

Le Gallerie Cenni

Tipologie

Caratteristiche tecniche e potenziali criticità

Specificità del lavoro in sotterraneo

Tecniche costruttive



**Politecnico
di Torino**

Prof. D. Peila

Peculiarità di uno scavo in sotterraneo

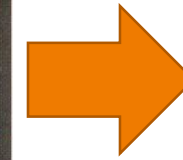
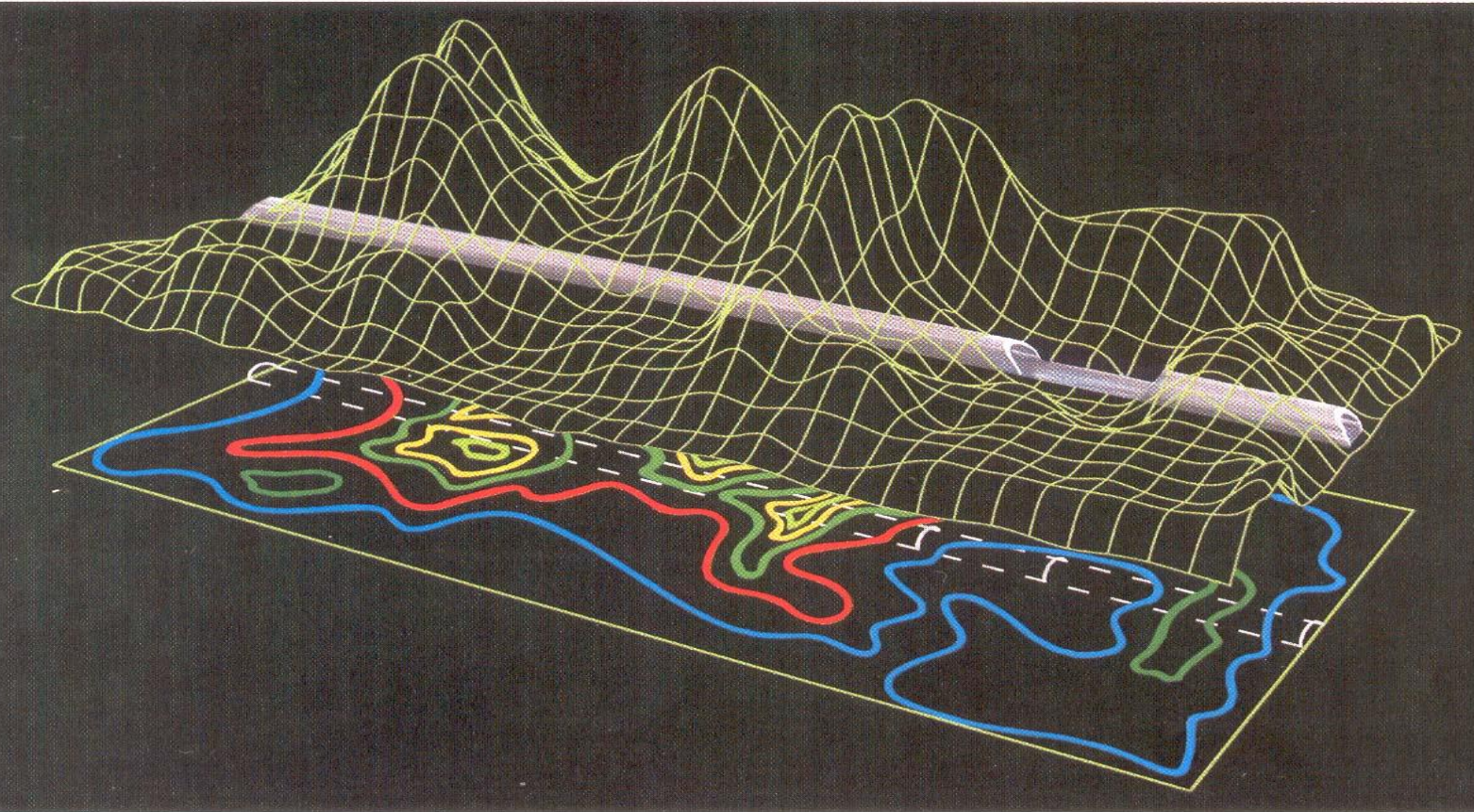


