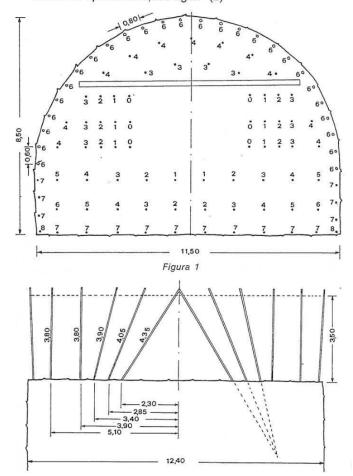Sfondo: 3,5 m
Volume di roccia abbattuta: 308 m^3
Esplosivo: Gelatina 1 - 40x400 mm-   Quantità 370 kg (1)
              Profil X- 17x460 mm - Quantità 18 kg (2)
Consumo specifico: 1,2 kg/m^3 (1)
Consumo specifico: 0,058 kg/m^3 (2)

Figura 1

Galleria sottomarina Alesund (Norvegia)

Si tratta di una galleria stradale, (3 corsie), collegante, con altre, le estremità di fiordi in Norvegia. Il tratto descritto (Alesund - Ellingsoia) è costituito da due canne di lunghezza L= 3483 m; Sezione circa 68 m2.
Roccia: gneiss e gabbri

Perforazione: 3 perforatrici ATLAS H175 a 3 bracci; 3 martelli COP 1238 ME; sfondo 4,15 m;

Avanzamento :15 cicli/ settimana; (50 *ml* settimana circa, in media).

Durata ciclo: Perforazione e caricamento fori: 3,5 h; ventilazione: 0,3 h; disgaggio: 0,2 h; smarino: 2h.

Totale (senza messa in opera sostegni: 6 ore)

Squadra per ogni attacco: 20 uomini (5 per turno) + capisquadra .

Piano di tiro: N= 11O + 4 fori scarichi (volata a fori paralleli); fori carichi: d= 45 mm ; fori scarichi O= 102 mm;

Esplosivo: ANFO a caricamento automatico in foro;

detonatori da 0,25 ms.

Durata materiale perforazione: utensile 380 m; barre 1700 m; manicotti 2700 m; bussola dell'impugnatura del fioretto: 3000 m.

Smarino: 1 CAT 980 C

Potenzialità 150 m3/h di solido; Volume mucchio per ciclo : 282 m3.

Durata smarino: 2 h.
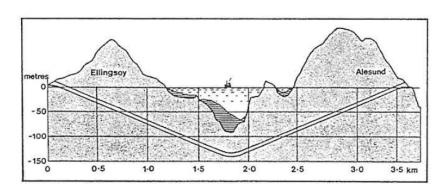
Sostegni: Bulloni cementati da 3 m;
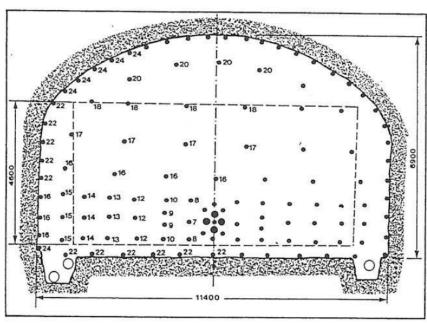
N bulloni per ciclo : 15- 25;

Durata bullonaggio 2h;Cls a umido a fibre di acciaio; quantità fibre: 75 kg/m3; potenzialità: 6 m3/h.

N:B: essendo in gran parte le gallerie sottomarine si eseguivano fori di monitoraggio ogni 30 m con sovrapposizione 10 m.

TIRO CONTROLLATO A CONTORNO LISCIO (*SMOOTH BLASTING)*

L'affermarsi dello scavo con macchine a piena sezione ha stimolato la nascita nel camp dell'abbattimento con esplosivo della tecnica di tiro detta a "contorno liscio" *(smooth blasting).*

Essa consiste nel proporzionare in modo opportuno la parte di schema di tiro relativa ai fori di corona. Essi vengono posti ravvicinati (30-60 cm) e caricati con esplosivo speciale di bassa potenza. Il foro è caricato solo per una quota parte e le cartucce, che hanno diametro inferiore a quello del foro (rapporto circa 1:2, detto rapporto di disaccoppiamento) sono post in posizione concentrica rispetto al foro mediante appositi distanziatori. E' possibile cosi controllare l'energia ceduta alla roccia evitando la massiccia fratturazione al contorno della galleria. Le cariche sono proporzionate nei limiti di 0.2 ÷ 0.44 kg/m a seconda della potenza dell'esplosivo e del diametro dei fori.
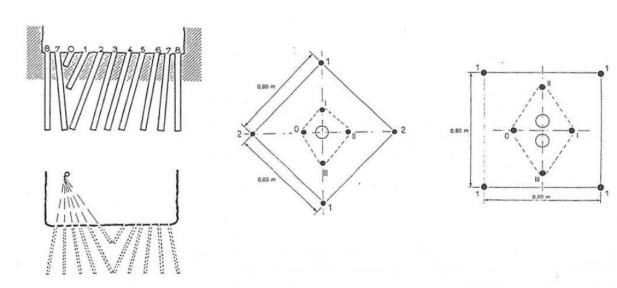
Il profilo liscio comporta numerosi vantaggi tra cui:

*   *minor disgaggio;*
*   *maggiore stabilità della roccia;*
*   *minor consumo di calcestruzzo;*
*   *minor ventilazione.*

Per contro si ha un costo maggiore rispetto ai metodi usuali.

IL PROPORZIONAMENTO DELLA CARICA ESPLOSIVA.

Si procede solitamente per via semi-empirica mediante l'uso di diagrammi predisposti in base a considerazioni teoriche e sperimentali
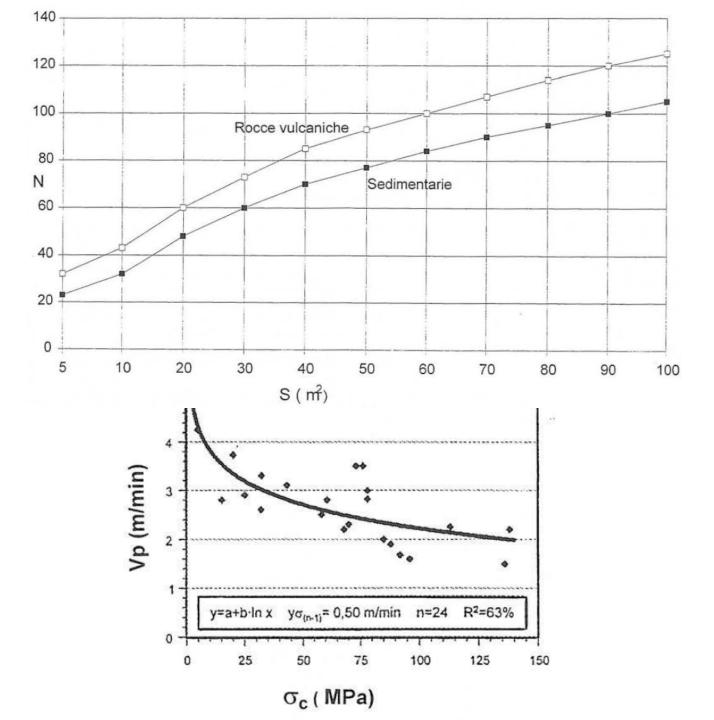
Schemi di intesto: a sinistra in alto lo schema a ventaglio, in basso lo schema a fori centrali convergenti (cuneo, piramide); a destra due schemi tipici dell'intesto a fori paralleli con fori scarichi centrali

INTESTO A FORI PARALLELI

Si usa in gallerie di piccola o media sezione in quanto permette sfondi notevoli. Esso consiste nel praticare nella zona centrale della sezione fori di mina paralleli all'asse della galleria quali circondano alcuni fori scarichi che hanno il medesimo diametro, o più' spesso, diametri maggiore degli altri. Spesso si adotta lo schema così detto a spirale, ove i fori carichi circondano i fori scarichi seguendo appunto un percorso a spirale.

La posizione relativa dei fori è stabilita secondo il principio che la mina deve "vedere" il foro scarico (successivamente il cratere creatosi) con un angolo di circa 50 gradi ed inoltre il vuoto deve permettere la dilatazione conseguente alla frantumazione della roccia (si adotta un coefficiente pari a 1,5). Lo sfondo ottenibile con il tiro a fori paralleli è pari a circa $s = 0,75 \sqrt{S}$ con vantaggio per le piccole e medie sezioni rispetto agli schemi di tiro a fori inclinati. La limitazione nello sfondo, comunque sempre esistente, deriva dal fatto che è difficile mantenere la direzionalità (e quindi il parallelismo dei fori) oltre una certa lunghezza.

Gli svantaggi dell'intesto a fori paralleli sono: maggiore lunghezza di perforazione , necessita di praticare fori a diametro maggiore, consumo specifico di esplosivo maggiore rispetto all'intesto a fori inclinati, impiego svantaggioso in rocce aventi discontinuità con direzioni preferenziali.

Rocce vulcaniche

Sedimentarie

N

S (m^2)

Vp (m/min)

$y=a+b \cdot \ln x$ $y\sigma_{(n-1)}= 0,50$ m/min $n=24$ $R^2=63\%$

σ_c (MPa)

LA PERFORAZIONE

Avviene mediante perforatrici o martelli perforatori sostenuti da appositi bracci o slitte, posizionate su carri di perforazione.

I dati reali possono essere verificati con prove di perforazione in posto. La velocità netta di perforazione non coincide ovviamente con la velocità' globale, per il calcolo della quale si deve tener conto dei tempi morti, (per es.: tempo per lo spostamento della perforatrice da foro a foro, cambio utensile, etc.).

Le perforatrici sono collegate mediante tubazioni di aria compressa (a 7-8 bar) con la centrale dei compressori che generalmente è situata all'imbocco della galleria.

Le perforatrici idrauliche sono contraddistinte dai seguenti dati di funzionamento:

peso
-*ingombro*
-*potenza (oppure pressione e portata del fluido motore)*
-*energia per colpo*
-*numero dei colpi*
-*diametro della barra di perforazione*
-*pressione e portata dell'acqua di spurgo dei detriti*

TEMPI MORTI NELLO SCAVO CON ESPLOSIVO

1- COLLEGAMENTO PERFORATRICE	10 min
2- ARRETRAMENTO "	8
3- " VENTILAZIONE	6
4- " CONDOTTE	8
totale	32

5- TRACCIAMENTO VOLATA	0,1 min/foro
6- POSIZIONAMENTO MARTELLI	0,1-1 min/foro (*)
7- PULIZIA FORI	0,2 min /foro (*)
8- CAMBIO FORO	0,1-0,3 min/foro (*)
9- CARICAMENTO FORI	0,5 min/m (**)
10- COLLEGAMENTI ELETTRICI	0,1-0,2 min/foro (**)
11- PROVA CIRCUITO	5 min
12- SFUMO	15-30 min
13- AVANZAMENTO VENTILAZIONE	12 min
14- DISGAGGIO	0,1-min/m3 (**)
	(10- 40 min)

(*) il numero dei fori va suddiviso per il numero G di perforatrici presenti sul fronte
(**) per ogni addetto all'operazione

Tempo della fase di perforazione: (Lperf)/(GVp) + somma tempi morti (Vp: velocità netta di perforazione).

3.1 MECHANICS OF ROCK BREAKING

When a tool is loaded onto a rock surface, stress is built up under the contact area. The way the rock responds to this stress depends on the rock type and the type of loading, for example, the drilling method.

Rock breakage by percussive drilling can be divided into four phases:

CRUSHED ZONE

As the tool tip begins to dent the rock surface, stress grows with the increasing load and the material is elastically deformed, zone III in **FIGURE** *3.1.-1*. At the contact surface, irregularities are immediately formed and a zone of crushed rock develops beneath the indenter (the button or insert of a drill bit) **FIGURE** *3.1.-1*. The crushed zone comprises numerous microcracks that pulverize the rock into powder or extremely small particles. 70-85% of the indenter's work is consumed by the formation of the crushed zone. The crushed zone transmits the main force component into the rock.
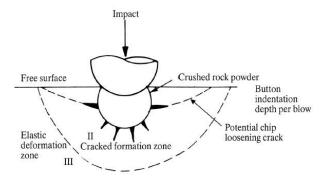

FIGURE *3.1.-1. Rock breakage in percussive drilling*

CRACK FORMATION

As the process continues, dominant cracks begin to form in the rock. This initial stage of restricted growth is described as an energy barrier to full propagation. The placement of major cracks depends on the indenter shape. Generally, the dominant placement of major cracks with blunt indenters, such as a sphere, is located just outside the contact area, pointing down and away from the surface.

CRACK PROPAGATION

After the energy barrier has been overcome, spontaneous and rapid propagation follows, zone II in **FIGURE** *3.1.-1*. At a lower depth than the contact dimension, the tensile driving force falls below that necessary to maintain growth, thus the crack again becomes stable. The crack is then said to be "well developed".

CHIPPING

When the load reaches a sufficient level, the rock breaks and one or more large chips is formed by lateral cracks propagating from beneath the tip of the indenter to the surface. This process is called surface chipping. Each time a chip is formed, the force temporarily drops and must be built up to a new, higher level to achieve chipping. Crushing and chipping creates a crater.

3.2 TOP-HAMMER DRILLING

There are four main components in a drilling system, **FIGURE** *3.2.-1*. These components are related to the utilization of energy by the system for attacking rock in the following way: 1. The piston inside the rock drill is the prime mover, converting energy from its original form (fluid, electrical, pneumatic or combustion engine drive) into mechanical energy to actuate the system. 2. The shank adapter transmits impact energy from the piston to the rod(s) or tube(s). Additionally, rotation torque is delivered via the shank adapter. 3. The rod or tube transmits impact energy and rotation torque. 4. The bit applies the energy in the system, mechanically attacking rock to achieve penetration.
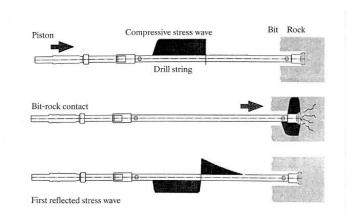

FIGURE *3.2.-1. Percussion dynamics*

3.3 PRINCIPLE OF DTH DRILLING

DTH (Down-The-Hole) drilling, also known as ITH (In-The-Hole) drilling, is a method in which the percussive hammer works in the hole during drilling, as opposed to above the hole in top-hammer drilling. DTH hammers are used in underground benching operations.

In DTH hammers, the rock drilling bit is a continuation of the shank, which the rock drill piston strikes directly. DTH machines are driven by compressed air and require a fairly large compressor to operate effectively. Since the piston is in almost direct contact with the drill bit, little energy is lost. This gives a nearly constant penetration rate regardless of hole length. Hole accuracy is also good. DTH machines are limited by their relatively low penetration rates and poor mobility, because they require a large separate compressor. Rotation is usually hydraulic. Energy consumption is also large compared to top-hammer drills.The hole sizes most commonly used for underground DTH drilling are 89 - 165 mm in diameter, and can extend up to 1,100 mm. Hole lengths in underground benching operations vary up to 60 meters. **(FIGURE 3.3.-1.)**
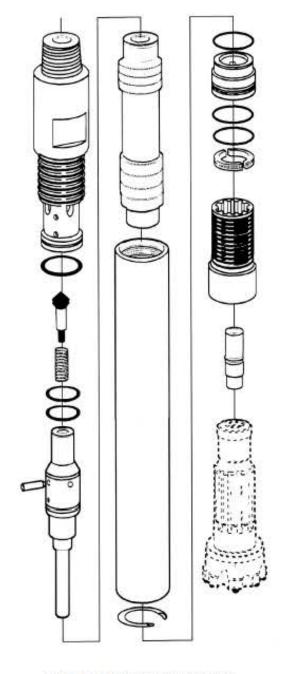

FIGURE 3.3.-1. DTH rock drill.

Drill & Blast - Drilling

Three parameters should be considered when choosing a drill bit: penetration rate, hole straightness and service life. In 95% of all rock drilling, a button bit is selected to drill the hole to a given diameter.

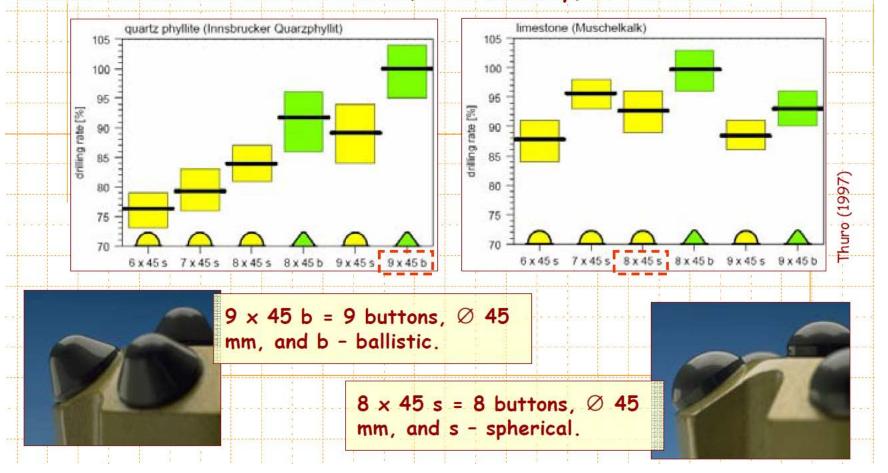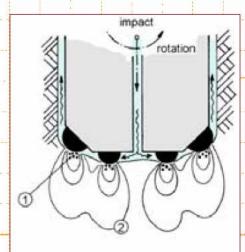| Button Shape	Characteristics	Application
Spherical	· "non aggressive" shape · minimum drilling rates · low bit wear · excavation mainly by impact	Rock with high UCS and high abrasivity (e.g. quartzite, granite, gneiss, amphibolite)
Semi-Ballistic	· "aggressive" shape · moderate drilling rates · moderate bit wear · excavation mainly by shearing/cutting	Rock with mid UCS and less abrasivity (e.g. slate, sandstone, limestone, weathered rock)
Conical (Ballistic)	· "very aggressive" shape · maximum drilling rates · high bit wear · excavation mainly by shearing/cutting	Rock with low UCS and low abrasivity (e.g. shale, weak sandstone, phyllite)

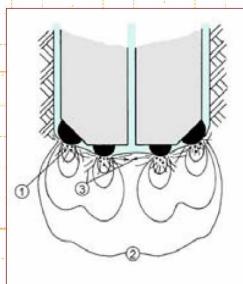Thuro (1997)

Drill & Blast – Drill Bit Buttons

The bit's ability to penetrate the rock efficiently depends on the contact surface of the buttons, their shape and number, the bits' flushing characteristics and the brittleness, or drillability, of the rock.
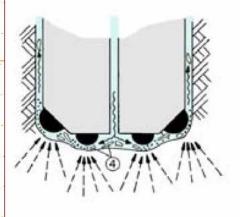

9 × 45 b = 9 buttons, ∅ 45 mm, and b – ballistic.

8 × 45 s = 8 buttons, ∅ 45 mm, and s – spherical.

Drill & Blast – Drill Bit Buttons

1. *Begin of impact:*
Rotating hard metal buttons are forced into the rock mass. Extremely high local stresses cause the prompt formation of crushed zones ① below the tips. From there, low level stress fields ② are built up in the drilling direction.

2. *Cracking:*
The rising stresses exceed the rock strength, initial cracks ③ form at the edge of the crushed zones and propagate into the rock. Cracks from neighbouring zones begin to interact and form chips. Shearing takes place due to bit
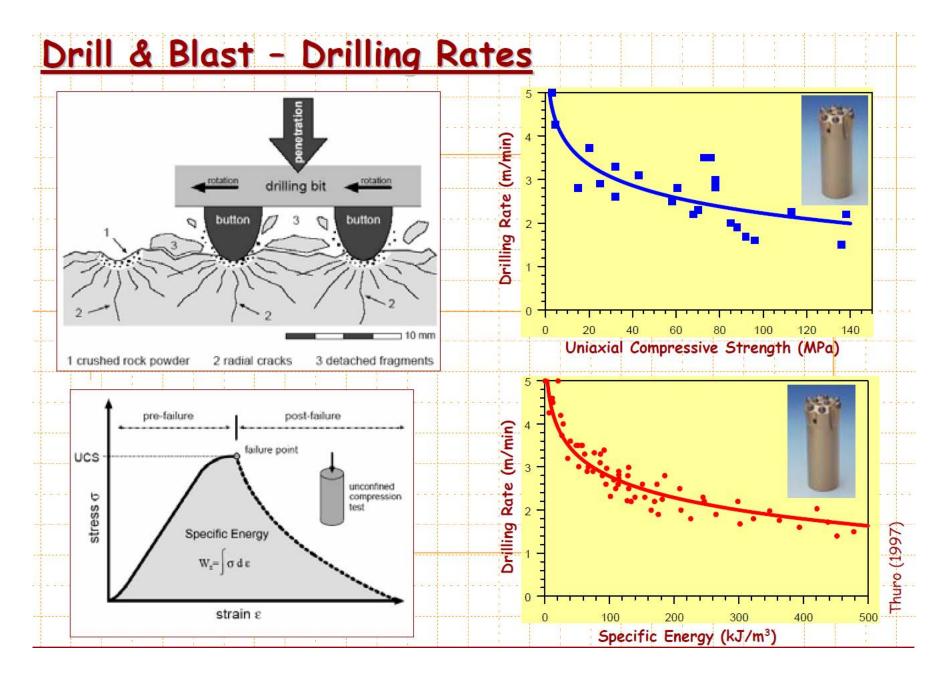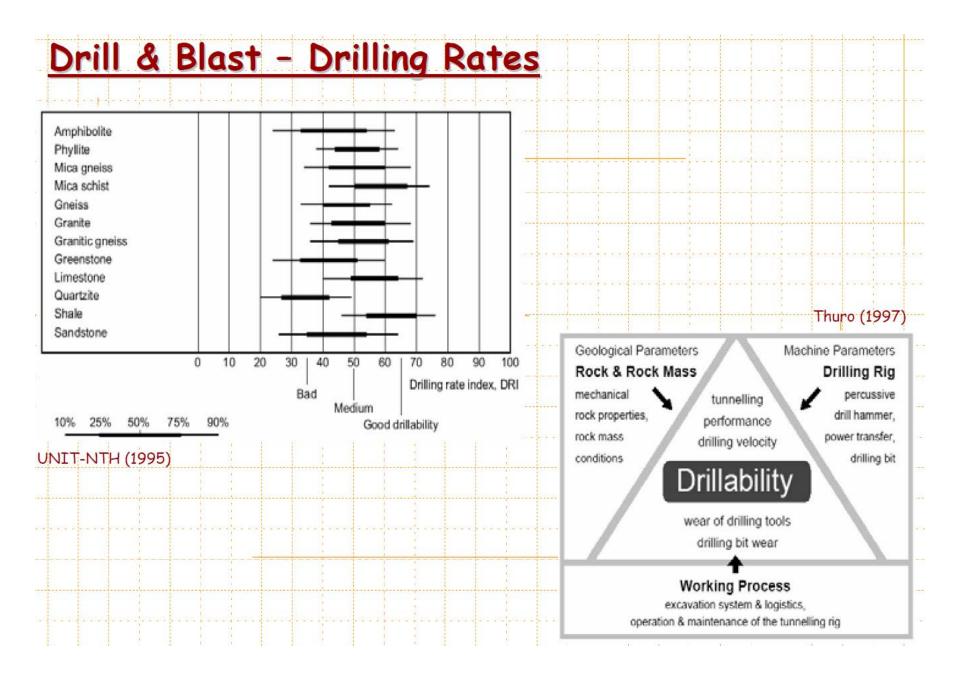
3. *End of stroke:*
The bit is pulled back, the stresses are released. Elastic rebound of the rock mass and the flushing system separate chips and crushed material ④ from the front. They are flushed out of the hole consequently.

Plinninger et al. (2002)

Drill & Blast - Drilling Rates

Drill & Blast - Drilling Rates

UNIT-NTH (1995)

Thuro (1997)

CARICAMENTO DELL'ABBATTUTO E SGOMBERO

E' la fase del ciclo atta a liberare il fronte della galleria dal materiale (roccia terreno abbattuto. Si suddivide in:
*   *caricamento sui mezzi di trasporto*
*   *trasporto all'esterno*
*   messa *in discarica.*
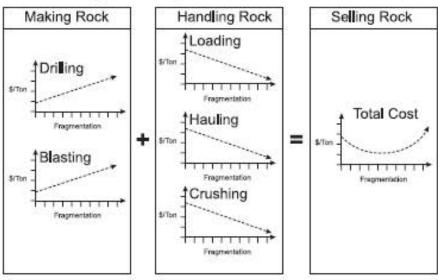
Le operazioni di sgombero (in gergo "smarino") sono influenzate:
*   *dalle caratteristiche litologiche del detrito*
*   *dalla granulometria*
*   *dalla forma dei detriti (a spigoli vivi od arrotondati, imbibiti d'acqua* o *no etc.)*
*   *dalle venute d'acqua.*

I mezzi di caricamento e trasporto sono scelti in funzione:
*   *delle dimensioni della galleria*
*   *della distanza tra fronte della galleria e discariche*
*   *del tracciato (curve e pendenza)*

Optimizing Production Costs

CARICAMENTO   GALLERIE DI MEDIA E GRANDE SEZIONE

Nelle sezioni medio-alte può essere vantaggioso l'uso di caricatrici su pneumatici sfruttando l'elevata potenzialità di questo mezzo. A seconda della potenzialità richiesta (che è funzione della sezione, dello sfondo e della lunghezza di sgombero) si possono usare caricatrici a bracci mobili su pneumatici, che, per sezioni non inferiori a 16 m2 hanno potenzialità sino a 3 m3/min.