Cortesia P. Lunardi

Peculiarità di uno scavo in sotterraneo

	Costruzioni in superficie	Costruzioni sotterranee
Materiali da costruzione	Le proprietà dei materiali da costruzione sono definite e sono garantite durante il processo di costruzione	Il terreno con le sue incertezze è il vero materiale in cui avviene la costruzione. E' difficile cambiare le proprietà dei terreni (anche se non impossibile) Le strutture di sostegno interagiscono con gli ammassi naturali.
Carichi agenti	I carichi agenti sono chiaramente definiti	I carichi sono definiti mediante assunzioni e stime. Il processo costruttivo influenza i carichi agenti sia in modulo che in direzione

Importanza della conoscenza della geologia

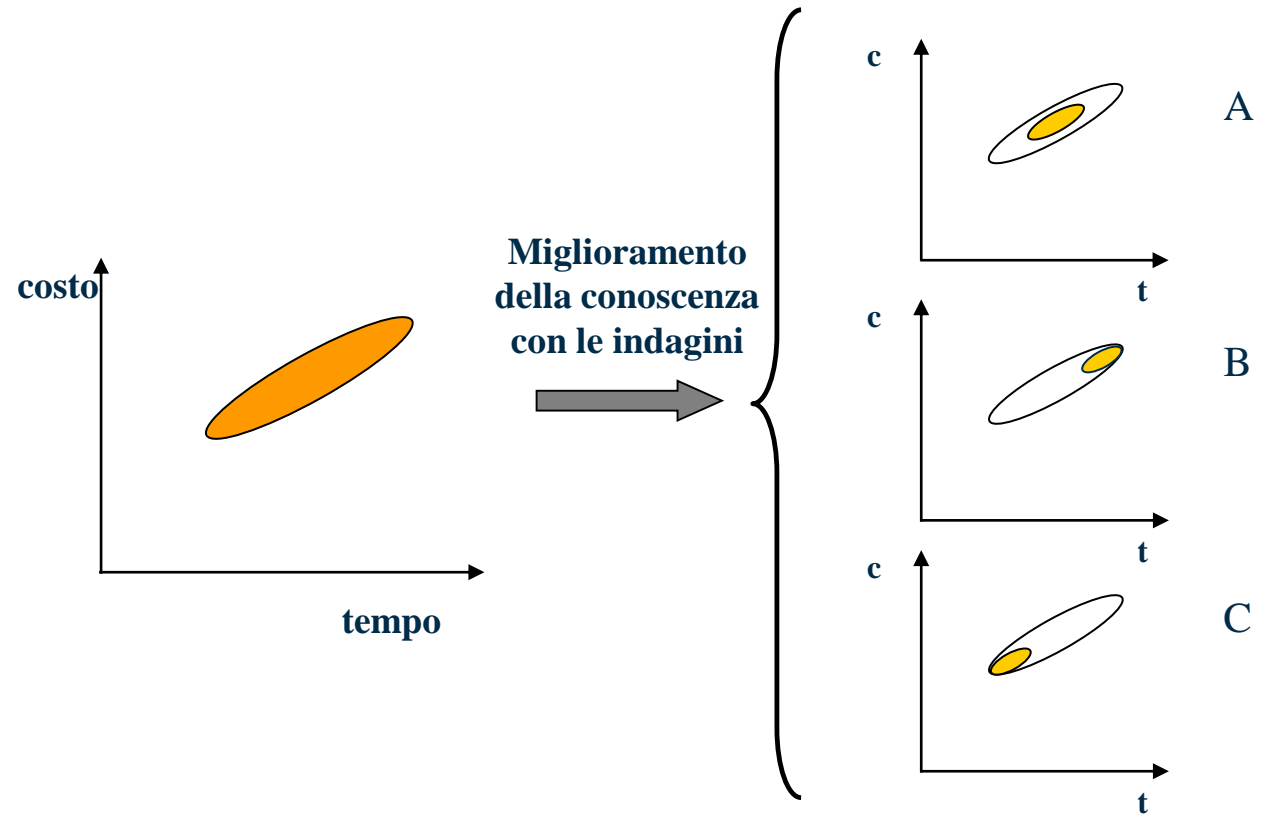
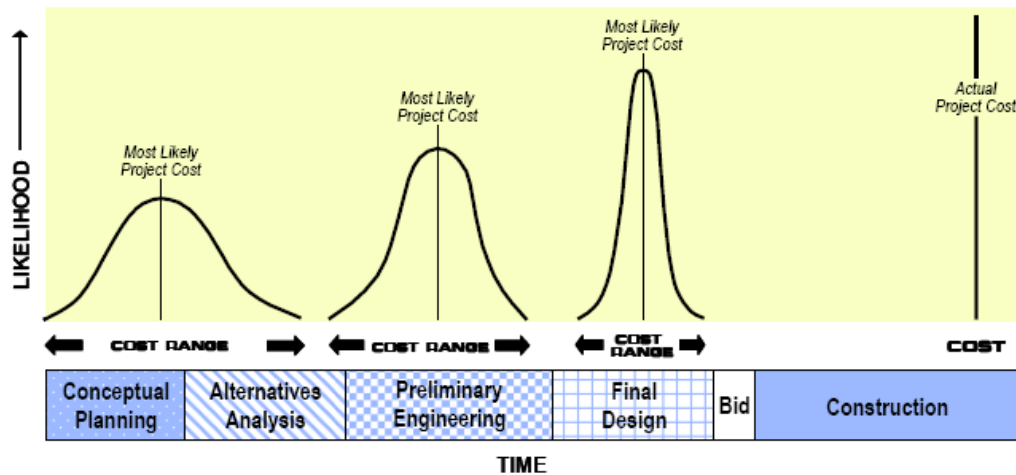