Per medie sezioni a profilo ribassato, utile si dimostra l'adozione di caricatrici scarico laterale, il cui unico inconveniente è la minor robustezza della benna rispetto agli altri modelli.

Per grandi sezioni può essere conveniente l'uso di caricatrici articolate dei medesimi modelli adottati per il movimento di terra a cielo aperto, soluzione certamente ottimale quando le possibilità di movimento agile sono ben assicurate.

Il tempo del ciclo di caricamento è dato da: $Tci=Tc+Tt+Ts$,

dove: Tci=tempo di ciclo; Tt=tempo di traslazione e manovra; Ts=tempo di scarico; Tc=tempo di caricamento.

Per pale su pneumatici il tempo di carico scarico e manovra è stimato mediamente in 0.4 min: il tempo di traslazione dipende dalla distanza tra il mucchio ed il mezzo d trasporto.
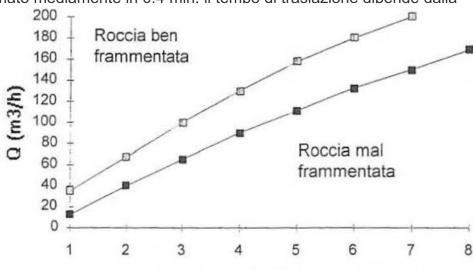
Il tempo di manovra è funzione della velocità, cioè:

$Tt=LN$,

dove L e' la distanza di carico e V la velocità della pala.

Il tempo di scarico è valutato tra 0,04-0,1 min.

Il numero di cicli orari è dunque: $Nci=60/Tci$, e la quantità di detrito caricato è: $Q=q*Nci*x$, ove x è il coefficiente riempimento della benna (compreso tra 0,6 e 0,95).

La figura permette altresì di valutare la potenzialità di una pala in funzione della capacità della benna

SGOMBERO

Il trasporto può avvenire indifferentemente su rotaia o su pneumatico, restando dominante il fattore economico.

I mezzi su rotaia hanno il vantaggio di non indurre inquinamento dell'aria se azionati da motori elettrici e sono preferiti nel caso di scavo con fresa a piena sezione, anche per gallerie di grande dimensione e di grande lunghezza, a causa del fatto che possibile, attraverso il caricamento diretto del detrito sui vagonetti usufruire appieno di tutti i vantaggi anzidetti dei mezzi su strada ferrata.
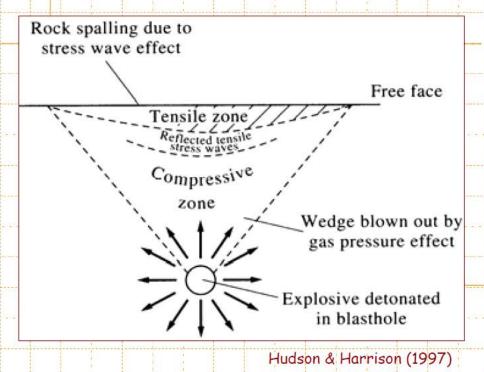
Per le medie e grandi sezioni, comunque, la soluzione più comunemente usata rappresentata da autocarri.
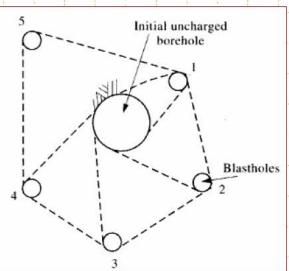
Gli autocarri corazzati *(dumpers)* attualmente sul mercato permettono di sgomberare volumi notevoli di materiale in tempo relativamente breve date le elevate velocità a pieno carico (se permesse dal fondo della galleria, sino a 20-25 km/h) *e* le notevoli capacità dei cassoni (20-30 t). Per sotterraneo queste macchine oltre che dotate di motore Diesel devono essere fornite di appositi filtri di depurazione dei gas di scarico.

La fase di perforazione con le sottofasi accessorie (carica dei fori di mina, lo sparo, lo sfumo, il disgaggio), la fase di sgombero dei detriti (*smarino)* e l'eventuale messa in opera dei sostegni costituisce, come già detto, il ciclo, nello scavo con esplosivo

Blasting Rounds – Blast Pattern Design

One of the basic principles of designing the configuration and sequential detonation of blastholes in a one blast, is the presence of a free face parallel or sub-parallel to the blast holes, as detonation occurs. In some cases, these free faces may already be present (benches in an open pit mine), but in other cases may need to be created by the blast itself (a tunnel face).

Rock spalling due to stress wave effect

Free face

Tensile zone

Reflected tensile stress waves

Compressive zone

Wedge blown out by gas pressure effect

Explosive detonated in blasthole

Hudson & Harrison (1997)

5

Initial uncharged borehole

1

2

Blastholes

3

4
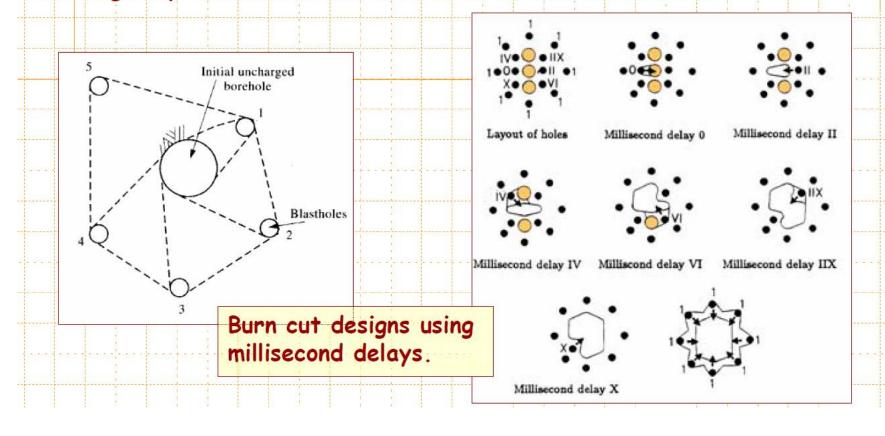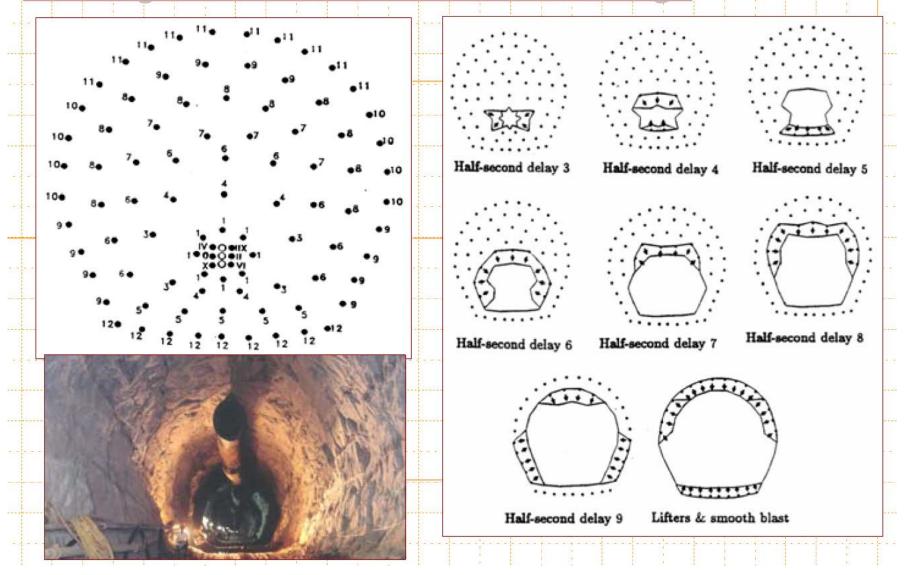
Practical application of the free-face concept using one form of the burn cut.

Blasting Rounds – Burn Cut

The correct design of a blast starts with the **first hole** to be detonated. In the case of a tunnel blast, the first requirement is to create a **void** into which rock broken by the blast can **expand**. This is generally achieved by a wedge or **burn cut** which is designed to create a clean void and to **eject** the rock originally contained in this void clear of the tunnel face.

Burn cut designs using millisecond delays.

Blasting Rounds – Blast Pattern Design

Half-second delay 3

Half-second delay 4

Half-second delay 5

Half-second delay 6

Half-second delay 7

Half-second delay 8

Half-second delay 9

Lifters & smooth blast

Blasting Rounds – Blast Pattern Design
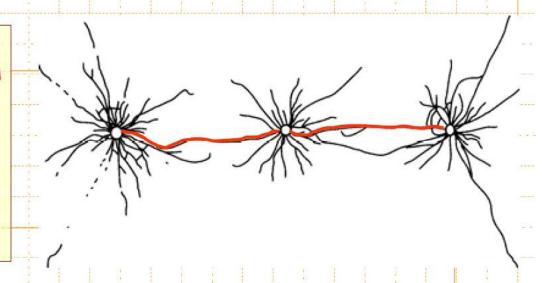
Specialized Blasting Techniques
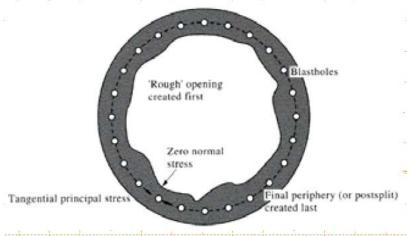
During blasting, the explosive damage may not only occur according to the blasting round design, but there may also be extra 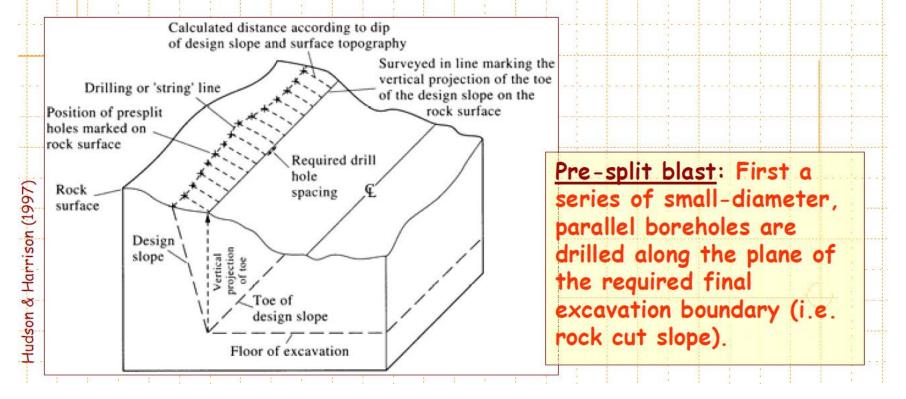rock damage behind the excavation boundary. To minimize damage to the rock, a pre-split blast (surface excavation) or smooth-wall blast (underground) may be used to create the final excavation surface.

Hudson & Harrison (1997)

Calculated distance according to dip of design slope and surface topography

Surveyed in line marking the vertical projection of the toe of the design slope on the rock surface

Drilling or 'string' line

Position of presplit holes marked on rock surface

Rock surface

Required drill hole spacing

Design slope

Vertical projection of toe

Toe of design slope

Floor of excavation

Pre-split blast: First a series of small-diameter, parallel boreholes are drilled along the plane of the required final excavation boundary (i.e. rock cut slope).

Pre-Split & Smooth-Wall Blasting

The principle is then to tailor the explosive parameters such that detonation of the explosives in these initial holes will primarily create a plane of intersecting holes through the coalescence of several induced fractures.

Blastholes
'Rough' opening created first
Zero normal stress
Tangential principal stress
Final periphery (or postsplit) created last
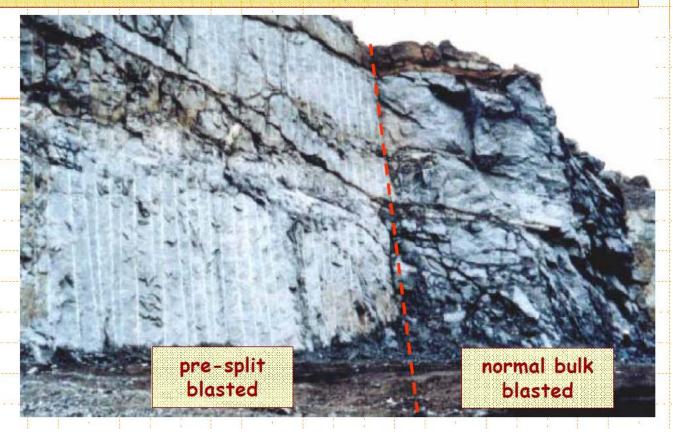
Hudson & Harrison (1997)

The smooth-wall blast follows a similar process to the pre-split blast, except in the reverse order. First a rough opening is formed using a large bulk blast, and then the smooth-wall blast follows along a series of closely spaced and lightly charged parallel holes.

Pre-Split Blasting

When, subsequently, the main body of rock is blasted to form the cutting, the pre-split reflects the stress waves back into the rock being excavated and dissipates excess gas pressure, such that the bulk blast has little effect of the rock behind the pre-split plane.

pre-split blasted

normal bulk blasted

Blasting Rounds - Explosives

Commercial explosives are mixtures of chemical compounds in solid or liquid form. Detonation transforms the compounds into other products, mostly gaseous.

The following are the main criteria applied to select an explosive for a given type of blasting:

- available energy per unit weight of explosive (i.e. strength)

- density of the explosive

- detonation velocity

- sensitivity (ease of ignition)

- reaction rate

- temperature and pressure

- stability (chemical and storage)

Blasting Rounds - Explosives

The following are the more common explosives used in hard rock excavation:

- dynamites (nitroglycerin made stable by dissolving it in an inert bulking agent – moderate bulk strength)

- ANFO (Ammonium Nitrate & diesel Fuel Oil – low bulk strength)

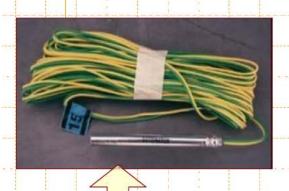- slurries (water gels – high bulk strength for wet conditions)

- emulsions

ANFO is the most prevalent explosive used in mining because it is the least expensive and the safest to transport and handle. ANFO type explosives are susceptible to water and, therefore, are not suitable for wet blastholes.

Blasting Rounds - Explosives

Low explosives, like black powder, can be fired by the flame from a fuse or a match. High explosives require stronger ignition, usually a powerful high temperature shock from a substance that detonates at a very high rate. Some of these devices include:

- Blasting caps
- Squibs/Delays
- Safety fuse
- Primacord
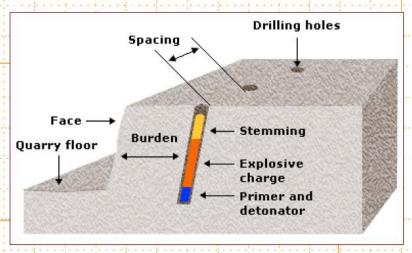
Delays: used to orchestrate rotational firing.

Primacord: ignition velocity is approx. 6,400 m/s.

Safety fuse: Gives miner time to light all fuses and still have time to seek a point of safety before the blast occurs.

Blasting Rounds - Stemming

"Stemming" materials (e.g. pea-sized gravel), are used to top-off the blastholes. The stemming material acts to provide confinement, preventing the explosive gases and energy from travelling (venting) up through the drill hole, and instead are contained within the rock mass.

Blasting Rounds - Blasting Caps

Blasting caps come in a variety of forms. Electric detonators consist of an aluminum tube with an electrically activated fusehead which initiates a priming charge and then a base charge of high explosive.

Fuse caps are non-electric blasting caps that use primary explosives such as mercury fulminate (very sensitive) or lead azide (in copper shells) to provide a quick heat source. They come in small metal tubes (3-5 cm long), closed on one end and open on the other to accept the end of a safety fuse.

Except for the means of firing, there is little difference between electric and fuse-type blasting caps.

Word to the wise: Do not crimp fuse-type blasting caps to fuses using your teeth.

Blasting Rounds - Delays

Delay, or rotational, shooting has many advantages over instantaneous firing in almost all types of blasting. It generally gives better fragmentation, more efficient use of the explosive, reduced vibration and concussion, and better control of the rock. For these, and sometimes other reasons, most blasting operations are now conducted with a delay system. Generally, delay detonators are produced as either 'short delay', measured in milliseconds, or 'half-second delay', measured in seconds.
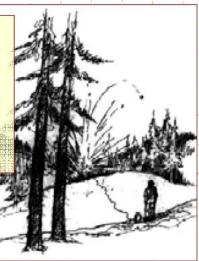
Blasting Rounds – Fly Rock

Fly rock is a constant concern to blasters and their co-workers. It can be controlled if proper preparation, blasting techniques and safety procedures are followed. Four of the major causes of excessive fly rock are:

- Geology conditions.
- Inaccurate drilling and loading.
- Poor hole design.
- Poor pattern timing.

Incidents have been recorded where flyrock has travelled in excess of 1 km and resulted in significant damage, injury and/or death.
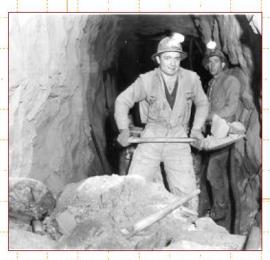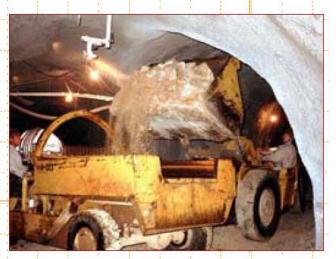
Blasting Rounds – Fragmentation

How efficiently muck from a working tunnel or surface excavation can be removed is a function of the blast fragmentation. Broken rock by volume is usually 50% greater than the *in situ* material. In mining, both the ore and waste has to be moved to surface for milling or disposal. Some waste material can be used underground to backfill mined voids. In tunnelling, everything has to be removed and dumped in fills – or if the material is right, may be removed and used for road ballast or concrete aggregate (which can sometimes then be re-used in the tunnel itself).

Blasting - Summary

CONTROLLABLE VARIABLES		
DRILLING	**CHARGING**	**BLASTING**
- Diameter drill hole	- Type of explosives	- Firing system
- Drilled length	- Energy of explosives	- Firing interval
- Drill pattern	- Charging method	- Water (partly)
- Incorrect drilling	- Design of charging	
	- Charged length	
	- Firing pattern	

NON-CONTROLLABLE VARIABLES	
GEOLOGY	**OTHER**
- Rock parameters	- Incline/Decline
- Rock mass joint	- Water (partly)

CHARGED ROUND

Typical production round fires in less than 7 seconds

RESULT
- Fragmentation
- Throw
- Muck pile shape
- Loadability
- Vibrations
- Advance per round
- Contour
- Flyrock
- Non-detonating holes
- Poor blast result

NTNU (1995)

GROUND VIBRATIONS

Seismic waves

The most common type of blasting damage is caused by ground vibrations. When an explosive detonates in a blasthole, it generates intense stress wave motion in the rock.

Three types of seismic waves are normally observed in engineering and blasting seismology: compression (P), shear (S) and Rayleigh surface waves. The first two are body waves which propagate along the surface or into the sub-surface, returning to the surface by reflection or refraction. The third propagates only along the surface and dies out rapidly the deeper it goes.

Each type propagates with a different velocity. Substitution of parameter values show that the P wave travels at the highest velocity. The S wave travels at roughly one-half of the P wave velocity.

Damage prevention criteria

When foundations are exposed to vibrations, damage can be caused by elongation, shearing and bending. The connection between these magnitudes and those of the ground vibrations is first determined in regard to the wall's elastic properties. Allowance must also be made for the fact that local irregularities and the possible static state of the tension can lower the damage limit.

Structure damage and human tolerance to the blasting vibrations have been analyzed through data collected in various studies. An international summary indicates that particle velocity is the best and most practical description for defining in potential structure damage.

As ground vibrations are approximately a sine-formed vibration, particle velocity can be estimated by the following formula (**FIGURE 3.10.-27.**):

$$v = 2\pi fA$$

where   v = Particle velocity (mm/sec)
              f = Frequency (periods/sec)
              A = Displacement in mm

Vibration acceleration can be calculated from the formula:

$$a = 4\pi^2 f^2 A$$

where   a = Acceleration in g (9.81 m/sec²)
              A = Displacement in mm

In order to recommend realistic limiting values for buildings, blasting and vibration measurement experience is necessary. Restrictions, such as low-particle velocity limiting values can
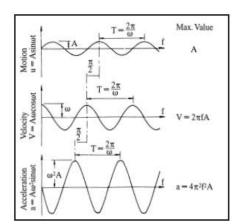
FIGURE 3.10.-27.
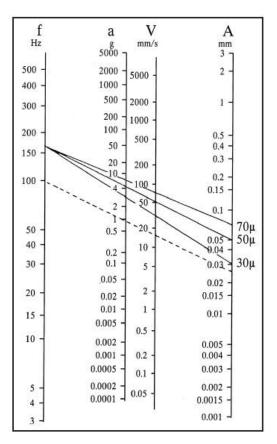Basis terms determining wave motion.

FIGURE 3.10.-28.
Nomogram for determining the relation between frequency (f), acceleration (a), oscillation velocity (v) and amplitude (A).

considerably increase excavation costs. Therefore, before starting and during early planning stages of a blasting project, it is important to execute visual inspection and risk analysis. Based upon these results, it is possible to judge the sensitivity of the buildings and foundations to vibrations. Many factors influence the permitted vibration values. Some of the most important are:

- Vibration resistance of the building materials
- General condition of the building
- Duration and character of the vibrations
- Presence of sensitive vibration equipment
- Foundations
- Condition of foundations
- Propagation characteristics of wave in rock, earth and building material, respectively
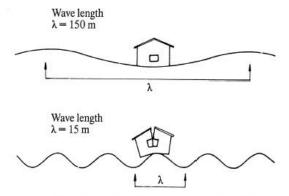- Replacement costs / highest likely repair cost

FIGURE *3.10.-29. The effect of wave length on damage risk.*

A high-velocity seismic wave front produces a longer wave length than a wave with the same frequency but traveling at lower velocity, as shown in **FIGURE** *3.10.-29.* If the wave length is short, the risk of damage caused by tearing is considerably larger as the end of the building is subjected to a different type of movement. Surface waves produce a similar effect.

The specific frequency of ground and rock is mainly dependent on its homogeneity, solidity and the distance between the blast and building.

As higher seismic velocities have longer wave lengths, vibration v (mm/s) in rocks with lower velocities c (m/s) (thus shorter wave lengths) may increase the risk of damage.
If buildings are built on material softer than rock, the empirical values must be divided approximately by 2 or 3 (*Table 3.10.-3b.*).

As the dominating frequency is smaller when the distance is greater, the permissible value for the peak particle velocity must be low when the distance is great.

Finnish limit values for peak particle velocity (v) are very similar to the Swedish and Norwegian standards and can be calculated accordingly:

$$v = F_k \cdot v_1$$

F_k = structural coefficient.
v_1 = peak particle velocity as a function of the distance
(R) for structures and buildings that have been
founded on different materials/vertical component.

Table 3.10.-3a. shows a categorization of seven classes for several structures and buildings. The structural coefficients for curing concrete are also given in *Table 3.10.-3a.* and are based on past experience as well as the test series. The F_k values given for electrical cables and pipelines, as well as for rock masses, are quite certain based on experience.

Table 3.10.-3b. shows the values for peak particle velocity (v_1) as a function of the distance (R) for structures and buildings that have been founded on different materials, based on the fact that the dominating frequency is lower when the distance is greater. The recommended peak particle velocices, while the low frequencies are more dangerous for structures than high frequencies.

Table 3.10.-3a. Structural coefficients F_k (v = $F_k \bullet v_1$, where v_1 = Fd (v_0)

Structural categories (structures in good condition)	Structural coefficient F_k
1. Heavy structures like bridges, piers etc.	2.00 *
2. Concrete and steel building, rock caverns with shotcrete reinforcement	1.50 *
3. Office and commercial buildings of brick and concrete. Wood-frame houses on concrete or stone foundation	1.20 *
4. Brick and concrete residential buildings with no light concrete, limestone-sand brick etc. Rock caverns with no shotcrete reinforcement. Curing concrete > 7 days old*. Electrical cables etc.	1.00
5. Building with light concrete structures. Curing concrete 3-7 days old*.	0.75
6. Very vibration sensitive buildings, such as museums, churches, and other buildings with high vaults and great spans. Buildings of limestone-sand bricks. Curing concrete < 3 days old*. *v	0.65
7. Old historical buildings at the point of collapse such as ruins.	0.50

* Values over one (1) are permitted only when a blasting or vibration specialist is present.