Criticità
specifiche del
sottterraneo

Importanza della conoscenza della geologia

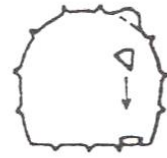
Per un corretto progetto è fondamentale

- un corretto sviluppo delle indagini
- la risk analysis



Vari tipi di instabilità (hazards)

IMPATTO SULLA
SICUREZZA



ROCK FALL



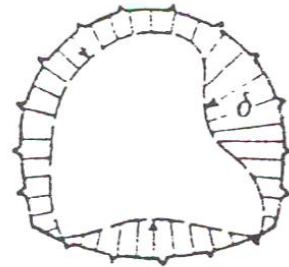
BREAK DOWN



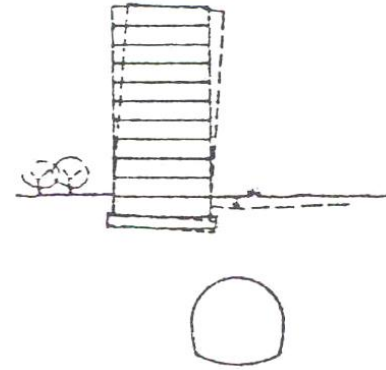
COLLAPS

STABILITA'
LOCALE

IMPATTO SUGLI
SPOSTAMENTI



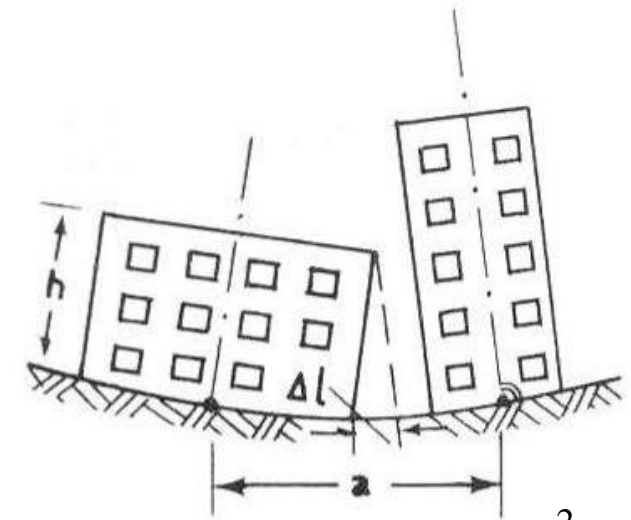
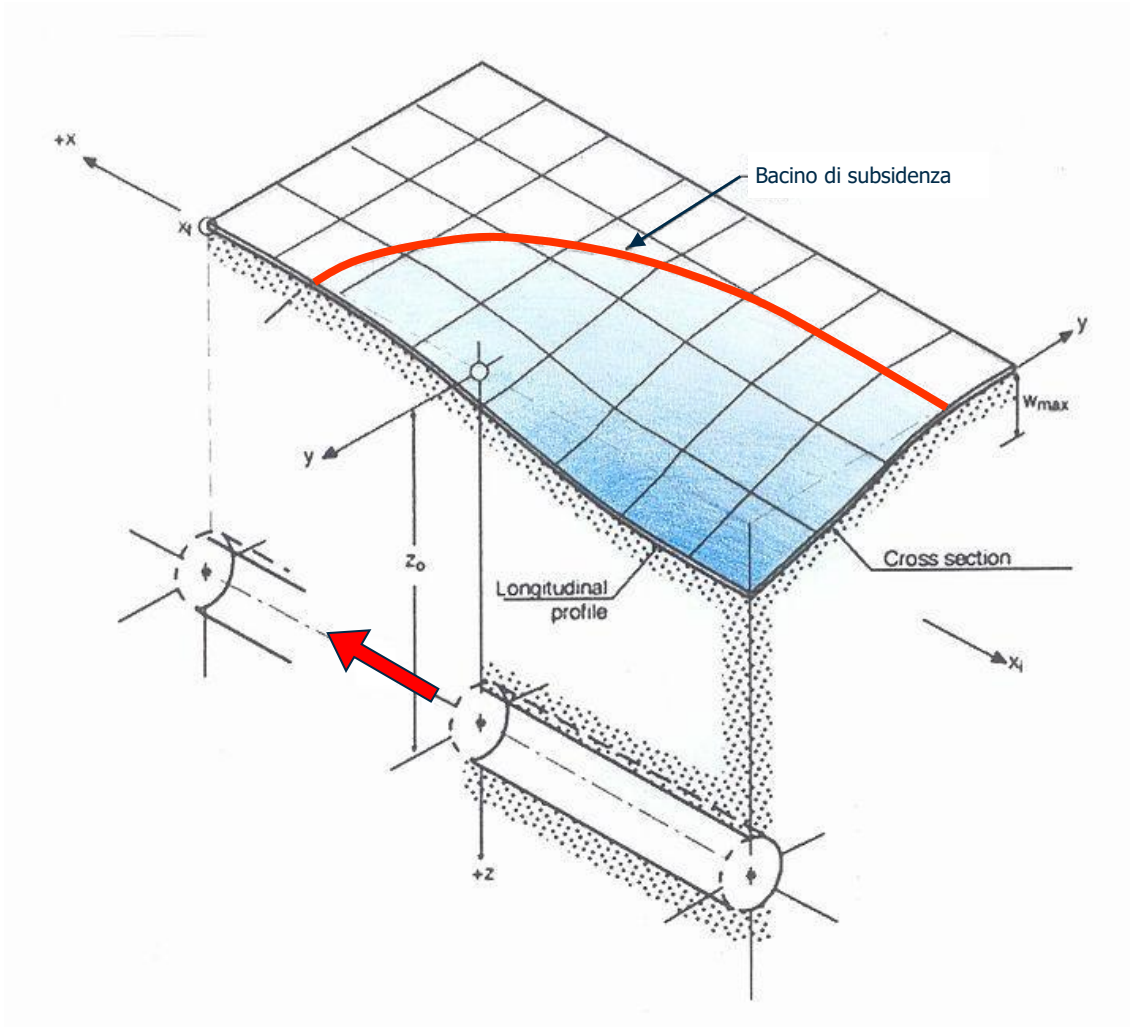
CLOSURE



SETTLEMENTS

STABILITA'
GLOBALE






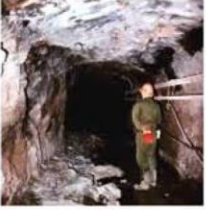














Esempio dell'influenza di una galleria sulla superficie concetto di subsidenza



$$S(x) = w_{\max} \cdot e^{-\frac{x^2}{2i^2}}$$

cedimenti del soprassuolo
durante lo scavo di una
galleria superficiale

Hazards per gallerie lunghe e profonde

		ROCK MASS QUALITY				
		MASSIVE	BLOCKY	HEAVILY JOINTED	CRUSHED	SHEARED
RATIO OF ROCK MASS STRENGTH / IN SITU STRESS <i>Low stress</i>	STABLE		STRUCTURAL FAILURE 	UNSTABLE FACE 	MARGINAL STABILITY 	UNSTABLE FACE 
	SPALLING		BLOCK FAILURE 	MARGINAL STABILITY 	IMPROVED STABILITY 	MILD SQUEEZING 
	SEVERE SPALLING		STABLE 	IMPROVED STABILITY 	MILD SQUEEZING 	SQUEEZING 
	ROCKBURST		STRESS FAILURE 	FACE COLLAPSE 	SQUEEZING 	SEVERE SQUEEZING 
<i>High stress</i>						

(Hoek, 2010)

Le condizioni di stabilità di una galleria sono controllate da

Proprietà geomeccaniche degli ammassi rocciosi

La condizioni di stabilità sono controllate dalla resistenza dell'ammasso se confrontata con lo stato tensionale naturale ed indotto e dal comportamento del materiale.

Stato tensionale

Forma della galleria

La forma della galleria influenza punti e l'entità delle tensioni nell'intorno del vuoto. La geometria può essere rettangolare (ottimizzazione dell'uso ma con problem di concentrazioni di sforzo) a circolare che ha la migliore risposta a condizioni di carico idrostatico a policentrica che è una via di mezzo tra le due

Dimensioni della galleria

Influenza l'entità delle tensioni al contorno e delle tipologie e tecnologie dei sostegni che sono più complesse e difficili da installare

Metodo costruttivo

Influenza la sequenza di messa in opera dei sostegni, e dei rinforzi e quindi la gestione degli spostamenti

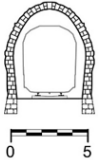
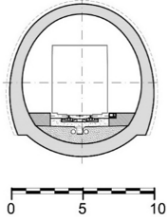
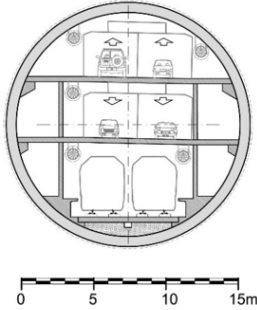
Presenza di acque sotterranee

L'interferenza dello scavo con le falde sotterranee influenza i cariche agenti sui sostegni a lungo termine, induce moti di filtrazione durante lo scavo, può indurre trasporti di materiale nello scavo, interferisce con le operazioni di scavo e con gli aspetti ambientali e con le problematiche di sicurezza del cantiere