Table 3.10.-3b. *Permitted peak particle velocity (vertical component) v_1 ($v_1 = F_d \cdot v_0$) as a function of distance (R) for structures and buildings founded on different materials. (The structural coefficient is $F_k = 1$).*

Distance R (m)	Soft moraine Sand Shingle Clay	Moraine Slate Soft limestone Soft sandstone	Granite Gneiss Quartzic Hard sandstone Hard limestone Diabase
		Wave velocities c	
	1000-1500 m/s	2000-3000 m/s	4500-6000 m/s
	Permitted peak particle velocity v_1 (mm/s)		
1	18	35	140
5	18	35	85
10	18	35	70
20	15	28	55
30	14	25	45
50	12	21	38
100	10	17	28
200	9	14	22
500	7	11	15
1000	6	9	12
2000	5	7	9

When there is a great distance between the blasting locations and the structure (approx. over 50 m-70 m) the limit v_1 values are conservative. In certain cases, more economical blasting can be achived by measuring all three components plus the time history of the vibration to carry out the frequency analysis. This allows for the use of higher limit values.

If the structure is not a residential building with a structural coefficient of 1, the permissible limit value for peak particle velocity should be calculated with Eq.

$$v = F_k \times v_2$$

F_k = structural coefficient
v_2 = particle velocity versus frequency,
  F_d (v_0) (**FIGURE 3.10.-30**)

The United States Bureau of Mines safe levels of ground vibration from blasting range from 12.5 mm/s to 50 mm/s peak particle velocity for residential type structures. Damage thres old values are a function of the vibration frequencies transmitted into the residences and the types of construction. Particularly serious cases are considered to be low frequency vibrations that exist in soft foundation materials and/or result from long blast-to-residence distances. These vibrations produce not only structural resonances (4 to 13 Hz for whole structures and 10 to 25 Hz for mid walls), but also excessive levels of displacement and strain (**FIGURE 3.10.-31.**).
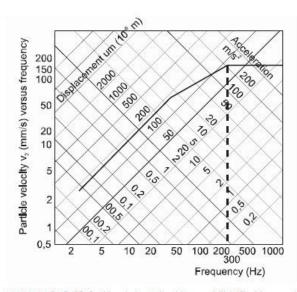

FIGURE 3.10.-30. *Particle velocity v2 (mm/s) versus f (Hz) (Finnish proposal)*
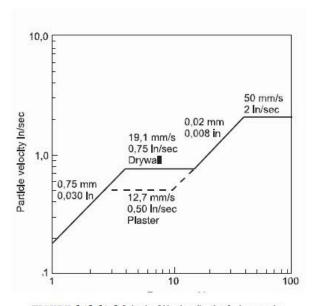

FIGURE 3.10.-31. *Safe levels of blasting vibration for houses using a combination of velocity and displacement (Bureau of Mines, USA 1980)*

According to German standards (**FIGURE** *3.10.-32.* and *table 3.10.-4.*) the criteria is listed for three classes of structures and triaxial measurements for frequencies under 10 Hz, from 10 to 50 Hz and over 100 Hz. Measurements should be taken in the foundation and on the roof of the building.

Table 3.10.-4. *Criteria for particle velocity v based to effects of short term vibrations.*

Line	Type of structure	Criteria for particle velocity v in mm/s			
		Base			Top of the highest round
		Frequenses			
		< 10 Hz	10 to 50 Hz	50 to 100*) Hz	all frequences
1	Commercial and industrial structures	20	20 to 40	40 to 50	40
2	Residences (also under construction)	5	5 to 15	15 to 20	15
3	Structures which are especially vibration sensitive (for example historical buildings)	3	3 to 8	8 to 10	8

*) For frequenses over 100 Hz should at least criteria for 100 Hz be used
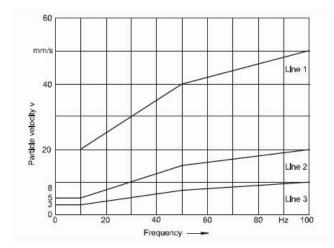

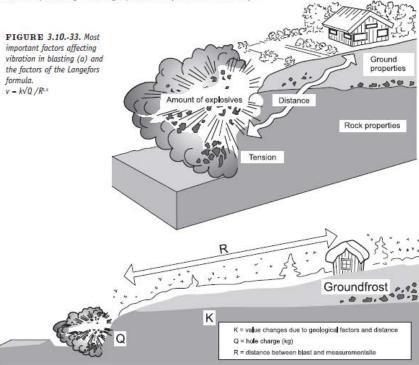**FIGURE 3.10.-32.** *Vibration in structures, DIN 4150, part 3/11/1986*

In the past, the same low damage threshold values, such as 0.25 g and 0.1 g, have been used for vibration sensitive equipment such as computers. These very stringent restrictions can sometimes create major problems for the contractor.

By using shock isolators it is possible to reduce shock severity by storing shock energy within the isolators, and also through the subsequent release of the energy over a longer period of time.

One method fore reducing blasting vibrations is to drill a slot in the rock, between the vibration source and the building. If the slot is drilled close to and along the foundation, the house is protected not only against vibration but also against back break and rock heaving below the foundation. By performing slot drilling in front of a vibration-sensitive building or plant, an almost 80 % reduction in vibration levels can been achieved.

Practical simple formula.

The ratio between charge/distance and ground vibration can be used to make a simple formula for planning blasting operations (**FIGURE 3.10.-33.**).

FIGURE 3.10.-33. *Most important factors affecting vibration in blasting (a) and the factors of the Langefors formula.*
$v = k\sqrt{Q}/R^{1.5}$

K = value changes due to geological factors and distance
Q = hole charge (kg)
R = distance between blast and measurementsite

Vibration velocity:

$$v = K \sqrt{Q}/R^{1.5}$$

where Q = instantaneously detonating charge (kg)
R = distance (m)
v = vibration (particle) velocity (mm/s)
K = transmission factor, constant depending on the
homogeneity of the rock and the presence of faults
and cracks. For hard granite, this can be approx.
400 but it is normally lower. And is lower as the distance is greater.

Practical methods to reduce ground vibrations by limiting the cooperating charging weight per interval are:

- Adapt ignition pattern so that the charging level is spread over more intervals and scattering in the delay elements of the detonators is utilized
- Reduce hole number and diameter
- Use decked charges by dividing the necessary drillhole chargeevel into more ignition intervals through sand plugs
- Use decoupled charges; charge diameter smaller than hole diameter
- Divide bench into more benches. Do not blast to final depth at once.

Upon detonation, there should be as little confinement as possible. This is obtained by:

- Carefully adapting the ignition pattern, so that all holes break the burden in the easiest way
- Increasing hole inclination (drillhole)
- Avoiding too large burdens and choke blasting

For blasting at distances shorter than 50 - 100 m, the risk of interaction between various intervals is small. Cooperation risk between intervals increases with large blasts in quarries, where, for example, vibration- sensitive structures are not in the vicinity. Vibration size is then influenced by:

- Charging level
- Interval times
- Resonance frequency of the ground (which depends on the distance, depth and the character of the ground)
- Local geology

Costs of reducing vibration levels

The costs of careful blasting near residential areas increase very rapidly with decreasing permissible vibration levels. The cost increase depends primarily on the following factors:

- Drilling   - smaller or greater number of drillholes.
- Charging   - more detonators and higher labor costs
- Blasting   - more rounds and longer standup time special charges

Planning and control work costs also increase in:

- Blasting
- Visual inspections
- Vibration measurement
- Blasting record
- Insurance administration

In addition to the above-mentioned costs, a number of problems also exist that are hard to estimate in terms of money.

Building inspections are performed to document the condition of a structure before and after blasting. Most structures have cracks which the building's occupants are usually not aware of.

To optimize blasting work, risk analysis is required to determine the acceptable vibration size and what size charge can be blasted at a certain distance without exceeding the vibration limit.

Risk analysis should be made through a careful examination of factors that affect blasting operations prior to blasting. The more information is available, the more accurate the result is. The decision should be based on as many points as possible in the list below.

Vibration measurements

Vibration measurements are performed to monitor and control the effect of vibrations on buildings, installations in buildings and to what degree the disturbance affects people. The underlying principle is to measure the vibrations where they are first transmitted to the object of concern. However, in the USA., gauges are usually attached to the ground outside the foundation, as home owners seldom allow gauges to be mounted on or inside the building.

THROW AND FLYROCK

In bench blasting, there are two types of rock movement:

- Forward movement of the entire rock mass which is mainly horizontal
- Flyrock, which is scatter from the rock surface and front of the blast

A specific charge of 0.2 kg/cu.m. does not cause forward movement of the rock; it only breaks the rock.

Hard-rock TBMs can be used in relatively soft to hard rock conditions, and best when rock fracturing & weakness zones are predictable. The TBM is most economical method for longer tunnel lengths, in which its high investment cost and timely build-up can be utilized by the high advance rate of excavation. TBM excavation produces a smooth tunnel with low rock reinforcement cost, and is optimal in terms of flow resistance in long ventilation or water tunnels.

Shielded TBMs or shield machines are used in loose soil and mixed ground, and in conditions where high water ingress is expected. The mechanical and/or pressurized shield prevents ground settlement and ground water inflow. Because of continuous ground control and no blast vibrations, this method is commonly used in urban tunneling. Pipe-jacking is a special application, in which the tunnel lining is continuously pushed by heavy hydraulic jacks as the tunnel advances. Microtunneling is a special application of pipe-jacking in no-man-entry sized tunnels.

Roadheaders can be used for tunneling in stable rock conditions of low-to-medium hardness. Where it is applied, the roadheader combines the versatility of drill & blast for producing various tunnel geometries, and the continuity of full-face mechanical excavation. As it lacks blast vibration, this method can be used in sensitive urban areas. In harder rock conditions, use of roadheaders is limited by a shorter lifetime of tools and increasing cutting tool cost.

Hammer tunneling evolved in the late 1980´ and combines a continuous method with low equipment costs. It has gained popularity mainly in the Mediterranean countries and Japan. The tunnel face geometry is unlimited, and the method is effective in rocks of low-to-medium compressive strength, when the rock mass is relatively fractured. In hard and compact ground, application is limited by low production rate.

6.2. METHODS

6.2.1 Drilling and blasting

DRILLING PATTERN DESIGN

The drilling pattern ensures the distribution of the explosive in the rock and desired blasting result. Several factors must be taken into account when designing the drilling pattern: rock drillability and blastability, the type of explosives, blast vibration restrictions and accuracy requirements of the blasted wall etc. The basic drilling & blasting factors, and drilling pattern design are discussed below. Since every mining and construction site has its own characteristics, the given drilling patterns should be considered merely as guidelines.

DRIFTING AND TUNNELING

Many mines and excavation sites still plan their drilling patterns manually, but advanced computer programs are available and widely used. Computer programs make it easier to modify the patterns and fairly accurately predict the effects of changes in drilling, charging, loading and production. Computer programs are based on the same design information used in preparing patterns manually.

Basic design factors

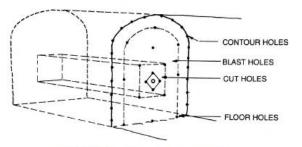The tunnel of drift face can be roughly divided into four sections (**FIGURE** *6.2.-1.*).

FIGURE *6.2.-1. Types of holes in a tunnel face.*

Drilling pattern design in tunneling and drifting is based on the following factors:

- Tunnel dimensions
- Tunnel geometry
- Hole size
- Final quality requirements
- Geological and rock mechanical conditions
- Explosives availability and means of detonation
- Expected water leaks
- Vibration restrictions
- Drilling equipment

Depending on site conditions, all or some of the above factors are considered important enough to determine the tunnel drilling pattern. Construction sites typically have several variations of drilling patterns to take into account the changing conditions in each tunnel. Drifting in mines is carried out with 5 to 10 drilling patterns for different tunnel sizes (production drifters, haulage drifters, drawpoints, ramps etc.) The pattern is finalized at the drilling site. Tunnel blasting differs from bench blasting in that tunnels have only one free surface available when blasting starts. This restricts round length, and the volume of rock

that can be blasted at one time. Similarly, it means that specific drilling and charging increases as the tunnel face area decreases.When designing a drilling pattern in tunneling, the main goal is to ensure the optimum number of correctly placed and accurately drilled holes. This helps to ensure successful charging and blasting, as well as produce accurate and smooth tunnel walls, roof and floor. A drilling pattern optimized in this way is also the most economical and efficient for the given conditions.

Hole size

Hole sizes under 38mm in diameter are often considered small, holes between 41mm - 64mm intermediate, and those over 64mm large. Most tunneling operations today are based on hole sizes between 38 - 51mm in diameter. Only cut holes are larger than 51mm. Rock drills and mechanized drilling equipment used in tunneling and drifting are designed to give optimum performance in this hole range.Drifting rods are designed to match hole sizes and needs of horizontal drilling. Typical applications use tunneling rods and 1 1/4" and 1 1/2" drill steel sizes. Drill steels between 1" and 1 1/8" are used for hole sizes less than 38mm.

The number of holes needed per tunnel face area decreases as hole size increases. The difference is not much in small tunnels, but becomes more significant in large tunnel face areas. Small hole sizes require smaller steels, but these bend more easily, giving rise to inaccurate holes and poor blasting.

Cut types

The blasting sequence in a tunnel or drift always starts from the "cut", a pattern of holes at or close to the center of the face, designed to provide the ideal line of deformation. The placement, arrangement and drilling accuracy of the cut is crucial for successful blasting in tunneling. A wide variety of cut types have been used in mining and construction, but basically they fall into two categories: cuts based on parallel holes, and cuts that use holes drilled at certain angles.The most common types of cut today is the parallel and V cut (**FIGURE** *6.2.-2*). The V cut is the older of the two and is still widely used in construction. It is an effective type of cut for tunnels with a fairly
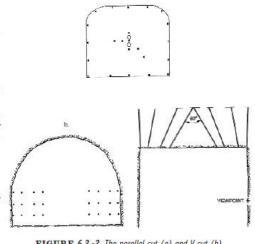

FIGURE *6.2.-2. The parallel cut (a) and V cut (b).*

large cross-section and requires fewer holes than a parallel cut. The parallel cut was introduced when the first mechanized drilling machines came on the market making accurate parallel drilling possible.

Parallel cut

The parallel cut has a large number of minor variations, however the basic layout always involves one or several uncharged holes drilled at or very near the center of the cut, providing empty space for the adjacent blasted holes to swell into. Uncharged cut holes are typically large, 76 - 127mm in diameter. A less common alternative is to use "small hole" openings (several small holes instead of one or two large holes). Small hole opening make it possible to use the same bit size throughout the whole drilling pattern. Experience proves that big hole openings give more reliable results than small hole openings.

To successfully blast a full round, the cut must be drilled, charged and blasted correctly. Cut holes are drilled very near to each other, as parallel as possible, as shown in **FIGURE** *6.2.-3*. Specific drilling in the cut section may rise above 10drm/m³. Apart from the large cut holes, other holes in the cut are the same size as the stope (face) holes. Large cut holes are normally drilled by reaming. First, a smaller, for example, 45mm diameter hole is drilled then reamed to the final size using a pilot adapter and a reaming bit.

Drilling holes several meters long as close together as possible demands great accuracy, but the advanced boom design and automated functions of modern drill jumbos make this quite easy. The parallel cut is especially suitable for modern mechanized tunneling equipment. This cut type has also made long rounds common in small tunnels. An earlier version of the parallel cut is the "burn cut" which does not use uncharged holes, relying instead on a very strong charge to burn the rock. Today, the parallel cut has replaced the burn cut.

Purpose of cut holes

In the parallel cut, the cut holes provide enough expansion space for the remaining blasted rock around it. The face area of a typical parallel cut varies from 1.6m x 1.6m to 2.5m x 2.5m. The right size is determined according to area of the tunnel face.

Big, uncharged cut holes (76 - 127mm dia.) provide an opening for the blasted, expanding rock from the surrounding cut holes. All holes are drilled very close to each other and detonated each with its own detonation number (**FIGURE** *6.2.-3*). The main idea is for each hole to loosen the rock in the front of it, allowing it to expand and fill the available open space. Cut holes are quite heavily charged and the blasted cut becomes a square opening. Basically, only drilling errors limit the gained advance per hole length.

The firing pattern

The firing pattern must be designed so that each hole has free breakage. The angle of breakage is smallest in the cut area where it is around 50°. In the stoping area the firing pattern should be designed so that the angle of breakage does not fall below 90° (**FIGURE** *6.2.-8.*)
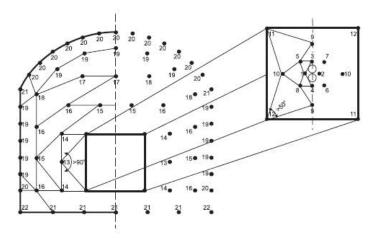

FIGURE 6.2.-8. *Firing sequence for tunnel in numerical order.*

It is important in tunnel blasting to have a long enough time delay between the holes. In the cut area, it must be long enough to allow time for breakage and rock throw through the narrow empty hole. It has been proven that the rock moves with a velocity of 40 - 70 meters per second. A cut drilled to a depth of 4 - 5 m would therefore require a delay time of 60 - 100 ms to be clean blasted. Normally delay times of 75 - 100 ms are used.

In the first two squares of the cut, only one detonator for each delay should be used. In the following 2 squares, two detonators may be used. In the stoping area, the delay must be long enough for the rock movement. Normally, the delay time is 100 - 500 milliseconds. For contour holes, the scatter in delay between the holes should be as little as possible to obtain a good smooth blasting effect. Therefore, the roof should be blasted with same interval number, normally the second highest of the series. The walls are also blasted with the same period number but with one delay lower than that of the roof.

Detonators for tunneling can be electric or non-electric. Contour holes should be initiating with detonating cord or with electronic detonators to obtain the best smooth blasting effect.

V cut

The V cut is a traditional cut based on symmetrically drilled, angled holes. It has lost some of its popularity with the widespread adoption of the parallel cut and longer rounds. However, it is still commonly used in wide tunnels where tunnel width sets no limitations on drilling. The working principle of the V cut is similar to surface excavation applications. The V cut requires slightly fewer hole meters than the parallel cut, which gives it an advantage in large tunnels. The V cut is based on surface blasting principles in which the angle for rock expansion equals or exceeds 90 degrees. The angle at the bottom of the cut holes should not be less than 60 degrees. Maintaining the right angle is the main difficulty in V-cut drilling; and, the correct drilling angle limits round length in narrow tunnels (**FIGURE** *6.2.-9a.*).
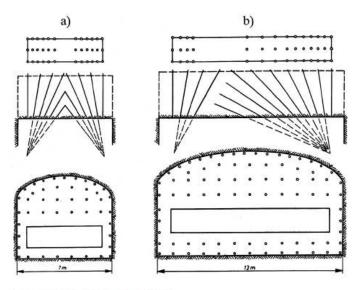

FIGURE 6.2.-9. *V cut (a) and Fan cut (b).*

Tunnel width limits the use of the V cut. In narrow tunnels, the advance per round can be less the one third of the tunnel width, which increases the number of rounds and the amount of drilled meters when excavating small tunnels. V cuts are easily drilled with mechanized rigs in large tunnels where tunnel width sets no limitations. The cut normally consists of two Vs but in deeper rounds the cut may consists triple or quadruple Vs.
Each V in the cut should be fired with the same interval number by MS detonators to ensure coordination between the blastholes in regard to breakage. As each V is blasted as an entity

one after the other, the delay between the different Vs should be in the order of 50 ms to allow time for displacement and swelling.

The fan cut

The fan cut (**FIGURE** *6.2.-9b*) is an other example of angled cuts. Like the V cut , a certain tunnel width is required to accommodate the drilling equipment to attain acceptable advance per round.

The principle of the fan is to make a trench-like opening across the tunnel and the charge calculations are similar to those in opening the bench. Due to the geometrical design of the cut, the hole construction is not large, making the cut easy to blast. Hole drilling and charging is similar to that of cut holes in the V cut.
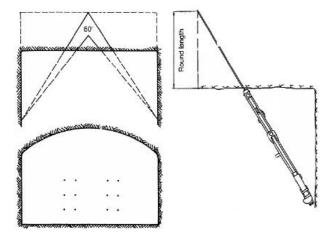

FIGURE *6.2.-10.* Feed set-up and drilling limitations in V cut.

Other design features

The design of the drilling pattern for tunnels should correlate with tunnel shape and size. The cut is normally placed vertically in the middle or side section, and horizontally on or slightly under the center line of the tunnel. The exact place is often left or right of the tunnel´s center point and varies with each round (**FIGURE** *6.2.-11.*).
Sometimes the tunnel is excavated in several sections, such as a top heading, followed by benching with lifters. The top is excavated as described above, but benching with lifters only requires stope holes since the excavated top heading acts as the "cut". It is also possible
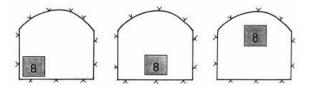

FIGURE *6.2.-11.* Various cut locations

that the opening for the blast or the cut section has been produced earlier by other means such as the full profile method (tunnel boring). In such cases, cuts are not required and the remaining excavation holes are drilled as stope holes. It is recommended that ditches and drains be excavated at the same time as the tunnel face but sometimes their design is more complicated and they must be excavated separately.

Look-out angle

The drilling pattern also includes information on the look-out angle needed at different points on the tunnel face. The look-out angle is the angle between the practical (drilled) and the theoretical tunnel profile (**FIGURE** *6.2.-12.*). If the contour holes are drilled parallel to the theoretical line of the tunnel, the tunnel face gets smaller and smaller after each round. To ensure that the correct tunnel profile is maintained, each contour hole is drilled at slight angle into the tunnel wall, the look-out angle, which of course can not be smaller than that permitted by the profile of the rock drill.
Adjusting the look-out angle by eye requires an experienced and skillful operator. Modern drilling rigs have electronic or automatic look-out angle indicators that enable correct adjustment of the look-out angle relative to standards alignment. Computerized drilling jumbos make setting, adjustment and monitoring of the look-out angle even easier. An incorrect
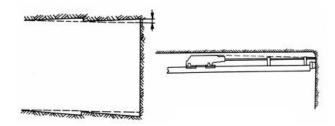

FIGURE *6.2.-12.* The look-out angle.

look-out angle produces over- or underbreak, both of which give uneconomical results. Other aspects such as curve and tunnel inclination also need to be considered when the drilling pattern is designed. Any excavation later on is both costly and time-consuming.

Tunneling accuracy

Inaccurate drill steel and rig set-up is often the result of "natural causes" or errors of human judgment. The tunnel may not provide enough room for proper alignment of the drilling unit. Cross cuts and curves can also cause similar difficulties due to the changed drilling boom alignment and coverage.

Inaccurate set-up causes misalignment of the entire tunnel and leads to over- and under-break. Rectifying the whole tunnel alignment later is extremely expensive.
The rock face frequently has cracks, joints, bumps and holes that prevent the hole from being drilled to its optimal position. When the hole is drilled in a new position, it can become unaligned or does not end in the same plane as the other holes. Inaccurate hole length leads to blasting difficulties causing uneven tunnel walls, roof and floor. Once started, misalign-ment can easily become compounded, making the following rounds even more difficult to drill (**FIGURE** *6.2.-13.*). The effect of hole accuracy on costs is described in the following example:

Example

A 5 x 5m construction tunnel has overbreak of 20% as a result of hole misalignment. After tests to correct misalignment five new holes are added to the pattern. A successfully drilled 5.1m round in this tunnel size would include fifty-four 45-mm, and two 89-mm cut holes. The difference in drilled meters per round is 25.5 drm and blasted rock volume approx. 25m³. In a 5000 meter-long tunnel, this adds up to 25,500 additional drilled and charged meters and 40,000m³ (loose) of extra rock to muck and haul away. Mucking and hauling would require more capacity, time and money. In addition to the direct effects, misalignment cre-ates other unfavorable factors such as increased need for rock support, such as increased bolting, shotcreting, concrete casting and unnecessary finishing works, e.g. filling or other support structures.

If overbreak is nearer 20% instead of the accepted or calculated 10%, the effect in a 5m x 5m tunnel is 12.5m³ of extra volume needing to be filled per round (5.1m hole length). For a 5,000 meter-long tunnel, the added volume would mean 12,500 m³ more concrete with corresponding costs. Extra concrete laying would require more time, which would set back the whole excavation process. If overbreak added one additional bolt per tunnel meter, the 5,000 meter-long tunnel would need 5,000 extra bolts, also increasing excavation costs and consuming more time.Underbreak always requires further excavation and is for this reason even more serious than overbreak.