Geometria delle gallerie

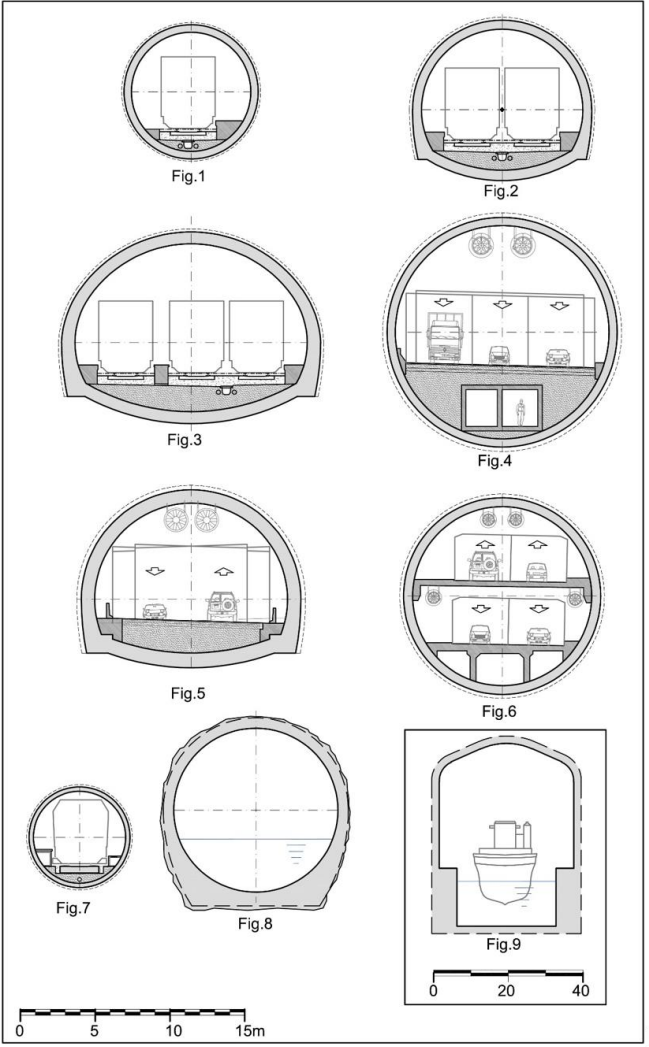


Sezioni tipiche

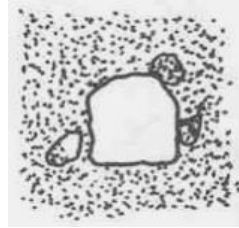
Project name	Tunnel function	Section peculiarity	Section sketch
Porrettana Railway line (1864) Bologna–Florence Italy	Railway tunnel	Horseshoe shape tunnel without invert	
High-Speed Railway Tunnel Milan–Genoa Italy	Railway tunnel	Polycentric shape tunnel with invert	
3 Kat Tunnel Istanbul Turkey	Mixed traffic metro & road tunnel	Circular shape tunnel	

Geometria delle gallerie - esempi

#	Project name	Tunnel function	Tunnel excavation methodology	Inner section data	Structural section data
1	Italian State Railway Standard Codes	Railway tunnel Single track V ≤ 200km/h	TBM	Radius 4.0m	Excavation area 65m ² Excavation radius 4.55m Segment thickness 40cm
2	Italian State Railway Standard Codes	Railway tunnel Double tracks V ≤ 200km/h	Conventional	Radius (crown and sidewalls) 5.4m	Excavation area 112m ² Preliminary support 20cm Final lining (crown and sidewalls) 60cm Final lining (invert) 70cm
3	Virgolo Tunnel Bolzano - Italy	Railway tunnel Three tracks	Conventional	Radius 8.3m (crown), 5.4m (sidewalls)	Excavation area 185m ² Preliminary support 20cm Final lining (crown and sidewalls) 80cm Final lining (invert) 80cm
4	S. Lucia Tunnel Florence - Italy	Highway tunnel	TBM	Radius 7.15m	Excavation area 201m ² Excavation radius 8.0m Segment thickness 55cm
5	Santa Caterina Tunnel Sicily - Italy	Road tunnel	Conventional	Radius 6.45m (crown and sidewall)	Excavation area 154.0 m ² Preliminary support 30cm Final lining (crown and sidewalls) 90cm final lining (invert) 100 cm
6	Eurasia Tunnel Istanbul -Turkey	Double deck road tunnel	TBM	Radius 6.0m	Excavation area 147m ² Excavation radius 6.85m Segment thickness 60cm
7	Green Line Doha - Qatar	Metro tunnel	TBM	Radius 3.1m	Excavation area 39m ² Excavation radius 3.5m Segment thickness 30cm
8	Gibe III Hydro-electric Project Ethiopia	Hydraulic power tunnel	Conventional	Radius 5.5m	Excavation area 140m ² Preliminary support 10cm Final lining (crown and sidewalls) 70cm Final lining (invert) 80cm
9	Stad Ship Tunnel Norway	Boat tunnel	Conventional	Height 49m Width 36m	Not available

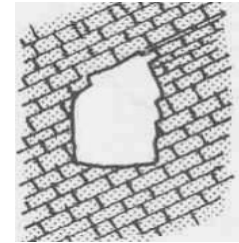


Comportamento degli ammassi geologici e l'impatto sugli scavi sotterranei



Overburden soil or heavily weathered rock

squeezing and flowing ground, short stand-up time.