Accurate tunneling, and accurate drilling and charging go hand-in-hand. The following topics need to be planned in advance to ensure accurate tunnel profile:

  - Known geological and rock mechanical conditions
  - Planned drilling pattern/patterns, correct hole size and hole length for the planned excavation
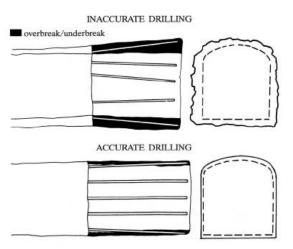

FIGURE *6.2.-13. Cumulative drilling errors in drifting and tunneling.*

 - Smooth blasting (contour blasting) procedure
 - Correct rig set-up
 - Correct hole alignment and look-out angle, with special consideration for the walls, roof and floor
 - Cut placement; inclined and curved tunnels are especially prone to under- and overbreak in the walls and roof and "bumps" in the tunnel floor
 - Accurate charging, the correct detonators and drilling pattern
 - Continuos follow-up procedures

Advance and yield

The parameter used to describe the advance of the excavation work in tunneling and drifting is called "pull" or advance per round, or yield per round.
In tunneling, the length to which the holes are drilled and charged is called the round length. It is one of the most important parameters when planning excavation since excava-tion depends on selecting the optimal round length.
The mechanization and automation of drilling equipment has led to longer rounds, typically 3 - 5 meters. Experiments have shown that round up to 8 meters long can be drilled and blast-ed successfully with special care and equipment (special explosives, rock conditions, special drilling equipment).

Round length must be optimized, bearing in mind several important aspects (**FIGURE** *6.2.-14.*).
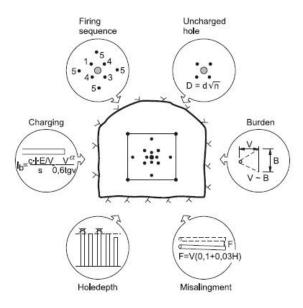

FIGURE *6.2.-14. Some aspects for optimizing the round length.*

- Stability
- Rock geological and mechanical conditions
- Drilling, charging, mucking and rock support equipment and related size, reach, maneuverability and efficiency
- Allocation of time within and between each round
- General working arrangements, work layout, distance between working places, support works needed, general regulations and legal questions (inspection needs, ground vibration restrictions etc.)
- Amount of equipment and labor, if restricted

A successfully blasted round still leaves some 20cm of unloosened drilled hole length. The excavated portion of the blasted round is called "pull" or the advance per round. Drilling accuracy, accurate hole placement and correct blasting methods are the most important

factors affecting pull. In the drilling pattern layout, the choice of cut and cut hole placement also affects the final advance.

The introduction of computerized drilling equipment has greatly improved hole and profile accuracy and extended the advance per round due to 97%. Computerization has proven especially efficient when drilling long rounds where poor accuracy with conventional drilling equipment leads to uneven hole bottoms. The preplanned optimal drilling patterns are described in three dimensional form and up-loaded into the drill jumbo´s on-board computer. The pattern includes information on the starting and ending point of the holes as well as hole length and look-out angle. Even when manual changes are made to the drilling pattern during operation, the program will adjust the new hole to finish at the same hole bottom as the other holes.

The effect of pull on the final result is easily seen when excavating a 5,000 meter long tunnel. If pull of a 5.1 meter long round is 90% instead of 95%, due to poor drilling or blasting accuracy, a total of 59 extra rounds must be drilled, blasted and mucked to complete the job. The cost of these extra rounds will depend on tunnel size, labor, equipment, time penalties and other site-related factors.

UNDERGROUND CHAMBER

As for rock blasting techniques, the construction of underground chambers does not differ from that of tunnels of the same magnitude. The width of underground chambers can not be too great due to the inability of the rock to support the roof with its own strength. For oil storage chambers and machine halls for hydro-electric power-plants, widths of 20 - 24 m have been constructed with no required heavy reinforcement. The height of the chambers may be up to 40m.
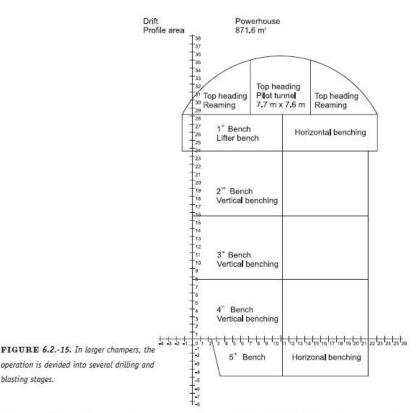
The construction of underground chambers is based on qualitative sound rock. Some economic aspects must be considered. If the chamber is located at too shallow a level, the cost of reinforcing the rock may be high because the quality of surface rock is normally poorer than rock at deeper levels. However, a deep location results in long access roads, which may cause problem during construction and when the chambers come into use.

Small underground chambers, with a height of less than 8 m are blasted as tunnels. In larger chambers, the operation is divided into several drilling and blasting stages (**FIGURE** *6.2.-15.*) in which different methods are used:

- Pilot tunnel with side stoping
- Horizontal benching
- Vertical benching

Example of a chamber excavation procedure plan.
Blasting a 31.5 m high x 21.1 wide rock cavern can be divided into three or four stages.

Drift
Profile area

Powerhouse
871.6 m²

FIGURE 6.2.-15. In larger champers, the operation is devided into several drilling and blasting stages.

First, the gallery with a height of 7.5m is drilled and blasted along the entire length of the cavern. A pilot heading is driven in the middle of the gallery (**FIGURE 6.2.-16.**) one or two rounds before the reaming of sides take place to enlarge the gallery to full width and length. The smooth blasting system is described in **FIGURE 6.2.-16 and FIGURE 6.2.-17.**

x-holes: Smooth blasting
ø 17 mm or ø 22 mm
•-holes: Anit ø 24 mm - 28 mm
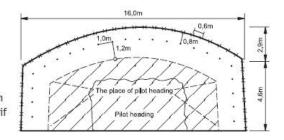o-holes and other holes: ANFO if
hole diameter d< 45 mm

FIGURE 6.2.-16. Smooth blasting system is in gallery.
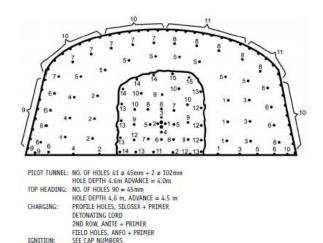Peak particle velocity on roof and walls v about 1000mm/s.

PILOT TUNNEL: NO. OF HOLES 41 ø 45mm + 2 ø 102mm
HOLE DEPTH 4.6m ADVANCE = 4.0m
TOP HEADING: NO. OF HOLES 90 = 45mm
HOLE DEPTH 4,6 m, ADVANCE = 4.5 m
CHARGING: PROFILE HOLES, SILOSEX + PRIMER
DETONATING CORD
2ND ROW, ANITE + PRIMER
FIELD HOLES, ANFO + PRIMER
IGNITION: SEE CAP NUMBERS
CONTOUR HOLE DISTANCE 0.6m
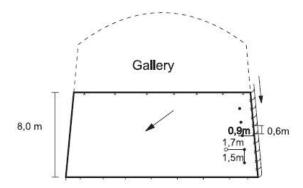
FIGURE 6.2.-17. Firing patterns in gallery.

The transient strain in the rock due to blasting depends upon the liner charge concentration per drill hole length, explosive strength and distance from the charge. For example, granite may fail in dynamic tension at a stress of approx. 30 Mpa or around a peak particle velocity of 1000 - 2000 mm/s depending on the wave type. Assuming that damage would occur around v = 1000mm/s, it is possible establish a proper blast pattern. Attention is paid also to rows adjacent to the perimeter row in order to minimize unwanted fracturing. In the stoping stage, an 8m-high bench was removed by horizontal stoping (**FIGURE 6.2.-18.**) and finally a vertical bench (**FIGURE 6.2.-19.**) or possibly two 8m horizontal benches are excavated.

The reinforcement methods are bolting and shotcrete lining. Systematic roofbolting is later carried out with a bolt density of 1 bolt/4 m². Bolt lengths in the arch part of the caverns range typically from 2.0 - 4.0 m, which is 0.15 - 0.30 times the width of the span. In walls, the corresponding lengths vary from 2.4 m - 6.0 m. The need for grouting has been limited.

When calculating the largest instantaneous charge permitted for different distances from buildings, the formula below is currently very commonly used when blasting large rock caverns.

$$v = k \, (R/\sqrt{Q})^{-n}$$

where (v) is the maximum particle velocity (mm/s); Q the cooperating charge and R the distance. The constants k and n vary with foundation conditions, blasting geometry and type of explosives.

x-holes: smooth blasting ø 17 mm or ø 22 mm
+ detonating cord
•-holes: Anit ø 32 mm
o-holes: ANFO

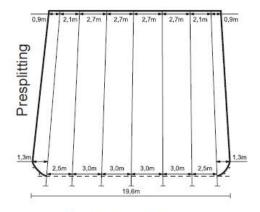FIGURE 6.2.-18. Presplitting system in horizontal stoping.

FIGURE 6.2.-19. Drilling, charge calculations.

ENVIRONMENTAL ASPECTS

Cautious Tunnel Blasting in this connection refers to tunnel blasting with reduced risk of ground vibrations, air shock waves or throw of stones (Chapter 3.10.). Ground vibrations constitute the primary problem when a tunnel passes under buildings or other sensitive installations or facilities. Air shock waves and stone throw occur when tunnels are being opened and, in many cases, this occurs in exposed places.

Often, mining problems with limited rock coverage and the need of reinforcement usually appear during initial blasting work on tunnels. The following measures are advised when carrying out initial blasting work on tunnels in built-up areas:

- Cautious blasting with limited hole depth, charges and holes per round
- Millisecond firing
- Suspended covering material.
- Ground vibration and air shock wave measurement (Chapter 3.10.).

In the opening up of tunnels, large hole cuts, preferably with two large holes, function well. Drilling is performed with a limited hole depth between 1.0 - 2.0 m depending on the location of the blasting site and the technical conditions of the rock. The first round consists of one cut hole, after which normally two cut holes per round are fired. In due course, the number of "cut spreader" holes and stoping holes per round increase depending on the weight of the covering and its capacity to remain in position during blasting. It is not advised to increase the number of drill holes per round to a great extent because in sensitive locations just a few too many holes can lift the covering material. Care is exercised even after the first advance so that the covering material used is able to block throw and reduce air shock waves.

Millisecond firing is the safest method to use. When using half-second firing, there is risk of the first delay lifting the covering material resulting in throw. Covering material should be used for each round until the tunnel has extended so far that air shock waves no longer have an influence. In straight tunnels, this can imply considerable distances. If vibration and air shock wave measurements are performed, blasting can be adapted to the values obtained. Since the air shock wave causes vibrations in the surrounding buildings, the horizontal shock wave component can be of the greatest interest in blasting of this type.

Air shock wave magnitude can be theoretically calculated based on charge amounts, delay sub-divisions and distance. The most difficult estimate is the charge enclosure factor which must be included when the explosive is charged in a drill hole. As more and more measuring material becomes available from air shock wave measurements, the accuracy of this type of calculation can be improved.

FIGURE 6.2.-20. shows the principle for opening a tunnel within a built-up area where buildings are located very close by.
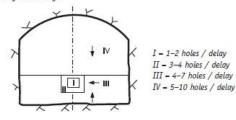

FIGURE 6.2.-20. Holes are closely located so that the charge in each drill hole can be limited.

LO SCAVO MECCANIZZATO

Lo scavo meccanizzato viene eseguito con macchine ed attrezzature di vario genere
- frese ad attacco localizzato (frese a.l., dette anche frese puntuali);
- frese a piena sezione (frese p.s. o TBM).

Mezzi che soddisfano in senso parziale il concetto d scavo meccanizzato sono inoltre il demolitore ad alta energia d'urto, per l'avanzamento sul fronte o per il completamento di particolari zone della sezione della galleria, nei metodi per fasi, od il ripper per l'esecuzione dei ribassi.

Lo scavo meccanizzato, in riferimento alle frese puntuali od alle frese a piena sezione, offre alcuni sostanziali vantaggi rispetto allo scavo con esplosivo, contro una certa mancanza di adattamento a molte condizioni geologiche e geotecniche per quel che concerne le TBM. Le frese puntuali, al contrario, potendo esser facilmente arretrate dal fronte, quando necessario, e sostituite con i consueti mezzi per lo scavo con esplosivo, rivelano una sufficiente flessibilità. C'è da osservare che questi due mezzi di scavo hanno in larga misura campi di applicazione del tutto differenti.

I vantaggi dello scavo meccanizzato sono in sintesi:
- maggiori velocità di avanzamento, quando le condizioni al contorno lo consentono;
- minore sovraprofilo;
- minor disturbo alle formazioni rocciose;
- minor manodopera;
- maggior sicurezza per il personale;
- minor disturbo all'ambiente esterno (mancanza di sviluppo di gas tossici, rumori e vibrazioni violente).

Per contro gli svantaggi possono essere:

-maggior costo d'investimento rispetto ai mezzi tradizionali dello scavo con esplosivo;

-difficoltà delle macchine a lavorare in condizioni di variabilità dell'ammasso roccioso

-costo degli utensili e dei ricambi;

-elevati tempi di montaggio e smontaggio , nel caso delle TBM;

-difficoltà di trarre la macchina (ciò vale per la TBM) dalla galleria in caso di guasti gravi od insuccesso;

-maggior consumo d'energia rispetto allo scavo con esplosivo ed impianti elettrici più costosi.

Machine Types and Systems

Tunnel Boring Machines (TBMs) nowadays are full-face, rotational (with cutter heads) excavation machines that can be generally classified into two general categories: Gripper and Segment as shown in Figure 6-11. Based on Figure 6-11, there are three general types of TBMs suitable for rock tunneling including Open Gripper/Main Beam, Closed Gripper/Shield, and Closed Segment Shield, as shown within the dashed box on the Figure.

The open gripper/beam type of TBMs are best suited for stable to friable rock with occasional fractured zones and controllable groundwater inflows. Three common types of TBMs belong to this category including Main Beam (Figure 6-12), Kelly Drive, and Open Gripper (without a beam or Kelly).

The closed shield type of TBMs for most rock tunneling applications are suitable for friable to unstable rocks which cannot provide consistent support to the gripper pressure. The closed shield type of TBMs can either be advanced by pushing against segment, or gripper. Note that although these machines are classified as a closed type of machine, they are not pressurized at the face of the machine thus cannot handle high external groundwater pressure or water inflows. Shielded TBMs for rock tunneling include: Single Shield (Figure 6-13), Double Shield (Figure 6-14), and Gripper Shield.

The typical machine elements and backup system for each category are discussed in the following section. Pressurized-face Closed Shield TBMs are predominantly utilized in tunneling in soft ground and are discussed in Chapter 7. Appendix D presents descrip
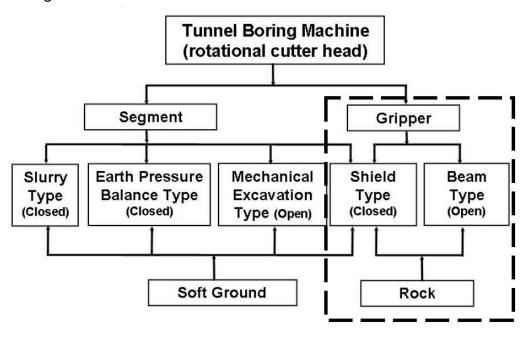

Figure 6-11   Classification of Tunnel Excavation Machines
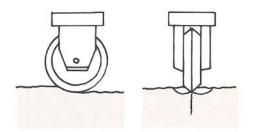
4.3   Mechanised excavation

The capability of machines which cut and excavate rock has improved greatly in recent years. The basic mechanisms and machines are shown below.

4.3.1   Drag pick

The drag pick is essentially a tool for soft rock, i.e. with a compressive strength $\sigma_c \le 80$ MPa (or less if the rock is massive or abrasive). Roadheaders are commonly used in the mining industry and are versatile for all types of openings.
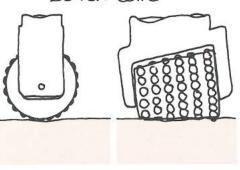

Drag pick

Disc cutter

4.3.2   Disc cutters/button cutters

Disc cutters and button cutters may be used for the mechanical excavation of much harder rocks: up to $\sigma_c = 250$ MPa compressive strength with discs and using buttons for harder rocks. Full-face tunnel boring machines (TBMs) are best suited to long lengths of relatively homogeneous rock. Their operation can be prevented by very high strength rock (inability to cut) or by very weak rock (inability of reaction rams to operate). The example of a full face TBM is from the Kielder project.
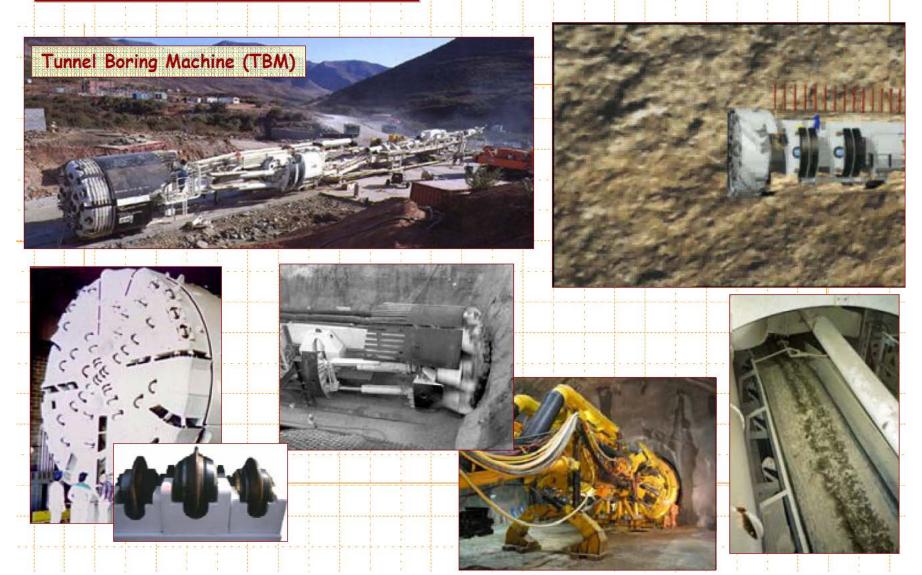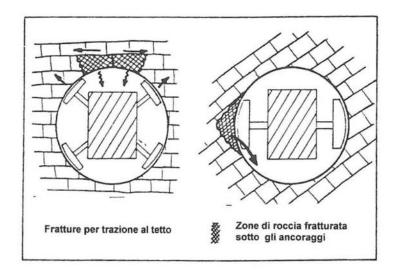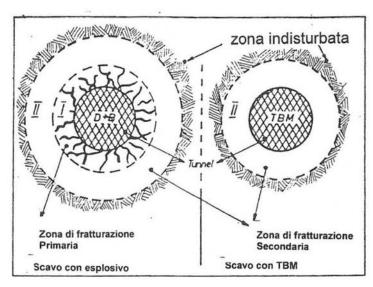

Button cutter

Roadheader

Tunnel boring machine

NORME AUSTRIACHE PER LO SCAVO CON FRESA (OSNORM 2203)

Classe di roccia	Influenza sull'avanzamento della fresa	Comportamento caratt. della roccia e provv. conseguenti		Posizione e tipo delle misure di sostegno.
		Nello scavo già eseguito	Nella zona delle piastre di ancoraggio	
I	Nessun coinvolgimento del cantiere per il sostegno della roccia	Stabile	Nessuna difficoltà	Non necessaria alcuna misura in zona fresa. Bullonatura < 0,3 m/m³
2		Nessuno sfornellamento in corrispondenza della macchina. Sono necessarie misure di sicurezza per prevenire distacchi.	Difficoltà limitate: non sono necessari provvedimenti particolari	Limitate misure di sostegno; bullonaggio locale della corona
3		Ripetuti crolli presso la macchina che provocano successivamente la perdita del profilo. Necessitano maggiori opere di sostegno, ma solo dopo alcune tratte di avanzamento.	Sgombero manuale di materiale distaccato.	Necessaria abbondante bullonatura da effettuarsi in coda alla macchina su parte del perimetro
4	Sono necessarie fermate della macchina per la messa in opera dei sostegni	Si devono fronteggiare crolli all'avanzamento durante e subito dopo l'azione della fresa. Sgombero di materiale attorno alla macchina	Rotture o cedimenti durante lo scarico o carico delle piastre. Sono necessarie misure per lo irrigidimento e la sostituzione del materiale disgregato con altre strutture.	Necessaria la posa in opera dei sostegni dalla zona dei carri ausiliari su parte del perimetro
5		Rotture e distacchi della roccia attorno alla macchina. Intervenire dietro la testa per evitare poss. crolli. Necessario lo sgombero di materiale.	E' necessaria la posa di elementi di ripartizione per ottenere un contrasto adeguato	Prevista la posa in opera, subito dietro la testa, di numerosi bulloni, spritz e lamiere ai piedritti ed in calotta
6	I provvedimenti per il sostegno devono essere presi davanti alla testa della fresa, eventualmente retratta. Per il contenimento laterale si deve procedere ad ingenti consolidamenti al contorno.	Incremento dei distacchi e delle def. plastiche della roccia. Per la messa in posa dei sostegni non si può attendere che il tratto dello scavo subito dietro alla testa sia liberato dalla macchina.	E' prevista la posa sistematica di elementi di ripartizione delle sollecitazioni ad ogni ciclo di avanzamento	E' necessaria la posa di bulloni, spritz e lamiere davanti alla testa, previo ritiro della macchina. Ricorso all'abbattimento convenzionale
7	Le cattive condizioni della roccia determinano il blocco della macchina	Impossibilità di impiego della fresa. Necessario procedere con metodi di scavo convenzionali provvedendo contemporaneamente al sostegno dello scavo.		

Mechanical Excavation

Tunnel Boring Machine (TBM)

Fratture per trazione al tetto

Zone di roccia fratturata sotto gli ancoraggi

zona indisturbata

D+B

TBM

Tunnel

Zona di fratturazione Primaria

Zona di fratturazione Secondaria
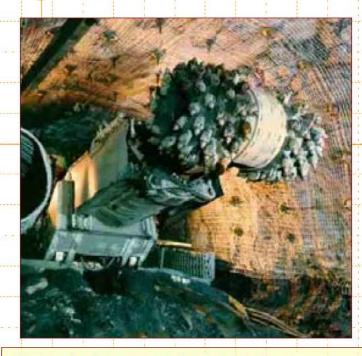
Scavo con esplosivo

Scavo con TBM

Schematizzazione dei problemi geomeccanici tipici del lavoro di una fresa p.s. In alto possibilità di rottura nella zona delle piastre di ancoraggio; in basso vantaggio dell'uso della macchina rispetto allo scavo con esplosivo

Mechanical Excavation

There are two basic types of machine for underground excavation: partial- and full-face machines:

Partial-face machines: use a cutting head on the end of a movable boom (that itself may be track mounted).

Full-face machines: use a rotating head armed with cutters, which fills the tunnel cross-section completely, and thus almost always excavates circular tunnels.

Mechanical Excavation

Full-face machines – when used for relatively straight and long tunnels (>2 km) – permit high rates of advance in a smooth, automated construction operation.

muck out

scoop

cut

Mechanical Excavation

The advance rate at which the excavation proceeds is a function of the cutting rate and utilization factor (which is the amount of time that the machine is cutting rock). Factors contributing to low utilization rates are difficulties with ground support and steering, the need to frequently replace cutters, blocked scoops, broken conveyors, etc.

The cutters may jam if the TBM is pushed forwards with too much force. Then they might scrape against the rock and become flattened on one side.

BAD

Mechanical Excavation – Tool Wear

Delays: When the tunnel boring machine is inside the tunnel, the cutters must be changed from the inside the cutting head.
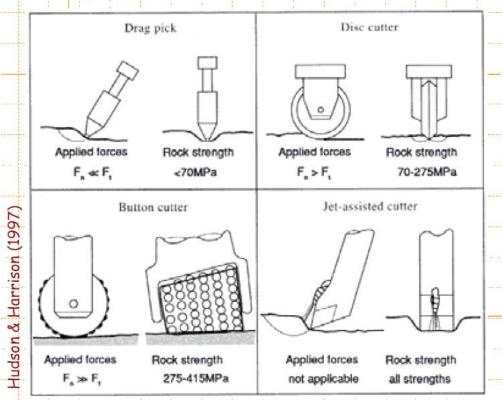
Mechanics of Rock Cutting – Tool Wear

The primary impact of disc wear on costs can be so severe that cutter costs are often considered as a separate item in bid preparation. In general, 1.5 hours are required for a single cutter change, and if several cutters are changed at one time, each may require 30-40 minutes. Even higher downtimes can be expected with large water inflows, which make cutter change activities more difficult and time-consuming.

Limestone, marl, conglomerates, phyllites, marbles

Bit life-span [m/bit]

Bit wear: very low, low, moderate, high, very high, extremely h.

new
uneven wear
normal wear
heavy wear

Mechanics of Rock Cutting

In tunnelling terms, a TBM applies both thrust (F_n) and torque (F_t) during the cutting process. In selecting the proper cutting tool, the engineer wishes to know how the tools should be configured on a machine cutting head, how to minimize the need to replace cutters, how to avoid damaging the cutter mounts, and how to minimize vibration.
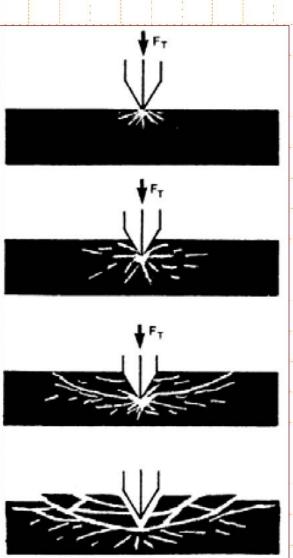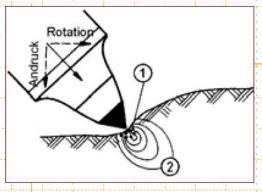

Hudson & Harrison (1997)

Drag pick		Disc cutter	
Applied forces $F_n \ll F_t$	Rock strength <70MPa	Applied forces $F_n > F_t$	Rock strength 70-275MPa
Button cutter		Jet-assisted cutter	
Applied forces $F_n \gg F_t$	Rock strength 275-415MPa	Applied forces not applicable	Rock strength all strengths

new

uneven wear

normal wear

heavy wear

Mechanics of Rock Cutting – Disc Cutter

The mode of cutting involves a complex mixture of tensile, shear and compressive modes of failure. With thrust, the cutting disc penetrates the rock and generates extensive crack propagation to the free surface. Further strain relief occurs as the disc edge rolls out of its cut, inducing further tensile cracking and slabbing at the rock surface.
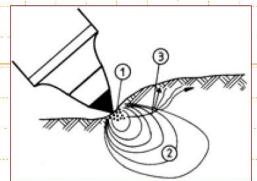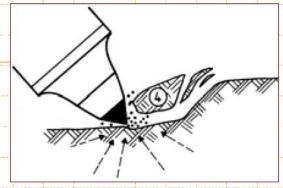

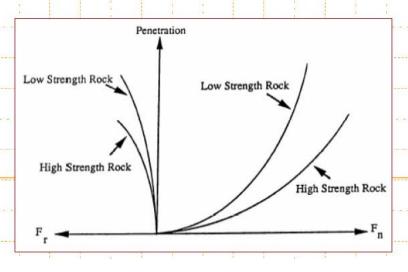Whittaker & Frith (1990)
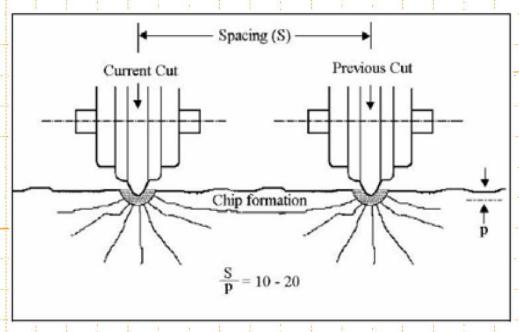
Mechanics of Rock Cutting – Drag Pick

① **Force applied causing zone of surface crushing**

② **Induced stresses from point load**

③ **Initiation and propagtaion of microfractures**
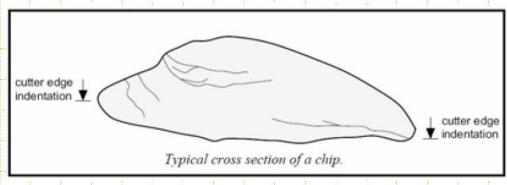
④ **Breaking and ejection of rock chip**

Mechanics of Rock Cutting

Spacing (S)

Current Cut   Previous Cut

Chip formation

$$\frac{S}{p} = 10 - 20$$

cutter edge indentation

cutter edge indentation

Typical cross section of a chip.
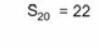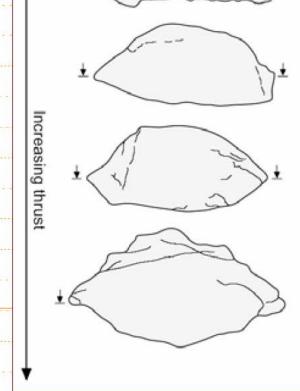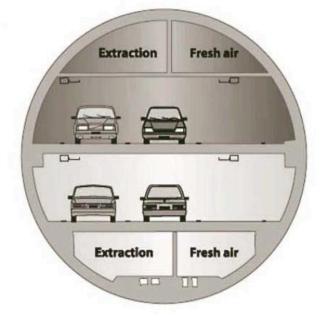
Amphibolitic gneiss
SJ = 30
S_{20} = 22

Increasing thrust

A-86 Road Tunnel in Paris, France (FHWA, 2006)

Figure 1-6   Chongming Tunnel under the Yangtze River

Tunnel Boring Machines (TBM)

While progress and mechanization continued to be applied to drill and blast excavation well into the 1960's, the actual advance rates were still quite low, usually measured in feet per day. Mechanized tunneling machines or tunnel boring machines had been envisioned for over a century but they had never proven successful. That began to change in the 1960's when attempts were made to apply oil field drilling technology. Some progress was made, but it was slow because the physics were wrong – the machines attempted to remove the rock by grinding it rather than by excavating it. All of that changed in the later 1960's with the introduction of the disk cutter. The disk cutter causes the rock to fail in shear, forming slabs (chips) of rock that are measured in tens of cubic inches rather than small fractions of a cubic inch. Much of the credit for this development, which now allows tunnels to advance at 10's or even 100's of feet per day, belongs to The Robbins Co.

Today, tunnel boring machines (TBM) excavate rock mass in a form of rotating and crushing by applying enormous pressure on the face with large thrust forces while rotating and chipping with a number of disc cutters mounted on the machine face (cutterhead) as shown in Figure.
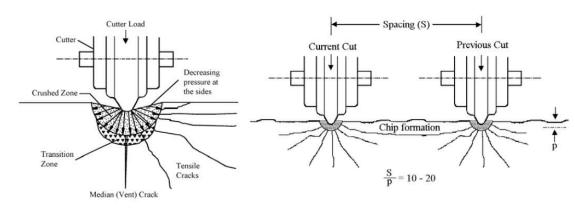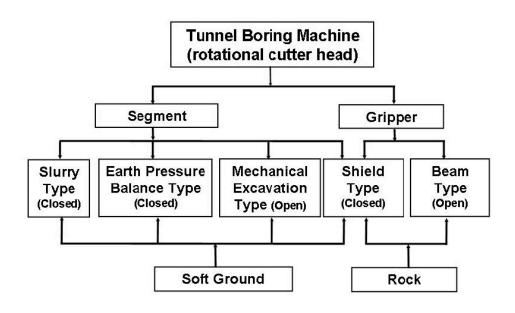

Figure 6-9   Chipping Process between Two Disc Cutters (After Herrenknecht, 2003)

TUNNEL BORING MACHINES (TBM)

A Tunnel Boring Machine (TBM) is a complex system with a main body and other supporting elements to be made up of mechanisms for cutting, shoving, steering, gripping, shielding, exploratory drilling, ground control and support, lining erection, spoil (muck) removal, ventilation and power supply. Figure 6 shows a general classification of various types of tunnel boring machines for hard rock and soft ground.

Classification of Tunnel Boring Machines (Figure 6-11)

Hard Rock TBM

As shown in Figure above, tunnel boring machines (TBM) suitable for rock tunneling nowadays are full-face, rotational (types of cutter head) excavation machines and can be generally classified into two general categories: Gripper and Segment based on the machine reaction force. Three common types of hard rock TBMs are described hereafter:
- Open Gripper Main Beam TBM (Open Gripper Type)
- Single Shield TBM (Closed Segment-Shield Type)
- Double Shield TBM (Closed Gripper/Segment-Shield Type)
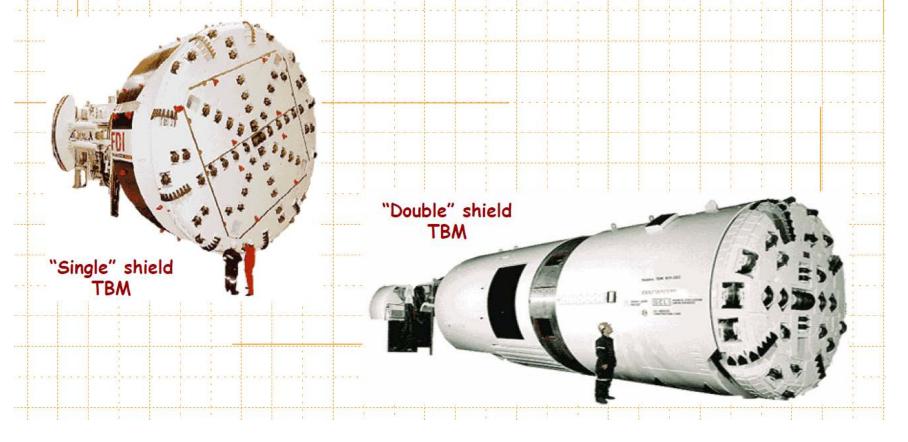
TBM Excavation & Design

TBM insertion through vertical shaft.

TBM gripper used to provide reactionary force for forward thrust by gripping onto sidewalls of tunnel.

TBM working platform for installing support (e.g. rock bolts, meshing, shotcrete).

TBM Excavation & Design

Single & Double Shield TBM's – Single-shield TBM's are cheaper and are the preferred machine for hard rock tunnelling. Double shielded TBMs are normally used in unstable geology (as they offer more worker protection), or where a high rate of advancement is required.
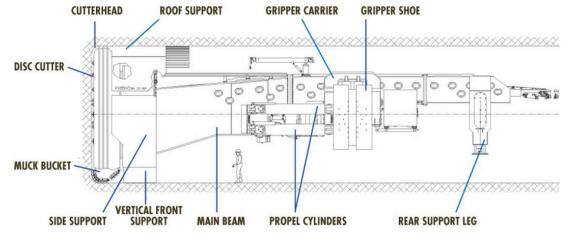

"Single" shield
TBM

"Double" shield
TBM

CUTTERHEAD   ROOF SUPPORT   GRIPPER CARRIER   GRIPPER SHOE

DISC CUTTER

MUCK BUCKET

SIDE SUPPORT   VERTICAL FRONT SUPPORT   MAIN BEAM   PROPEL CYLINDERS   REAR SUPPORT LEG

Figure 6-12   Typical Diagram for a Open Gripper Main Beam TBM (Robbins).

ARTICULATION CYLINDER   THRUST CYLINDER   INSTALLED SEGMENTS   CONVEYOR

CUTTERHEAD

DISC CUTTER
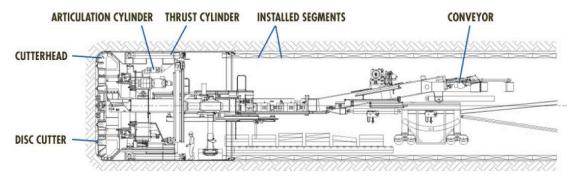
Figure 6-13   Typical Diagram for Single Shield TBM (Robbins)

CUTTERHEAD

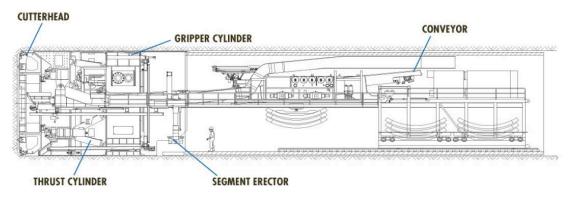GRIPPER CYLINDER   CONVEYOR

THRUST CYLINDER   SEGMENT ERECTOR

Figure 6-14   Typical Diagram for Double Shield TBM (Robbins)

- Various shovel types
- Cutterbooms
- Hammers

Drill rigs have also been mounted on-board for blasthole drilling and bolting. Consequently, such tunnel excavators are frequently used in small sections where standard-sized equipment is too big or can not get through the restricted available space.

B) FULL FACE

HARD ROCK

Contrary to soft-ground tunneling where the main objective is to control and support the ground, the goal of hard-rock tunneling is to cut the rock as fast as possible. Daily advance rates of 170 m (diameter 3,4m) have been reported. The application range is extensive and compressive strengths up to 300 MPa can be handled. The diameter range of available TBMs extend from 1.6m - 12m.

The tunnel length should take into consideration the investment costs including as to whether a new or refurbished TBM should be used. A TBM's life time (including some over-hauls) is up to 25 km. Full depreciation of the investment on one project is an exception.

Long and small tunnels can be driven effectively by Tunnel Boring Machines, TBMs; short and large tunnels (such as highway tunnels) often are more suited to D&B, where permitted.

The cutting tool used on TBMs are important. Starting with relatively small discs (< 14" dia)

FIGURE 6.2.-51. Example open hard-rock TBM.

it required more and more power and one solution was to increase the cutter discs diameter. Large disc diameters require higher loads to achieve reasonable penetration rates and levels

off at approx. 19". There is a tendency today to focus on 17" high performance discs which provide sufficient service life and which keep the design of the TBM in feasible limits.

Basic operation of a TBM

The cutting process is performed by disc cutters. These cutters - generally steel rings - are pressed against the face. The contact pressure between the disc and rock pulverizes the rock on contact and induces lateral cracking towards the neighboring kerf - and rock chipping. To achieve the best performance, kerf spacing (distance between two adjacent tracking cutters) and cutterload must have suitable values for each rock type. Average values of 80 - 110 mm spacing and 250 kN cutter load for 17" (= 430 mm) discs are sufficient in most cases.
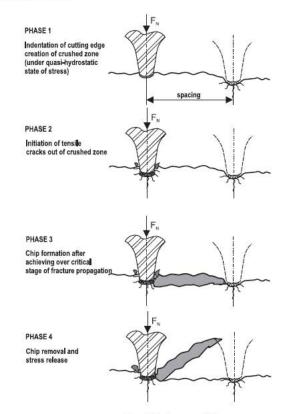

PHASE 1
Indentation of cutting edge creation of crushed zone (under quasi-hydrostatic state of stress)

spacing

PHASE 2
Initiation of tensile cracks out of crushed zone

PHASE 3
Chip formation after achieving over critical stage of fracture propagation

PHASE 4
Chip removal and stress release

FIGURE 6.2.-52. Cutting process TBM.

Double-gripper TBMs

Contrary to the single-gripper machine, the double-gripper TBM is supported by two sets of grippers that perform the whole guiding function of the TBM. The front dust shield only seals off the dust from the tunnel and cleans the invert.

The main frame, which is stabilized by the grippers, does not move. To advance the cutter-head, a sliding inner frame is used. Steering during boring is almost impossible; and there-fore double-gripper TBM´s bore a polygonal tunnel line.
Muck discharge is also done by a belt conveyor from the top of the frame to the end of the TBM.

Double grippers have the advantage of better distributing the gripper forces to the tunnel wall in weak ground. However a disadvantage is taking up free work space for passage and consolidation projects at least in smaller diameters.
Furthermore the skewed process stresses gage cutters and main cutterhead bearing.
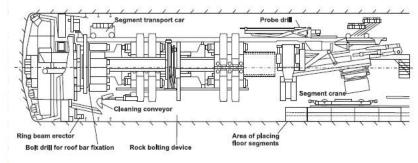(**FIGURE** *6.2.-54.*).

FIGURE *6.2.-54. Scheme Double-gripper TBM.*

Main TBM assembly groups

Cutterhead:
The cutterhead is a rigid steel structure that supports the cutters and loads the muck onto a belt conveyor. Depending on machine size and site conditions, the cutterhead can be one piece or of sectional design. For sectionally designed cutterheads bolted versions are used. Replacement of worn discs on the cutterhead is performed by replacing the cutters held in special saddles by bolts or a wedge lock system. Particularly 3.5 m double-gripper machines usually have front loading systems, which means cutter change can only be performed from

the front. In bad ground conditions, this procedure can be dangerous to people performing this job. Bigger machines have back-loading systems that allow cutter change from inside the head.

FIGURE *6.2.-55. ATB 50 HA Back loading Cutterhead.*

FIGURE *6.2.-56. ATB 35 HA Front loading Cutterhead.*

The buckets load the muck from the invert and discharge it into the hopper. It is very impor-tant to keep the bucket lips in good condition and as close as possible to the cut wall to reduce gauge wear on the cutters and on the cutterhead. Specially designed backloading buckets reduce the remaining fines in the tunnel invert.

Disc Cutters:

Disc cutters have an important role in tunnel boring including the layout of cutters on the cutterhead (kerf spacing) and the shape of the cutterhead itself. In special cases and if the diameter must be kept constant for as long as possible, button cutters with tungsten carbide inserts are recommended. Button cutters are commonly used on micro TBMs where access to the cutterhead is not possible.

The steel disc rings are mounted on a hub assembly which comprises the bearing and seal arrangement. The most common type of bearing is a pre-stressed pair of case-hardened conical roller bearings.

Cutter life varies extensively from approximately 30 bcm to 3000 bcm depending on the rock type and especially on its quartz content. The most popular disc shape today is the "constant section" ring, which means the disc footprint does not change significantly with wear.

Main Drive:

The main drive is integrated in the structure of the front dust shield (single gripper system). It comprises the main bearing, generally a three axis roller bearing; double conical roller bearing, the main seal arrangement and planetary drives for the main motor in smaller machines. Most of the machines are electric, with single and double speed run on pole-changing motors or frequency controlled drives in difficult geological conditions. There is a multiple-disc clutch located between the main motor and the planetary gear that protects the main drive against overload and for start-up if stalled. For cutter change and maintenance, an auxiliary drive allows the cutterhead to turn in slow motion.

Installed power is approx. 250 kW/m of diameter (only a rough indicative value depending on the cutter size and geological situation) which means a 3.5 m TBM has approx. 1000 kW installed power on the cutterhead.

Rear Gripper (single-gripper TBM):

The gripper is thrust against the tunnel wall and the TBM is propelled forward by hydraulic cylinders connected to the grippers. Gripper force is distributed via the grippers to the rock. Depending on the rock, the contact pressure is limited to approx. 350 N/cm≤. Studs in the gripper help in slippery conditions.

The gripper cylinder is carried in a frame which allows vertical and horizontal steering. The frame is guided by a specially designed guide along the main frame.

Consolidation, Probe drills

Consolidation Drills:

Provision for dealing with weak rock conditions provisions can be made by installing a pair of roof bolters just behind the dust shield. This allows a primary roof support in poor ground conditions. Due to restricted available space, systematic bolting should be done from the back-up.
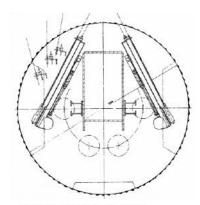

FIGURE 6.2.-57. Front Roof Bolting.

Probe Drills:

Most TBMs provide probe drill equipment, which are generally hydraulic percussion hammers that allow drilling up to 50 m ahead. Special rock sampling rigs are provided on request. It is highly recommended to perform probe drilling outside the tunnel diameter because if the probe hole jams the drill rod, advancing of the TBM is not hindered. If drilling in the tunnel cross-section and the drill rod gets stuck, it is hard to get the drill rod out because the cutterhead is not able to cut the steel, and this ultimately damages the cutters.
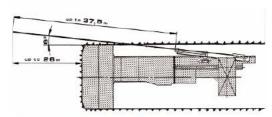

FIGURE 6.2.-58. Probe drill arrangement.

Operator location

The operator's location, whether on the TBM or on the back-up, is convenient because it comprises all necessary instrumentation to operate the TBM including the back-up system. Video cameras monitor the important points of the process such as the loading point, train change and areas of danger. All operating data are shown on a PLC display. Data recording of

the most relevant data is a standard today. The operator's location is sound-proofed and air-conditioned.

Shielded TBMs

For special conditions in which core sampling is impossible, or the rock is known to be very weak and fractured and if the contract also specifies partial or continuous concrete lining, the shielded TBM is the right equipment for the job.
The shielded TBM, as the name says, looks similar to a shield, but the working process is different.

A shielded TBM is a hard-rock TBM enclosed by a shielded body. The rear end of the machine has a pair of integrated grippers to stabilize the TBM in the tunnel. The front end with the cutterhead is pushed forward out of the telescopic shield via advance jacks. A ring of segments can be simultaneously erected under the shield tail cover. After completing the cutting stroke and segment lining erection simultaneously, the TBM´s rearpart with the grippers is reset into the next position.

If the rock is too weak to give enough resistance for advancing the TBM, the shield mode can be used. In this case, the rear thrust jacks will push against the segment ring and advance the machine. In this event, a parallel operation is not possible which slows the advance rate.

Segment systems used together with shielded TBMs usually serve as a primary lining; and is not watertight. Honeycomb or normal lining can be used. Developments of watertight lining systems have been developed, but provide at the time only sufficient tightness of low pressure conditions. Daily advance rates of up to more than 100 m can be achieved but require excellent logistics from the jobsite organization.
The backup system performs similar requirements as for open TBMs in addition with segment handling and grouting logistics.
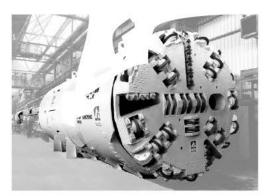

FIGURE 6.2.-59. Example of a shielded TBM.

6.2.3. Shaft excavation

Vertical or steeply inclined tunnels called raises or shafts are usually required for ventilation, access and hoisting in hydropower projects and penstock tunnels etc. A deeply inclined or vertical tunnel is usually called a shaft. A raise is an opening underground that goes from one level to another.

Shaft and raise excavation has always been considered one of the most difficult tasks in construction. Today, however, modern equipment offers efficient and safe methods for this type of excavation.

RAISE EXCAVATION USING THE DRILL AND BLAST METHOD

Four different methods are generally used for raise excavation by the drill and blast method. Method selection depends mainly on the length of the raise:

- Raise building
- Long-hole method
- Alimak method
- Inclined tunnel method

Raise building

Raise building is the oldest method of raise excavation.
Excavation progresses upward from a platform that must be built and dismantled before and after each blast. Drilling is performed with hand-held jackleg drills.
Excavation advancement is slow and working under a blasted roof on a high platform is hazardous. Therefore, the raise building method has been mostly replaced by more advanced methods.
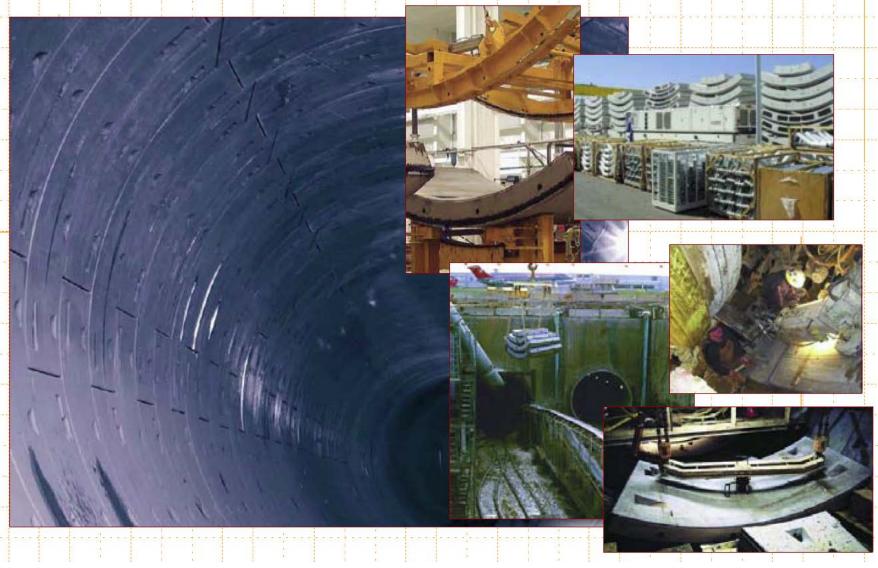
Long-hole method

The long-hole method is suitable for raises with more than a 45-degree inclination (sufficient for rock removal). Maximum raise length, normally from 10 to 60 meters, depends on drilling accuracy, hole alignment and geology. For successful blasting, maximum hole deviation should not exceed 0.25 meters (10").

Excavation via the long-hole method starts by drilling all the holes in the drilling pattern through to the next level. After drilling, each hole's accurate position is recorded to determine the right detonating sequence for the holes. This must be repeated after each blast, because the positions can vary in each blasting section due to hole deviations. (FIGURE 6.2.-60.).

Blasting starts from the bottom up with the center part always some rounds ahead. The last few meters can be blasted at one go.

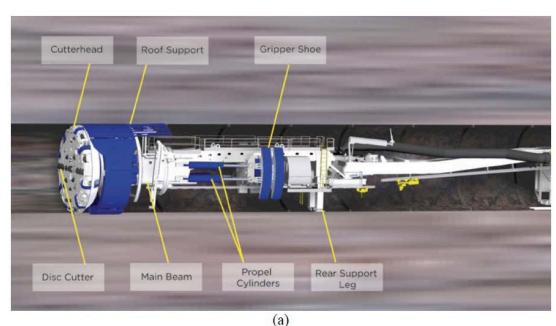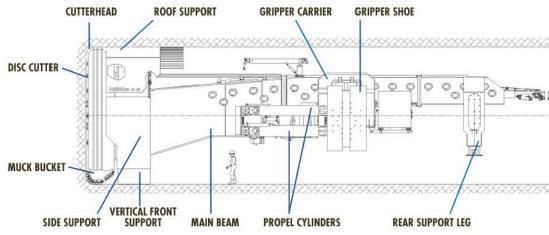# TBM Excavation & Design - Pre-Cast Linings

Open Gripper Main Beam TBM

The open gripper-beam category of TBMs is suited for stable to friable rock with occasional fractured zones and controllable groundwater inflows. Figure (Robbins) illustrates a typical diagram of a modern open gripper main beam TBM and highlights the major components including:

- Cutterhead (with disc cutters) and Front Support
- Main Beam
- Thrust (propel) Cylinder
- Gripper
- Rear Support
- Conveyor
- Trailing backup system for muck and material transportation, ventilation, power supply, etc.

The front of the gripper TBM is a rotating cutterhead that matches the diameter of the tunnel. The cutterhead holds disc cutters. As the cutterhead turns, hydraulic propel cylinders push the cutters into the rock. The transfer of this high thrust through the rolling disc cutters creates fractures in the rock causing chips to break away from the tunnel face. A floating gripper system pushes on the sidewalls and is locked in place while the propel cylinders extend, allowing the main beam to advance the TBM. The machine can be continuously steered while gripper shoes push on the sidewalls to react the machine's forward thrust. Buckets in the rotating cutterhead scoop up and deposit the muck on to a belt conveyor inside the main beam. The muck is then transferred to the rear of the machine for removal from the tunnel. At the end of a stroke the rear legs of the machine are lowered, the grippers and propel cylinders are retracted. The retraction of the propel cylinders repositions the gripper assembly for the next boring cycle. The grippers are extended, the rear legs lifted, and boring begins again.

(a)

(b)

D-2   Typical Diagram for an Open Gripper Main Beam TBM (Robbins).
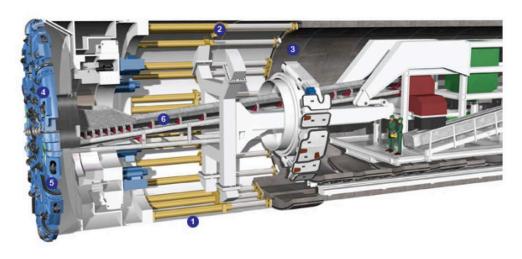
Figure shows the front of the Herrenknecht S-210 Gripper TBM used in the construction for the Gotthard Base Tunnel, Switzerland.

ıre D-3   Herrenknecht S-210 Gripper TBM (Herrenknecht)

Single Shield TBM

As shown in Figure, the Single Shield TBMs are fitted with an open shield (unpressurized face) to cope with more brittle rock formations or soft rock. The TBM is protected by the shield (1), and extended and driven forward by means of hydraulic thrust cylinders (2) on the last completed segment ring (3). The rotating cutterhead (4) is fitted with hard rock disk cutters, which roll across the tunnel face, cutting notches in it, and subsequently dislodging large chips of rock (Figuer 6-9). Muck bucket (5), which are positioned at some distance behind the disks, carry the dislodged rock pieces behind the cutterhead. The excavated material is brought to the surface by conveyers (6).

Notes:
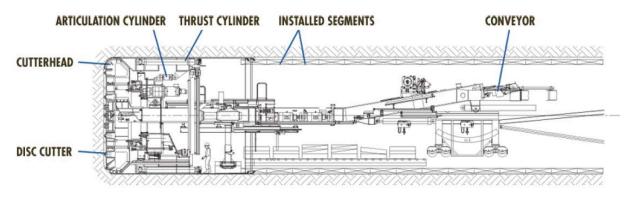(1) Shield; (2) thrust cylinders; (3) segmental lining; (4) cutterhead; (5) muck bucket; and (6) conveyers

Figure D-5   Typical Diagram for Single Shield TBM (Robbins)

Single Shield TBM

Figure above shows the cutterhead of the Herrenknecht S-256 Single Shield TBM used in the construction of the Islisberg tunnel, Switzerland, which on completion will be the longest underground section of the western Zurich bypass, will be directing transit traffic to central Switzerland around the city. The diameter of the cutterhead is about 38' (11.8 m).
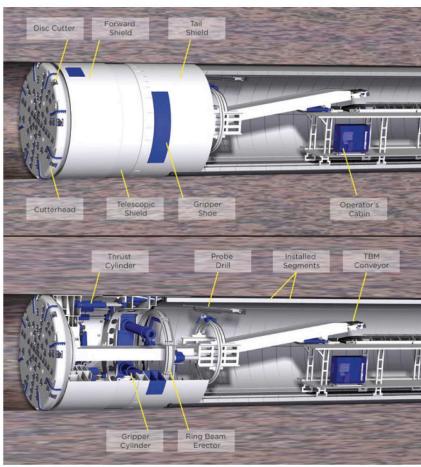
Double Shield TBM

A Double Shield TBM (Figure) consists of a rotating cutterhead mounted to the cutterhead support, followed by three shields: a telescopic shield (a smaller diameter inner shield which slides within the larger outer shield), a gripper shield and a tail shield.

In double shield mode, the gripper shoes are energized, pushing against the tunnel walls to react the boring forces just like the open gripper TBM. The main propel cylinders are then extended to push the cutterhead support and cutterhead forward. The rotating cutterhead cuts the rock. The telescopic shield extends as the machine advances keeping everything in the machine under cover and protected from the ground surrounding it.

The gripper shield remains stationary during boring. A segment erector is fixed to the gripper shield allowing pre-cast concrete tunnel lining segments to be erected while the machine is boring. The segments are erected within the safety of the tail shield. It is the Double Shield's ability to erect the tunnel lining simultaneously with boring that allows it to achieve high performance rates. The completely enclosed shielded design provides the safe working environment.

If the ground becomes too weak to support the gripper shoe pressure, the machine thrust must be reacted another way. In this situation, the machine can be operated in "single shield mode". Auxiliary thrust cylinders are located in the gripper shield. In single shield mode they transfer the thrust from the gripper shield to the tunnel lining. Since the thrust is transferred to the tunnel lining, it is not possible to erect the lining simultaneously with boring. In the single shield mode, tunnel boring and tunnel lining erection are sequential operations.
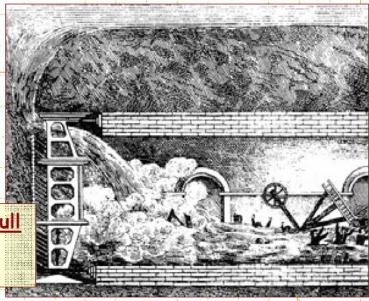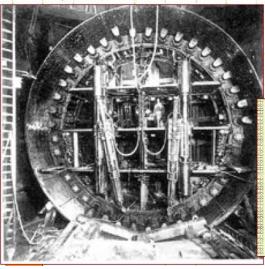
Figure D-8 Typical Diagram of a Double Shield TBM (Robbins).

Tunnel Excavation in Soft Ground Conditions

Started in 1825, flooding was a constant problem for Brunel in tunnelling under the Thames. In one such flood 6 men drowned. Brunel's complaint to those offering advice on tunnelling in such difficult conditions, "In every case they make the ground to suit the plan and not the plan to suit the ground".

Completed in 1843, Brunel's tunnel is still in <u>full</u> use as part of London's Underground railway system, exactly as built!

James Greathead's tunnel under the Thames (the 1869 Towers Subway) was built using a 7'1¾" (?) diameter circular shield propelled by screw jacks, that employed the first use of cast iron segments for the lining. Greathead's circular shield became the model for later open-face shields.

Pressurized Face Soft Ground TBM

As shown, various types of tunnel boring machines (TBM) are suitable for soft ground tunneling in different conditions. Chapter 7 presents briefly the history and development of shield tunneling machines. Table 7-4 (reproduced below) lists various types of shield tunneling methods in soft ground.

Nowadays modern pressurized-face closed shield TBMs are predominantly utilized in large diameter soft ground tunneling. Section 7.3 describes the principles of the two common types: earth pressure balance (EPB) machines and slurry face machines (SFM) , and offers guidelines for selecting between EPB and SFM. This appendix presents the components of each type of TBM and describes the construction sequences.

Table 7-4   Shield Tunneling Methods in Soft Ground (Modified from Hitachi Zosen, 1984)

Type	Description	Sketch
Blind shield	• A closed face (or blind) shield used in very soft clays and silts • Muck discharge controlled by adjusting the aperture opening and the advance rate • Used in harbor and rive crossings in very soft soils. Often results in a wave or mound of soil over the machine	
Open face, hang-dug shield	• Good for short, small tunnels in hard, non-collapsing soils • Usually equipped with face jacks to hold breasting at the face • If soil conditions require it, this machine may have movable hood and/or deck • A direct descendent of the Brunel shield	
Semi-mechanized	• The most common shield • Similar to open face, but with a back hoe or boom cutter • Often equipped with "pie plate" breasting and one or more tables • May have trouble in soft, loose, or running ground • Compressed air may be used for face stability in poor ground	
Mechanized	• A fully mechanized machine • Excavates with a full face cutter wheel and pick or disc cutters • Manufactured with a wide variety of cutting tools • Face openings (doors, guillotine, and the like) can be adjusted to control the muck taken in versus the advance of the machine • Compressed air may be used for face stability in poor ground	
Slurry face Machine	• Using pressurized slurry to balance the groundwater and soil pressure at the face • Has a bulkhead to maintain the slurry pressure on the face • Good for water bearing silts and sands with fine gravels. • Best for sandy soils; tends to gum up in clay soils; with coarse soils, face may collapse into the slurry	
Earth pressure balance (EPB) machine	• A closed chamber (bulkhead) face used to balance the groundwater and/or collapsing soil pressure at the face • Uses a screw discharger with a cone valve or other means to form a sand plug to control muck removal from the face and thereby maintain face pressure to "balance" the earth pressure • Good for clay and clayey and silty sand soils, below the water table • Best for sandy soils, with acceptable conditions	
Earth pressure balance (EPB) high-density slurry machine	• A hybrid machine that injects denser slurry (sometimes called slime) into the cutting chamber • Developed for use where soil is complex, lacks fines or water for an EPB machine, or is too coarse for a slurry machine	

Tunnel Excavation in Soft Ground Conditions

Location	Support			Excavation		Reaction Force	Machine	
	Cavity	System		Method	Tool		Category	Type
		Face						
Face and cavity	Shield			PFM	Rod header/ Back hoe/ Manual excavation	Thrust Jacks	Soft Ground Machines	Open Shield
		Mechanical		TBM	Cutting bits/ Cutting knives & teeth	Thrust Jacks		Mechanical Supported Closed Shield
				PFM	Road header/Back hoe			Mechanical Supported Open Shield
		Fluid	Compressed Air	TBM	Cutting bits/Cutting knives & teeth			Compressed Air Closed Shield
				PFM	Road header/ Back hoe/ Manual excavation			Compressed Air Open Shield
			Slurry	TBM	Cutting disk/ Cutting bits/ Cutting knives & teeth			Close Slurry Shield – Slurry Shield – SS-Hydroshield
				PFM	Road header/Back hoe			Open Slurry Shield – Special Open - Slurry Shields
			Earth Pressure Balance	TBM	Cutting disk/ Cutting bits/ Cutting knives & teeth			Earth Pressure Balance Shield - EPBS Special EPBS
	None or fluid	None or slurry or Earth Press. Balance						Combined Shield - Mix Shield - Polishield

Tunnel Excavation in Soft Ground Conditions
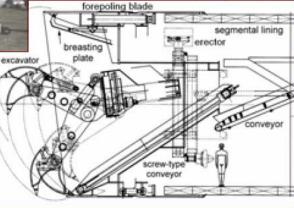
Machine	
Category	Type
Soft Ground Machines	Open Shield
	Mechanical Supported Closed Shield
	Mechanical Supported Open Shield
	Compressed Air Closed Shield
	Compressed Air Open Shield
	Close Slurry Shield – Slurry Shield – SS-Hydroshield
	Open Slurry Shield – Special Open - Slurry Shields
	Earth Pressure Balance Shield - EPBS Special EPBS
	Combined Shield - Mix Shield - Polishield

Open shields are favoured where the ground is free standing.

Closed shields are favoured where the ground is very weak, such as soft clay, silt or running sand.

Slurry shields are favoured for water saturated sandy soils and gravels (<10% clay and silt content; e.g. running sand).

EPB shields are favoured for water saturated silty soils (>7% clay and silt content; <70% gravel content).

Shield Tunnelling

Advantages of shield tunnelling in soft ground:

1. Tunnel construction can be performed as one step at its full dimensions.
2. Constant support is provided to the advancing tunnel even though it takes the form of a moving system.
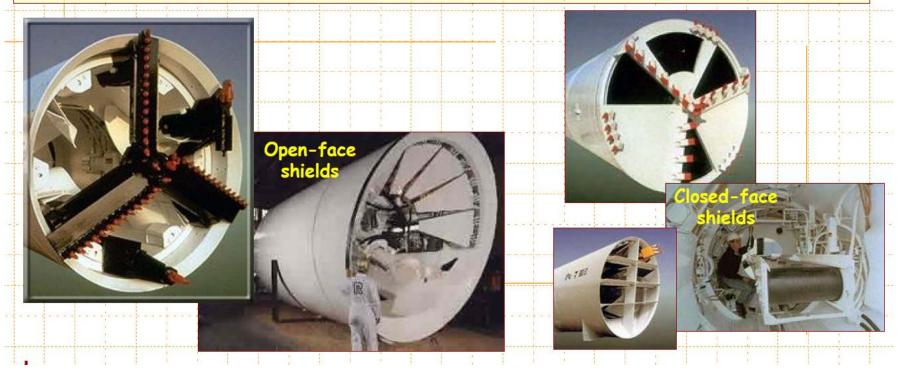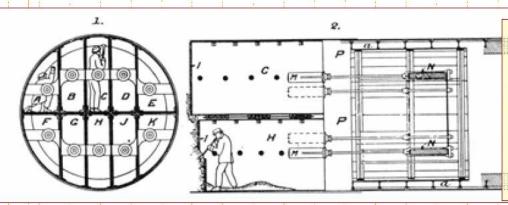3. Omission of temporary support is compensated for by virtue of the immediate installation of the permanent lining.

Whittaker & Frith (1990)

forepoling blade
segmental lining
erector
breasting plate
excavator
conveyor
screw-type conveyor

Shield Tunnelling

Open- & Closed-Face Shields – When the tunnel face is free standing and does not require continuous support, the shield is operated in 'Open Mode'. The face is mechanically supported by the cuttinghead while the flood control doors regulate muck flow from the face to the cuttinghead chamber. The excavated muck is rapidly extracted by the conveyor. With a closed-face, an airlock and bulkhead are used to allow the "excavation chamber" to be pressurized with compressed air or a slurry to aid face support.
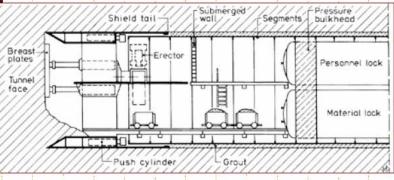

Open-face shields

Closed-face shields

Shield Tunnelling – Compressed Air

James Greathead solved the problem of containing groundwater during the construction of subaqueous tunnels in loose soil, by combining shield tunnelling with the use of compressed air during his 1886 construction of the London Underground.

This led to a considerable increase in the number of shield driven tunnels world-wide. At the beginning of the 20th century, the majority of the tunnels were built with Greathead shields.
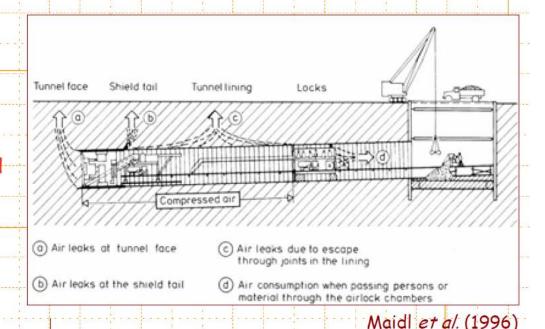
Shield Tunnelling – Compressed Air

Factors to account for when tunnelling with compressed air:

- Air pressure must be kept in balance with the hydrostatic pressure;
- Maximum pressure cannot exceed 4 bar (or 400 kPa), i.e. 3 bar excess pressure;
- Earth pressure cannot be resisted directly, it has to be withstood by natural or mechanical support;
- Ability to maintain pressure may be compromised by the air permeability of the ground (i.e. leakage);
- Cover above the tunnel must be 1-2 tunnel diameters (depending on ground type) to avoid blow-outs;

Tunnel face   Shield tail   Tunnel lining   Locks

Compressed air

(a) Air leaks at tunnel face

(b) Air leaks at the shield tail

(c) Air leaks due to escape through joints in the lining

(d) Air consumption when passing persons or material through the airlock chambers
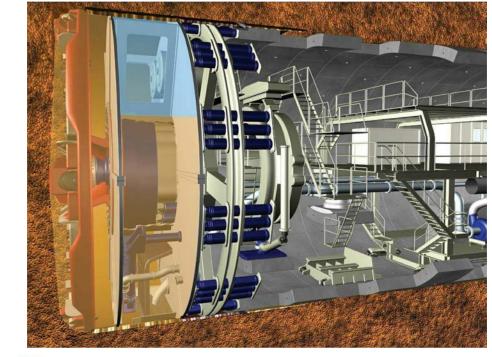
Maidl *et al.* (1996)

- Shorter working hours result from loss of time during compression and decompression;
- Reduced performance of miners (danger of caisson's disease);
- Increased danger of fire (due to increased oxygen content).
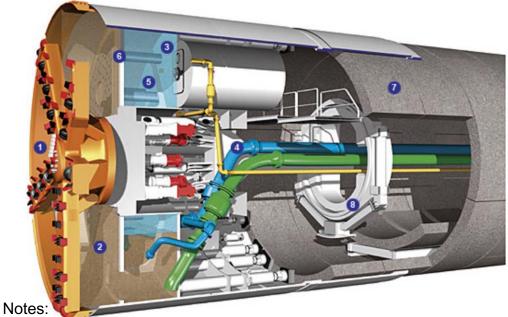
Slurry Face Machine

Slurry face machine (SFM) are pressurized face shield machines specially designed for tunneling in soft ground especially where the ground is loose waterbearing granular soils that are easily separated from the slurry at the separation plant. **The SFM provides stability at the face hydraulically by bentonite slurry kept under pressure to counteract the native earth and groundwater pressure, and to prevent an uncontrolled penetration of soil or a loss of stability at the tunnel face.**

Figure shows typical diagrams of Herrenknecht's mixshield machine which employs the slurry face support principle. At the mixshield machine face the soil is loosened by the cutterhead (1) rotating in the bentonite suspension. The soil then mixes with the bentonite suspension. The area of the shield in which the cutterhead rotates is known as the excavation chamber (2) and is separated by the pressure bulkhead (3) from the section of the shield under atmospheric pressure.

The bentonite suspension supplied by the feed line (4) is applied in the excavation chamber via an air cushion (5) at a pressure equaling the native soil and water pressure, thus preventing an uncontrolled penetration of the soil or a loss of stability at the tunnel face. For this reason the excavation chamber behind the cutting wheel is separated from the pressure bulkhead by a so-called submerged wall (6). The area of the submerged wall and pressure bulkhead is known as the pressure/working chamber. Note that unlike the typical slurry shield machines, in the mixshield machines. the support pressure in the excavation chamber is not directly controlled by suspe sion pressure but by a compressible air cushion between the pressure bulkhead and the submerged wall.

Notes:
(1) Cutterhead; (2) excavation chamber; (shion; (6) wall; (7) Segmental Lining; and (8) segment erector
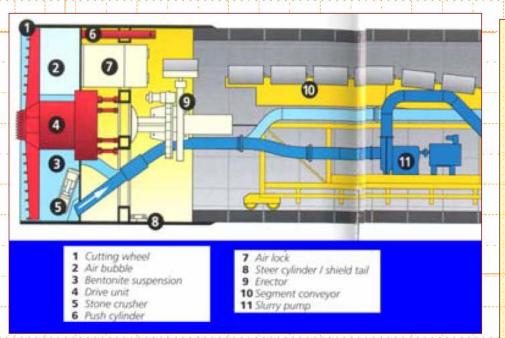
Figure shows the Herrenknecht S-317 Mixshield TBM used in the construction of the Shanghai Changjiang Under River Tunnel Project in China. The diameter of the cutterhead is over 50' (15.4 m).

Slurry Shields

Due to problems regarding health and safety as well as operational aspects (in highly permeable ground, maintaining air pressure at the tunnel face is difficult), compressed air shields are being used less and less. Instead, slurry shields and earth-pressure balance shields are being favoured more.
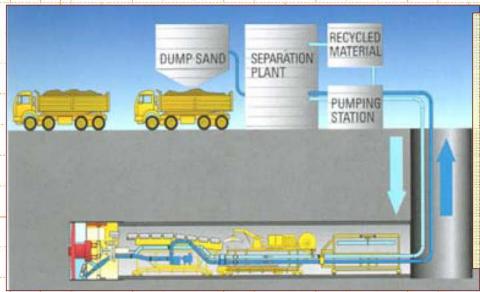

1 Cutting wheel
2 Air bubble
3 Bentonite suspension
4 Drive unit
5 Stone crusher
6 Push cylinder
7 Air lock
8 Steer cylinder / shield tail
9 Erector
10 Segment conveyor
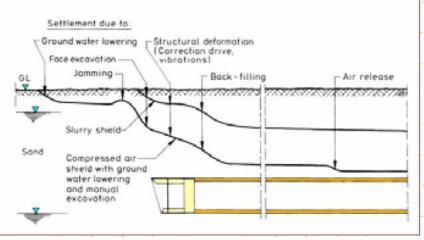**11** Slurry pump

Slurry shield operating principle:

· Tunnel face is supported by bentonite slurry (i.e. tunnel is free from compressed air);
· The slurry is mixed and pumped into a closed excavation chamber;
· The slurry enters the ground, sealing it (filter cake) and enabling pressure to be built up and balanced with the earth and water pressure.
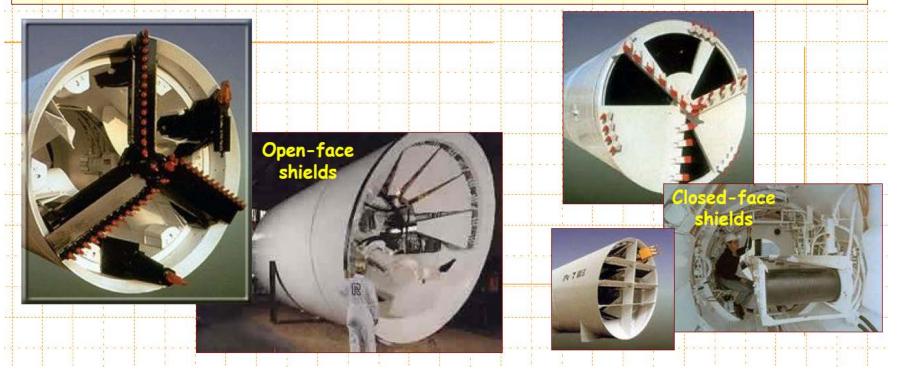
Slurry Shields

As the ground is excavated, it is mixed with the slurry in the excavation chamber. The ground/suspension mixture is then pumped to the surface. In a separation plant, the slurry is sparated from the ground. New bentonite is added as required, and the fluid is pumped back to the tunnel face.

Overall, slurry shields provide a safe tunnelling method causing low settlements. Application is possible in all kinds of loose ground with/without groundwater. Disadvantages include the separation plant (cost, space, energy requirements) and environmental hazards related to tailings (non-separable bentonite slurry containing fines).
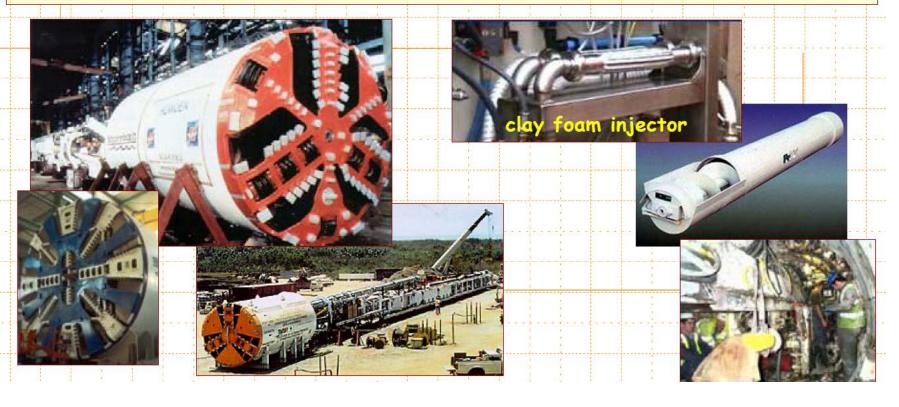

Maidl et al. (1996)

TBM Excavation & Design

Open- & Closed-Face Shields – When the tunnel face does not require a continuous and pressure balanced support, the TBM is operated in 'Open Mode'. The face is mechanically supported by the cuttinghead while the flood control doors regulate muck flow from the face to the cuttinghead chamber. The excavated muck is rapidly extracted by the conveyor. With a closed-face, an airlock and bulkhead are used to allow the "excavation chamber" to be pressurized with compressed air to aid face support.
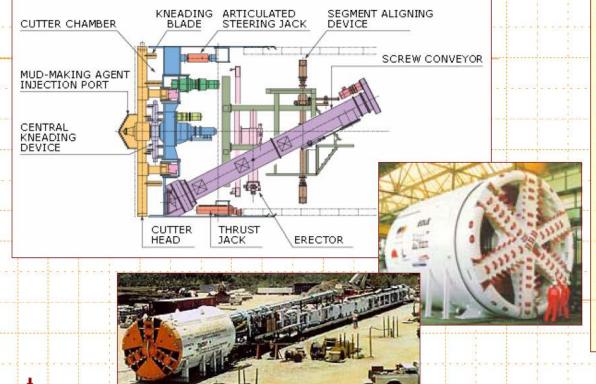

Open-face shields

Closed-face shields

TBM Excavation & Design

Earth Pressure Balance (Closed-Face Shield) – This method provides continuous support to the tunnel face by balancing earth pressure against machine thrust. As the cutterhead rotates and the shield advances, the excavated earth is mixed with foams in the cutterhead chamber to control its viscosity. The pressure is then adjusted by means of the rate of its extraction (by screw conveyor) to balance the pressure exerted by the ground at the tunnel face. This enables near surface tunnelling in bad ground conditions with minimal surface settlement.

clay foam injector
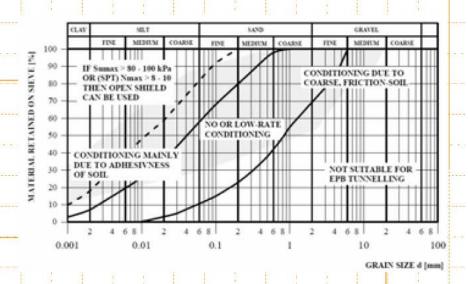
Earth Pressure Balance Shields

With a growing percentage of fines, slurry shield tunnelling requires an increasing degree of sophistication and cost for separation (and increasing frequency of slurry renewal). Apart from the high costs and environmental hazards involved, the confined space in most major cities makes the installation of a separation plant on surface difficult. Such were the conditions encountered in the early 70's in Japan, which led to the development of Earth-Pressure Balance shields (EPB).

CUTTER CHAMBER
KNEADING BLADE
ARTICULATED STEERING JACK
SEGMENT ALIGNING DEVICE
SCREW CONVEYOR
MUD-MAKING AGENT INJECTION PORT
CENTRAL KNEADING DEVICE
CUTTER HEAD
THRUST JACK
ERECTOR

EPB Shields: provide continuous support to the face by balancing earth pressure against machine thrust. As the cutterhead rotates and the shield advances, the excavated earth is mixed with foams in the cutterhead chamber to control its viscosity. The pressure is then adjusted by means of the rate of its extraction (by screw conveyor).
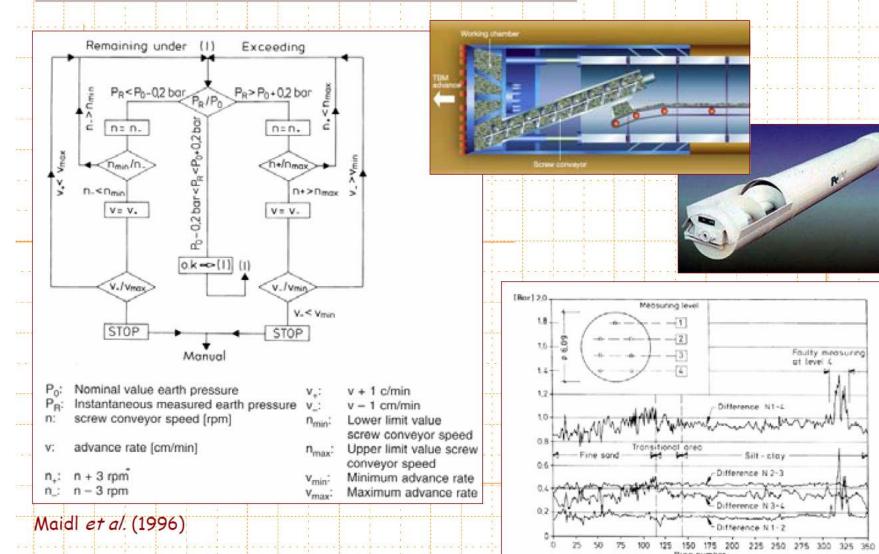
Earth Pressure Balance Shields

The key advantages of EPB Shields are that no separation plant is required and that the method is economically favourable in ground with a high percentage of silt/clay.
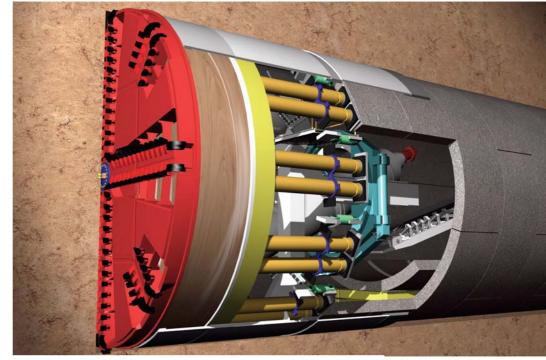

clay foam injector

When using EPB tunnelling mode, no bentonite and special treatment plants are necessary and the outcoming soil is nearly natural. If additives like Foam or Polymers are used, highly biodegradable versions exist which can be 95% destroyed after 28 days.
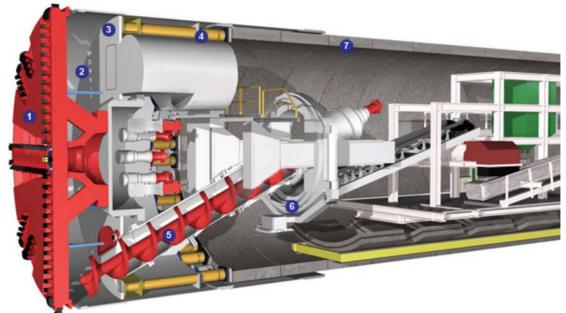
Earth Pressure Balance Shields

Remaining under (I)   Exceeding

$P_R < P_0 - 0.2$ bar P_R / P_0 $P_R > P_0 + 0.2$ bar

$n = n_-$ $n = n_+$

n_{min} / n_- n_+ / n_{max}

$n_- < n_{min}$ $n_+ > n_{max}$

$v = v_+$ $v = v_-$

$P_0 - 0.2$ bar $< P_R < P_0 + 0.2$ bar

o.k $\rightarrow$ (I)   (I)

v_+ / v_{max} v_- / v_{min}

$v_+ < v_{max}$ $v_- < v_{min}$

STOP   STOP

Manual

P_0:   Nominal value earth pressure
P_R: Instantaneous measured earth pressure
n: screw conveyor speed [rpm]
v: advance rate [cm/min]
n_+: $n + 3$ rpm
n_-: $n - 3$ rpm

v_+: $v + 1$ c/min
v_-: $v - 1$ cm/min
n_{min}:   Lower limit value screw conveyor speed
n_{max}:   Upper limit value screw conveyor speed
v_{min}:   Minimum advance rate
v_{max}:   Maximum advance rate

Maidl *et al.* (1996)

Earth Pressure Balance Machine

Earth pressure balance machines (EPB) are pressurized face shield machines specially designed for operation in soft ground especially where the ground is silty and has a high percentage of fines bot of which will assist the formation of a plug in the screw conveyor and will control groundwater inflows.

Notes:
(1) Cutterhead; (2) excavation chamber; (3) bulkhead; (4) thrust cylinders; (5) screw conveyor; (6) segment erector; and (7) Segmental Lining

The EPB machine continuously supports to the tunnel face by balancing the inside earth and water pressure against the thrust pressure of the machine. The working area inside the EPB machine is completely sealed against the fluid pressure of the ground outside the machine.

As shown in Figure, the soil is excavated (loosened) by the cutterhead (1) serves to support the tunnel face. The area of the shield in which the cutterhead rotates is known as an excavation chamber (2) and is separated from the section of the shield under atmospheric pressure by the pressure bulkhead (3). The excavated soil falls through the openings of the cutterhead into the excavation chamber and mixes with the plastic soil already there. Uncontrolled penetration of the soil from the tunnel face into the excavation chamber is prevented because the force of the thrust cylinders (4) is transmitted from the pressure bulkhead onto the soil. A state of equilibrium is reached when the soil in the excavation chamber cannot be compacted any further by the native earth and water pressure.

The excavated material is removed from the excavation chamber by a screw conveyor (5). The amount of material removed is controlled by the speed of the screw and the cross-section of the opening of the upper screw conveyor driver. The pressure in the excavation chamber is controlled by balancing the rate of advance of the machine and the rate of extraction of the excavated material by the screw conveyor. The screw conveyor conveys the excavated material to the first of a series of conveyor belts. The excavated material is conveyed on these belts to the so-called reversible conveyor from which the transportation gantries in the backup areas are loaded when the conveyor belt is put into reverse.

The tunnels are normally lined with reinforced precast lining segments (7), which are positioned under atmospheric pressure conditions by means of erectors (6) in the area of the shield behind the pressure bulkhead and then temporarily bolted in place. Grout is continuously injected into the remaining gap between the segments' outer side and the surrounding medium injection openings in the tailskin or openings directly in the segments.

Manual or automatic operation of the EPB system is possible through the integrated PLC and computer- control systems.

As discussed above, the EPB machines support the tunnel face with pressure from the excavated (and remolded) soil within the excavation chamber and crew conveyor. Therefore, EPB machines perform more effectively when the soil immediately ahead of the cutterhead and in the excavation chamber forms a plastic plug, which prevents water inflow and ensures face support. This is accomplished by conditioning the soils ahead of the cutterhead with foams and / or polymers. O'Carroll 2005 lists the benefits of soil conditioning for the EPB machine operation including:
• Improved ground control
• Torque and power requirement reduction
• Abrasion reduction
• Adhesion (stickiness) reduction, and
• Permeability reduction.

Figure shows the front of the Herrenknecht S-300 EPB TBM used in the construction of the M30-By-Pass Sur Tunel Norte project in Madrid, Spain. The diameter of the cutterhead is almost 50' (15.2 m). See Table D-1 for more data about the machine (Herrenknecht).

TBM Excavation & Design

Impacts of Geotechnical Conditions on TBM Operations

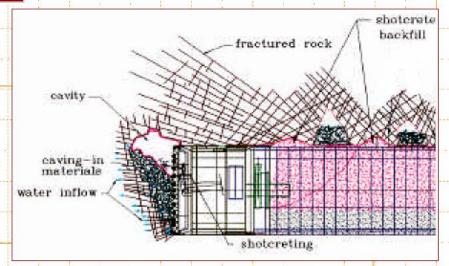| Major Geotechnical Conditions	Consequences/Requirements
Loosening loads, blocky/slabby rock, overbreak, cave-ins	At the face: cutterhead jams, disc impact loading, cutter disc and mount damage possible, additional loss on available torque for cutting, entry to the face may be required with impact on equipment selection, recessed cutters may be recommended for face ground control. In the tunnel: short stand-up time, delays for immediate and additional support (perhaps grouting, hand-mining), special equipment (perhaps machine modifications), gripper anchorage and steering difficulty, shut-down in extreme cases of face and crown instability. Extent of zones (perhaps with verification by advance sensing/probe hole drilling) may dictate shield required, and potential impact on lining type selection (as expanded segmental linings may not be reasonable), grouting, and backpacking time and costs may be high.
Groundwater inflow	Low flow/low pressure - operating nuisance, slow-down, adequate pumping capability high flow and/or high pressure - construction safety concerns, progress slow or shut-down, special procedures for support and water/wet muck handling, may require advance sensing/probe hole drilling. Corrosive or high-salt water - treatment may be required before disposal, equipment damage, concrete reactivity, problems during facility operation. Equipment modifications (as water-proofing) may be required if inflow is unanticipated - significant delays.

TBM Excavation & Design

Impacts of Geotechnical Conditions on TBM Operations
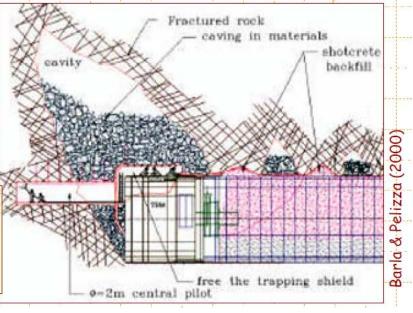
Major Geotechnical Conditions	Consequences/Requirements
Squeezing ground	Shield stalling, must determine how extensive and how fast squeeze can develop, delays for immediate support, equipment modifications may be needed, if invert heave and train mucking - track repair and derail downtime.
Ground gas/hazardous fluids/wastes	Construction safety concerns, safe equipment more expensive, need increased ventilation capacity, delays for advance sensing/probing and perhaps project shut-down, special equipment modifications with great delays if unanticipated, muck management and disposal problems.
Overstress, spalls, bursts	Delays for immediate support, perhaps progress shut-down, construction safety concerns, special procedures may be required.
Hard, abrasive rock	Reduced $PRev$ and increased F_n - TBM needs adequate installed capacities to achieve reasonable advance rates, delays for high cutter wear and cutterhead damage (especially if jointed/fractured), cutterhead fatigue, and potential bearing problems
Mixed-strength rock	Impact disc loading may increase failure rates, concern for side wall gripping problems with open shields, possible steering problems.
Variable weathering, soil-like zones, faults	Slowed progress, if sidewall grippers not usable may need shield, immediate and additional support, potential for groundwater inflow, muck transport (handling and derails) problems, steering difficulty, weathering particularly important in argillaceous rock.
Weak rock at invert	Reduced utilization from poor trafficability, grade, and alignment - steering problems.

TBM Excavation & Design

The two main factors that will stop tunnel boring machines are either the rock is too hard to cut or that the rock is too soft to sustain the reactionary force necessary to push the machine forward. TBM's will operate within certain ranges of rock deformability and strength, where the machine can be tailored to a specific range to achieve maximum efficiency (the risk being if rock conditions diverge from those the TBM is designed for) .

Instability problems at the tunnel face, encountered during excavation of the 12.9km long Pinglin tunnel in Taiwan.

Barla & Pelizza (2000)
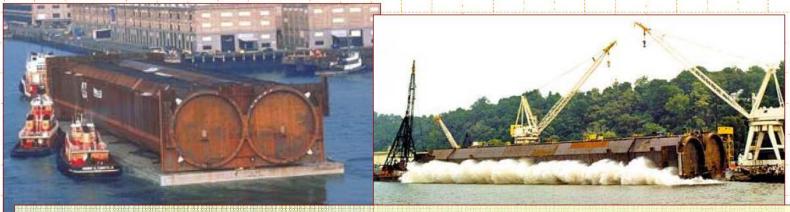
TBM Excavation & Design - Benches

Benched excavations are used for large diameter tunnels in weak rock. The benefits are that the weak rock will be easier to control for a small opening and reinforcement can be progressively installed along the heading before benching downward. Variations may involve sequences in which the inverts, top heading and bench are excavated in different order.
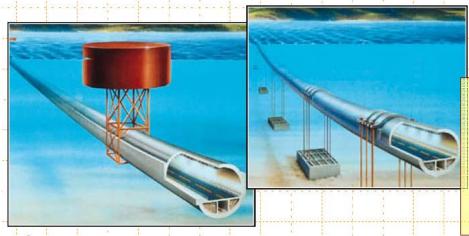
Special Cases – Immersed/Floating Tunnels

Immersed tunnels can be constructed in otherwise difficult/expensive conditions (e.g. soft alluvial deposits characteristic of large river estuaries). They can also be designed to deal with the forces and movements in earthquake conditions.
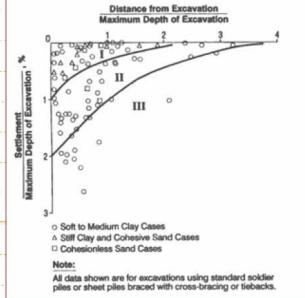
Submerged floating tunnels allow for construction in extremely deep water, where alternatives are technically difficult or prohibitively expensive. Likely applications include fjords, deep, narrow sea channels, and deep lakes.

Cut & Cover

For shallow tunnels, cut & cover provides one of the most cost effective means of tunnelling (in terms of direct construction costs and operating economics, although incidental costs can change the balance completely).

Construction typically involves excavating a trench and placing pre-cast concrete tunnel segments in the trench. The trench is then backfilled and the road restored.

Athens Metro Cut-cover station

$$\frac{\text{Distance from Excavation}}{\text{Maximum Depth of Excavation}}$$

Settlement
Maximum Depth of Excavation, %

I
II
III

o Soft to Medium Clay Cases
△ Stiff Clay and Cohesive Sand Cases
□ Cohesionless Sand Cases

Note:
All data shown are for excavations using standard soldier piles or sheet piles braced with cross-bracing or tiebacks.

Zone I
Sand and Soft to Hard Clay
Average Workmanship

Zone II
a) Very Soft to Soft Clay
   1) Limited depth of clay below bottom of excavation
   2) Significant depth of clay below bottom of excavation but
      $\frac{\gamma H}{C}$ < about 5

b) Settlements affected by construction difficulties

Zone III
Very Soft to Soft Clay to a significant depth below bottom of excavation and with
$\frac{\gamma H}{C}$ > about 5

Notations:
γH = Total overburden stress at bottom of excavation (subgrade)

C = Undrained shear strength of the clay at subgrade (also designated "S_u")
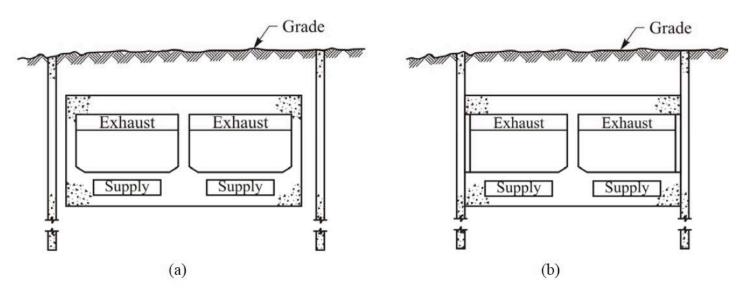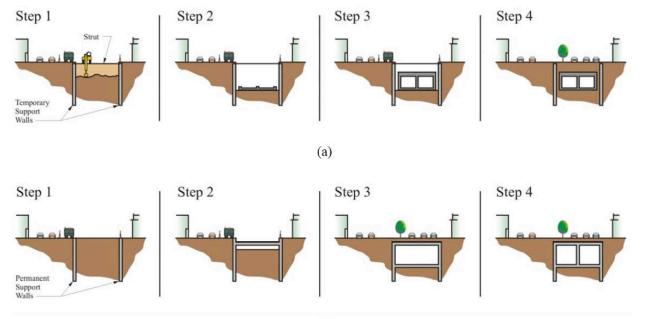
CUT AND COVER TUNNELS

(a)

(b)

Figure is an illustration of cut and cover tunnel bottom-up and top-down construction.
(a) illustrates Bottom-Up Construction where the final structure is independent of the support of excavation walls.
(b) illustrates Top-Do n Construction where the tunnel roof and ceiling are structural parts of the support of excavation walls.
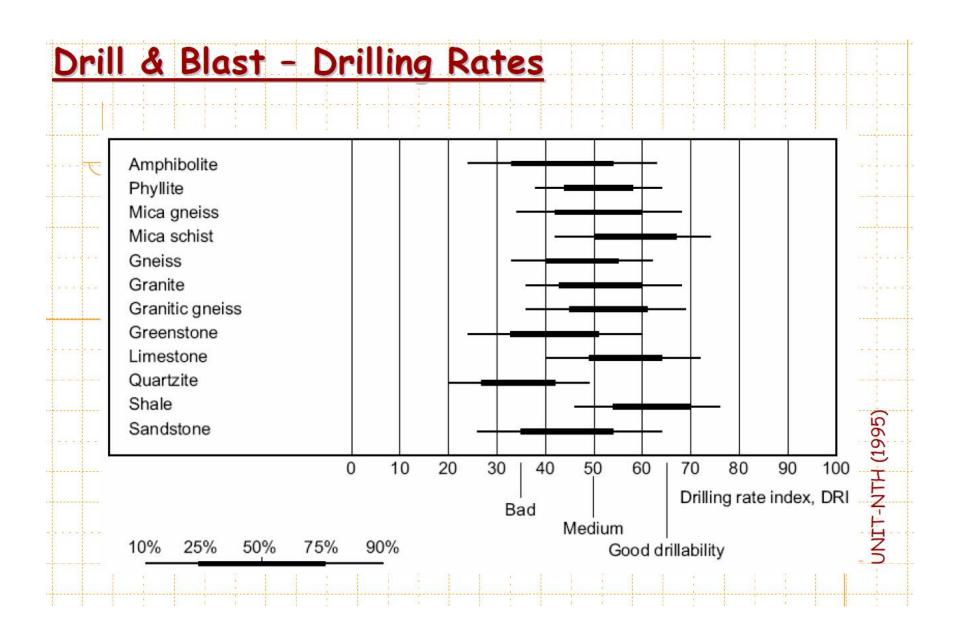

(a)

(b)

Bracing & Shoring

__Shoring__: involves any method used to prevent the collapse of ground surrounding an excavation, built top-down as excavation proceeds.

Shotcrete

Sheet Piling

Lagging

Caisson Wall

Toronto (Sheppard Subway)

Drill & Blast - Drilling Rates

Amphibolite
Phyllite
Mica gneiss
Mica schist
Gneiss
Granite
Granitic gneiss
Greenstone
Limestone
Quartzite
Shale
Sandstone

0 10 20 30 40 50 60 70 80 90 100

Drilling rate index, DRI

Bad

Medium

Good drillability

10% 25% 50% 75% 90%

UNIT-NTH (1995)

Mechanical Excavation in Rock

There are two basic types of machine for underground rock excavation:
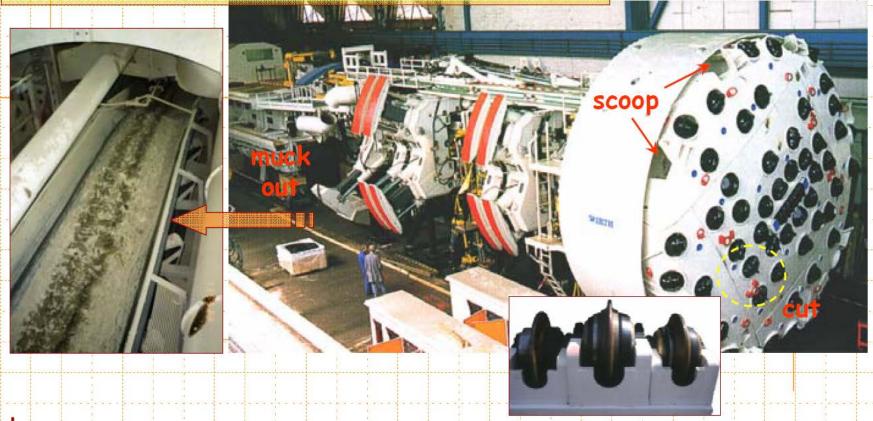
Partial-face machines: use a cutting head on the end of a movable boom (that itself may be track mounted).

Full-face machines: use a rotating head armed with cutters, which fills the tunnel cross-section completely, and thus almost always excavates circular tunnels.
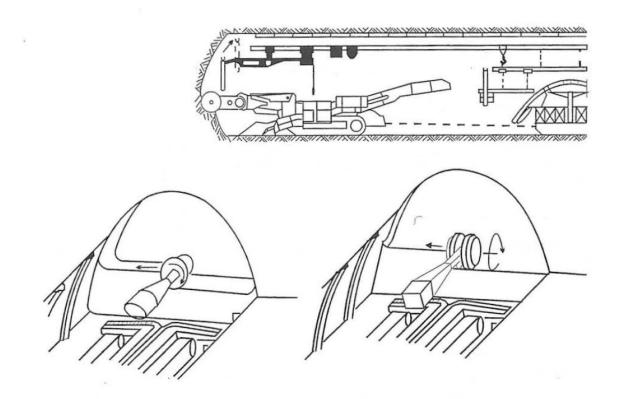
Mechanical Excavation in Rock

Full-face machines – when used for relatively straight and long tunnels (>2 km) – permit high rates of advance in a smooth, automated construction operation.

muck out

scoop

cut

Mechanical Excavation

Partial-face machines
are cheaper, smaller
and much more flexible
in operation.

cut

muck
out

scoop

In alto: schema di funzionamento di una fresa puntuale; in basso a sinistra schema di testa di taglio ad attacco laterale; a destra schema di testa ad attacco frontale

which controls the ventilation according to the stage in the drill & blast cycle. During drilling, charging, loading & hauling, the system is used for conventional blowing ventilation. After blasting, a transverse fan is used to remove explosion gases through the duct while the other fan blows fresh air towards the face to ensure that all explosive gases are mixed and removed. The one-duct system removes explosion gases fast and effectively, and is more cost-effective than the two-duct system. The one-duct system also requires good duct quality and tightness to prevent impurities from leaking back into the tunnel (**FIGURE** *6.2.-36.*).

Diesel engine exhaust gas

In the ventilation system and required fresh air flow in the tunnel, loading and transportation diesel equipment is usually the determining factor. Exhaust gas from diesel engines contains N_2, CO_2, H_2O, O_2 and some harmful solid particles. In most countries, engines must be approved for underground use, and the engine manufacturer is required to provide documents for approved concentrations of toxic gas or impurities in exhaust gas. However, the most important factor affecting these harmful contents is the service and maintenance of mobile equipment. Engine adjustments are important as well as the condition of the exhaust purifier. The most typical purifiers are catalytic, water scrubbers, exhaust gas ejectors and solid particle filters.

Ventilation requirements for diesel exhaust are usually estimated as the amount of fresh air per kW engine power or per kg of diesel fuel that is used. Typical values are approximately 3 - 3.5 m³/min per engine kW, or 1.400 - 1.600 m³ per kg used diesel fuel. Ventilation requirements also depend on road quality (tramming speed, creation of dust, rolling resistance) and tunnel inclination.

Some explosive gas is bound in the muckpile after blasting so adequate ventilation and water spraying during loading work is important and should be stressed. Released gases during loading work must be diluted and removed. The NO_2 concentration is removed and dust is minimized by spraying water onto the muckpile.

6.2.2. Mechanical tunneling
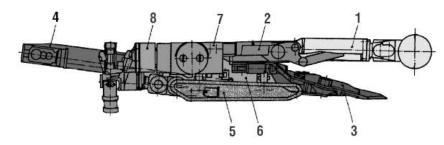
A) PART FACE

ROADHEADERS

The first roadheaders were used for tunneling in the 1960s. By the early 1970s, approximately 150-200 roadheaders were used for underground civil construction. It was during this early phase that boom-type cutting equipment in shields or on other hauling structures such as excavators also became popular.

Basic design and operating features

The standard roadheader features the following functions:

- Rock excavation (rock cutting)
- Gathering of excavated muck
- Muck transfer to secondary conveying equipment
- Machine transfer

1 Cutter Boom   2 Turret   3 Loading Assembly   4 Chain Conveyor
5 Track drive   6 Frame   7 Electric Equipment 8 Hydraulic Equipment

FIGURE *6.2.-37.* *Roadheader main assembly groups.*

Cutter boom

The cutter boom comprises the roadheader's actual rock disintegration tool. (**FIGURE** *6.2.-38.*) The cutter boom has the following components: its base, motor, coupling between the motor and gear, and the head.
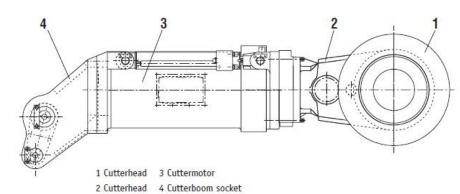

1 Cutterhead   3 Cuttermotor
2 Cutterhead   4 Cutterboom socket

FIGURE *6.2.-38.* *Cutter boom components.*

Cutter heads

Two main design principles are applied:

- Longitudinal or milling type cutter heads rotating parallel to the cutter boom axis
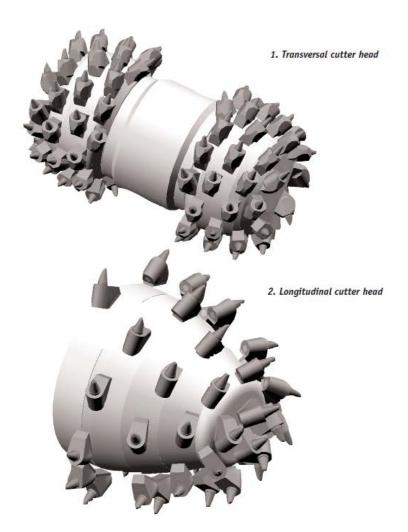- Transversal or milling type cutter heads with rotation perpendicular to boom axis.

1. Transversal cutter head

2. Longitudinal cutter head

FIGURE *6.2.-39. Types of cutter heads*

Both cutter heads have several advantages and disadvantages.

Some main features important to tunneling are mentioned here:

- Transversal cutter heads cut in the direction of the face. Therefore, they are more stable than roadheaders with longitudinal heads of comparable weight and cutter head power.

- At transversal heads majority of reactive force resulting from the cutting process is directed towards the main body of the machine.

- On longitudinal cutter heads, pick array is easier because both cutting and slewing motions go in the same direction.

- Roadheaders with transversal-type cutter heads are less affected by changing rock conditions and harder rock portions. The cutting process can make better use of parting planes especially in bedded sedimentary rock.

- If the cutter boom's turning point is located more or less in the axis of the tunnel, a cutter head on longitudinal booms can be adapted to cut with minimum overbreak. For example, cutter booms in shields where the demand can be perfectly met are often equipped with the same type of cutter head. Transverse cutter heads always cause a certain overbreak regardless of machine position.

- Most longitudinal heads show lower figures for pick consumption, which is primarily a result of lower cutting speed.

- The transverse cutter head offers greater versatility, and with the proper layout and tool selection, has a wider range of applications. Its performance is not substantially reduced in rock that presents difficult cutting (for example, due to the high strength or ductile behaviour).

- Additionally, the reserves inherent in the concept offer more opportunities for tailoring the equipment to existing rock conditions.

Cutter picks

Since its first application on a roadheader cutter boom in 1972, the conical pick equipped with tungsten-carbide tips (also called point-attack picks) has become more important and is today the most commonly used pick. (**FIGURE** *6.2.-40.*).

1 WC-inset
2 Cone
3 Shaft
4 Retainer ring
5 Pick box
C Cutting depth
F_C Cutting force
F_N Normal force
F_D Driving force due to friction on rock
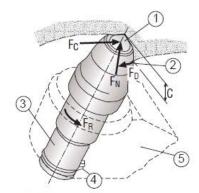F_R Frictional resistance between pick and pick box

FIGURE 6.2.-40. *Point-attack-pick, design and indentation parameters*

Process tuning

Tuning the cutter head's cutting process to the existing rock conditions is crucial to achieve optimal cutting.
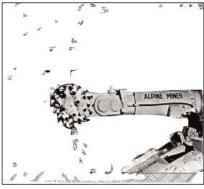Theoretically, the highest possible spacing of cutters results in the optimal interaction between the cutter head and rock:

- Relative pick track per unit volume of excavated rock is reduced
- Reduced pick-track length also results in better energy utilization and, therefore, a faster cutting rate
- Less dust generated
- Reduced wear (picks/bank m³)
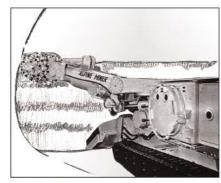
Excavation sequence

Contrary to TBMs, which simultaneously attack the entire face with a fixed tool configuration, the operation of a roadheader comprises different steps of the excavation process.
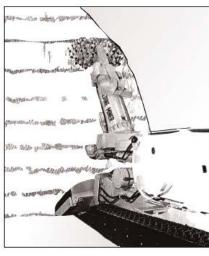(**FIGURE 6.2.-41.**)

The first step, the sumping of the cutter head into the face, is performed by the forward movement of the entire roadheader via its crawler tracks or alternatively through special cutter boom design. Telescopic or articulated cutter boom design can also perform this task.
(**FIGURE 6.2.-42.**) Because the sumping process requires the most power in the cutting sequence, there is less impact to the floor because the sumping is performed without engaging the crawler tracks. Further excavation of the face is primarily performed by the horizontal swiveling of the cutter boom with vertical offset of the boom when reaching the tunnel outline. All horizontal and vertical movements of the boom are performed by the turret. The turret itself serves for the horizontal movement of the boom. Closed rack and pinion drives or external hydraulic cylinders are used for this task.
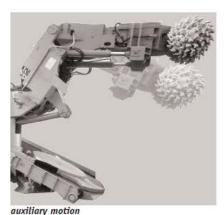

1 Sumping

2 Cutting of face

3 Profiling (if required)

FIGURE 6.2.-41. *Steps of excavation by a roadheader*

Vertical movement is performed by various swivel cylinders; the reactive forces are again transferred into the turret. If necessary, an extra profiling step minimizes the tunnel's ribs and brings it closer to its theoretical shape. This excavation process is fundamental to roadheader versatility regarding the shape and size of the tunnel section.

A roadheader can, within its design dependent geometrical limits (defining minimum and maximum cross sections etc.) cut practically any required shape and size. It can also follow all necessary transitions and alterations and is highly adaptive to differing excavation processes. By using cutter booms with telescopic or special design, this important feature can be enhanced even further.

main motion

auxiliary motion

FIGURE 6.2.-42. *Examples of telescopic and articulated cutter booms*

The excavation of short roof sections and consecutive benching from one machine position can be effected, making properly equipped roadheaders the perfect tool for coping with the demands of the NATM in ground conditions with poor stability.

Loading and transferring muck:

Mucking can be performed during the excavation process.
Relevant loading and hauling devices are an integral part of the roadheader.
A loading apron in front of the machine´s main body consists of:

- Gathering arms, which are considered best suited to handlecoarse, blocky muck. This application is also well suited for tunnel operations.
- Wear-resistant spinner loaders that can handle high muck volumes when used for mineral production, such as in coal mines.
- Swinging loading beams which form a very simple and rugged solution, but offer a some what restricted loading capacity.

Various loading devices can be used. The most common are shown in **FIGURE** 6.2.-43.

Tramming facilities

Roadheader weight, together with the high loads and vibrations of the cutting process, makes crawler tracks the only reliable solution.
In tunneling, roller-type crawler tracks are considered generally advantageous because they offer better maneuverability and higher tramming speeds (up to 35 m/min.). Nevertheless, sledge type crawler tracks offer superior resistance against shockloads and are used in hard rock applications.

Classification of roadheaders, performance

Main classification features:

Two interrelated features form the main figures for classification:

- Machine weight
- Power of cutter motor

Machines with two types of cutting range are featured in the table: Machines with standard and extended cutting range. *Table 6.2.-1.* indicates the range of the defined classes with regard to their main features and limit of operation.
The max. section in the table represents the position max. area which the roadheader can cut according to its design parameters.

Capacity and performance:

Technical capacity, such as the highest cuttable rock strength, is also shown in *Table 6.2.-1.* This represents the highest strengths that can be handled according to the weight and power of a machine equipped with certain features.
The above-mentioned limitations regarding rock strength must be seen as the first indication of capacity and performance. In practice operating limits and performance are influenced by other rock parameters and also depend on the actual layout of the machine and actual site conditions (**FIGURE** 6.2.-44.).

FIGURE 6.2.-45. shows the involved parameters. It also outlines the practical way to determine the most important parameters of roadheader operation:

- Cutting rate
- Pick consumption

1 Gathering arms

2 Spinner loader

3 Two lateral loading beams

4 One central loading beam

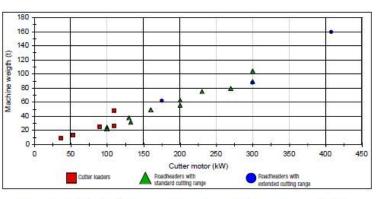**FIGURE** 6.2.-43. *Main types of loading assemblies on roadheaders.*

FIGURE 6.2.-44. Relation between weight and cutter head power of roadheaders. This table also provides an introduction to machine selection for various project conditions.
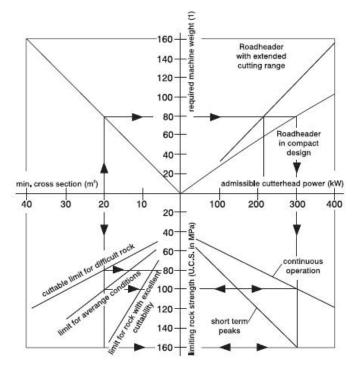
Table 6.2.-1. Classification of roadheaders.

Roadheader class	Range of weight (to)	Range of cutter head power (kW)	Range of operation			
			Roadheaders with standard cutting range		Roadheaders with extended cutting range	
			max. section (m²)	max. u.c.s. (MPa)	max. section (m²)	max. u.c.s. (MPa)
Light	8 -40	50 - 170	~ 25	60 - 80	~ 40	20 - 40
Medium	40 - 70	160 - 230	~ 30	80 - 100	~ 60	40 - 60
Heavy	70 - 110	250 - 300	~ 40	100- 120	~ 70	50 - 70
Extra heavy	> 100	350 - 400	~ 45	120 - 140	~ 80	80 - 110

FIGURE 6.2.-44B. Indiative diagram for roadheader selection. This diagram can be used for first selection of an appropriate machine for certain project conditions. It indicates the maximum weight installed power to be used on this machine and maximum rock strength, which can be tackled. Smaller machines with lower powering can be also used, if they cope with the demandes of rock and project.

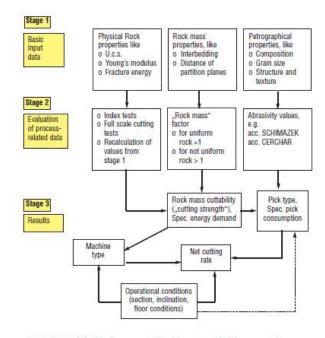**FIGURE 6.2.-45.** Assessment of cutting rate and pick consumption for roadheader operation.

Rock types

For hammer tunneling to be economic, a reasonable productivity rate is required. This can be achieved in different rock types. Rock to be excavated has relatively incoherent structure. Distance between cracks, joints and other discontinuities should not be more than 30 - 50 cm. The rock to be excavated is compact but soft enough to allow a reasonable productivity rate by tool penetration (best case: an excavator bucket is barely insufficient).

Rock strength, abrasion level and general toughness also influence productivity to some extent. Rock is seldom homogenous in long tunnels. If extremely compact rock is encountered, auxiliary blasting is recommended. It is often sufficient to fracture the rock, enabling further excavation with a hammer. Auxiliary blasting is applied at the lower middle part of the tunnel where excavation normally would start. This way hammer excavation is best enhanced and the negative effects of blasting (such as overbreak) are minimized.

Ground vibrations

Considerably less ground vibration is associated with hammer excavating than with the drilling and blasting method. The vibration level caused by hammer excavation is 5 - 10% the level of blasting. This can be a decisive factor when excavating rock in the vicinity of structures that require vibration limitations.

Working methods

The working method is dictated by the section area and length of the tunnel.

Areas 30 - 70 m²:

Hammer tunneling is suitable for tunnels with a cross-section greater than 30 m². With smaller areas, an excavator suitable to carry a 2000 kg hammer will have difficulties fitting or operating properly.

In a small and narrow width (less then 8m) tunnel profile, only one excavator-hammer combination can work at the front of the tunnel. This divides work into 5 phases:

- Excavating
- Transportation of muck
- Scaling
- Transportation of scaling muck
- Reinforcement and support of tunnel walls

In an 8-hour shift, excavating and transporting muck takes about 2 hours each. Scaling and transportation of scaling muck takes approximately an hour, and the rest of the time is used for reinforcement of the walls.

Area more than 70 m²:

A larger tunnel profile allows hammer excavating and muck transportation to be done simultaneously. This reduces the actual amount of work phases into two:

- Excavating (and scaling) + transportation of muck.
- Reinforcement and support of tunnel walls.

Broken rock can be removed during excavation of a 70 m² tunnel face, which can accommodate an excavator equipped with a hydraulic hammer, and a loader and truck. The excavating and transportation work phases actually complement one another. When material has been excavated from one side and instantly taken away, the hammer can immediately be transferred to the opposite side. Immediate muck removal also improves visibility to the material to be broken.
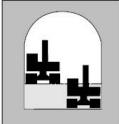
Tunnel height more than 7 m:

When tunnel height becomes too high, the reach of the hammer is insufficient for excavation in one stage. Excavation is then done in two stages (**FIGURE 6.2.-46**):

- Tunnel excavation with suitable height for hammer and excavator.
- Another excavator-hammer combination starts approx. 100 - 150m behind the initial tunnel front to deepen the existing tunnel with the trenching method (**FIGURE 6.2.-46.**)

When a hydraulic hammer is used, the work force requirement becomes smaller in comparison to traditional drilling and blasting excavation. This is largely because the drilling and blasting method calls for more highly trained personnel. Drilling and blasting operations also mean regular interruptions and disturbances to the tunneling process as a whole, while hammer excavating is a continuous process.
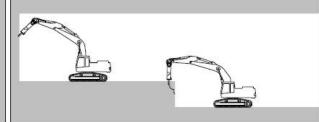

FIGURE 6.2.-46. *Two-phase tunneling with two hammers.*

Long tunnels

If the tunnel is sufficiently long, it is advantageous to start at both ends and in the middle to cope with tight schedules.

Starting in the middle improves equipment and operator availability. The hammer excavates at one side, while the other side is reinforced. When each working phase is completed, the excavation group and the reinforcement group trade places.

When starting in the middle of the tunnel, hammer and wheel-loader trade places with the stabilization team, as support is erected and concrete spraying completed.

The hammer work cycle

Excavation starts at the center of the tunnel at a height of 1.0 - 1.5m. A hole with the depth of 1.5 - 2.0m is excavated. Tunneling then continues from the sides of the hole as close as possible to the final sides of the tunnel. Once this stage is reached, work continues in the same way from the floor up until the roof of the tunnel has been formed (**FIGURE 6.2.-47**).

If the rock is jointed, excavating follows the shear planes in the normal manner from floor to roof, using the rock's natural weak points and planes to maximum the effect (**FIGURE 6.2.-48**).

Technical considerations

Tunnel work is among the toughest jobs a hammer can do. During tunneling, hammer availability is extremely high (60 - 80% of excavator time compared to 30 - 50% in primary breaking). The contact force applied by the excavator to the tool is much higher in a horizontal position than in a vertical position. Due to extreme circumstances, frequent preventative and regular maintenance is essential in effective and productive hammer tunneling. This is best handled with service contracts.

When uninterrupted production is critical, a system utilizing two hammers and one on stand-by is the perfect solution.
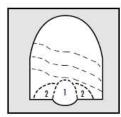

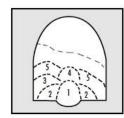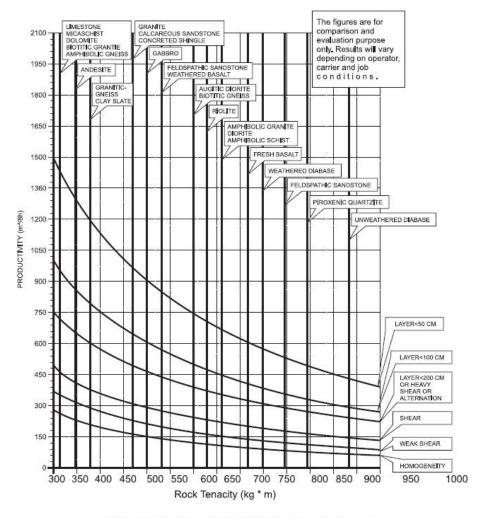**FIGURE 6.2.-47.** Hammer working sequence from floor to roof.

FIGURE 6.2.-48. Hammer working sequence when rock layers are inclined.

FIGURE 6.2.-49. G 100 hydraulic hammers productivity, in open pit quarrying.

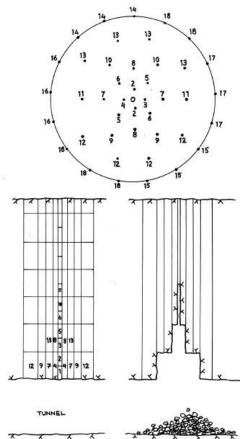FIGURE 6.2.-60. *Drilling pattern and blasting order of long-hole method in raise excavation.*

FIGURE 6.2.-61. *Alimak method*

Alimak method

The Alimak method is based on a lift-type climber, which has a platform, safety canopy, lift basket and motor. The climber travels on rails that are fixed onto the rock wall and is driven by air, or an electric or diesel motor. The water and air lines are attached to the rail.

The Alimak method represents the first mechanized form of raise building. It is more efficient than traditional raise building and is much safer as the work is always performed under a protective canopy.

The Alimak method is a relatively inexpensive alternative for construction sites that have a few variable length raises.
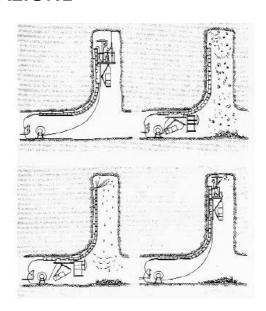
The Jora method is similar to the Alimak method with the exception that the lift is operated by a winch. A pilot hole through to the upper level is required for operating the winch.

Inclined tunnel method

One application of mechanized raise excavation is the inclined tunnel method. It can be utilized on steeply inclined raises. Excavation progresses from top down similar to tunneling. Specially made drilling units, such as rail-mounted jumbos lowered by a winch, are used.

RAISE BORING

In the past, all shafts and raises were made by drilling and blasting (methods described previously.) However, during the last decades, full-face raise boring methods have by and large surpassed drill and blast methods for making raises both in mining and civil contracting (**FIGURE 6.2.-62.**). In full-face raise boring, the entire cross section is bored to its final diameter. Explosives are not used. There are various alternative methods to bore the full face holes:

Boxhole boring is a special method in which the raise is made in advance from the lower level up. This must be ready when tunneling reaches the area. The rig is on the level beneath

the hole and bores up. Boring is performed either by using pre-drilled pilot holes or boring straight with the final diameter boring head.

Blind (down) boring, is another type of boring where the hole is bored downwards. The name "blind boring" comes from the early use of boring down to the final diameter in one pass. Down boring via a pre-drilled pilot hole was developed from blind boring. In small diameter holes, a normal pilot drilling diameter 9 to 13-3/4 is used; in bigger holes the pilot hole is reamed with raise boring to 3 to 8 ft in diameter.

Raise Boring is the most established full-face excavation method of shafts and raises. This method consists of first drilling a pilot hole and then reaming it to the final diameter. The pilot hole diameter is somewhat larger than the drill rods. Reaming is performed in the opposite direction (back reaming) (**FIGURE** *6.2.-63.*).

In normal raise boring, pilot drilling is performed from the upper level vertically down or inclined to the lower level.
Sometimes the pilot hole is drilled up and back reaming is done downward.

FIGURE *6.2.-64. Shaft excavation by Raise Borer.*

FIGURE *6.2.-63. Cutter used in Raise Boring.*

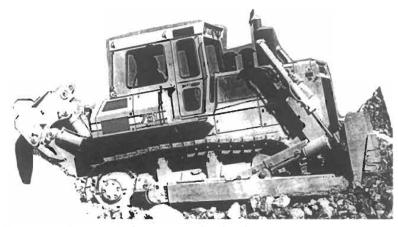**FIGURE** *6.2.-62. Rhino 1200 raise bohrer.*
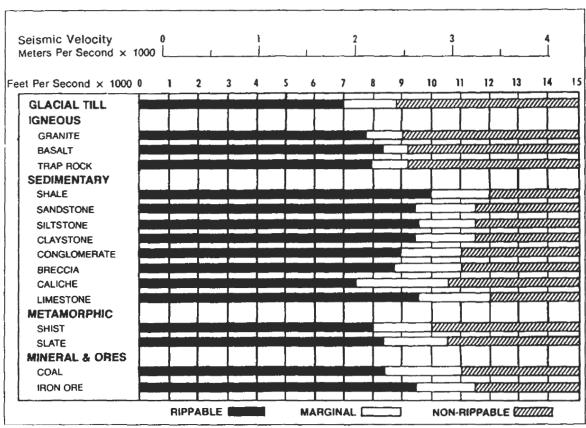
Figure 15.22 Large tracked-type tractor fitted with

Figure 15.23 Rippability in terms of seismic velocity. From Caterpillar Performance Handbook (1983).