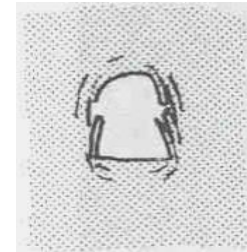
Blocky jointed rock partially weathered

gravity falls of blocks from roof and sidewalls.



Massive rock with few unweathered joints

no serious stability problems.

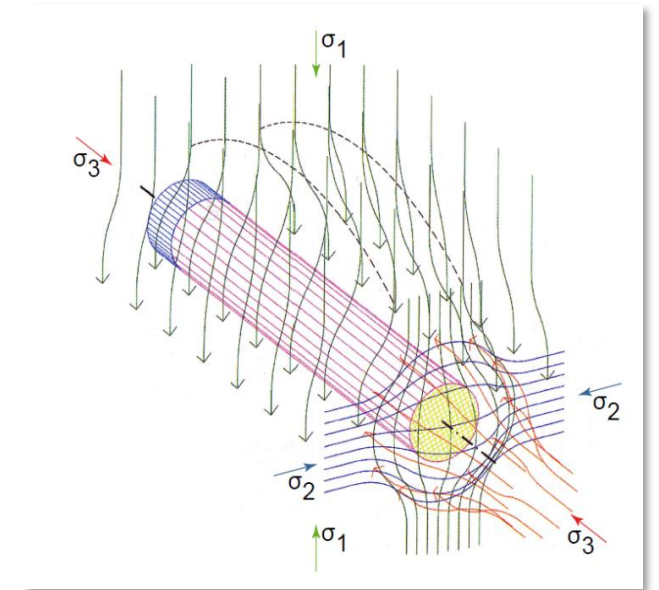
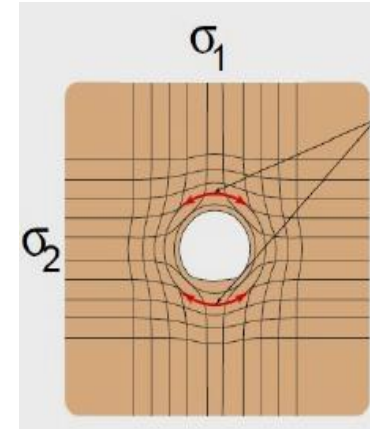
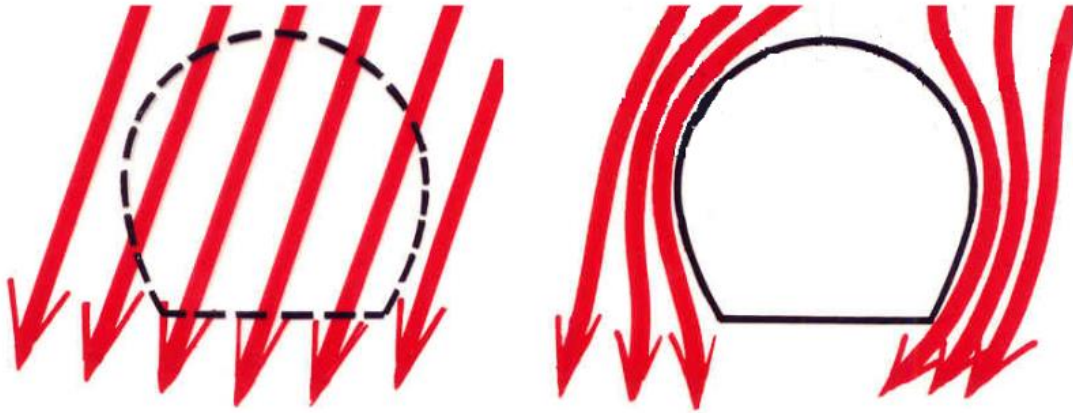


Massive rock at great depth
stress induced failures, spalling and popping with possible rockbursts.

Ground geotechnical quality

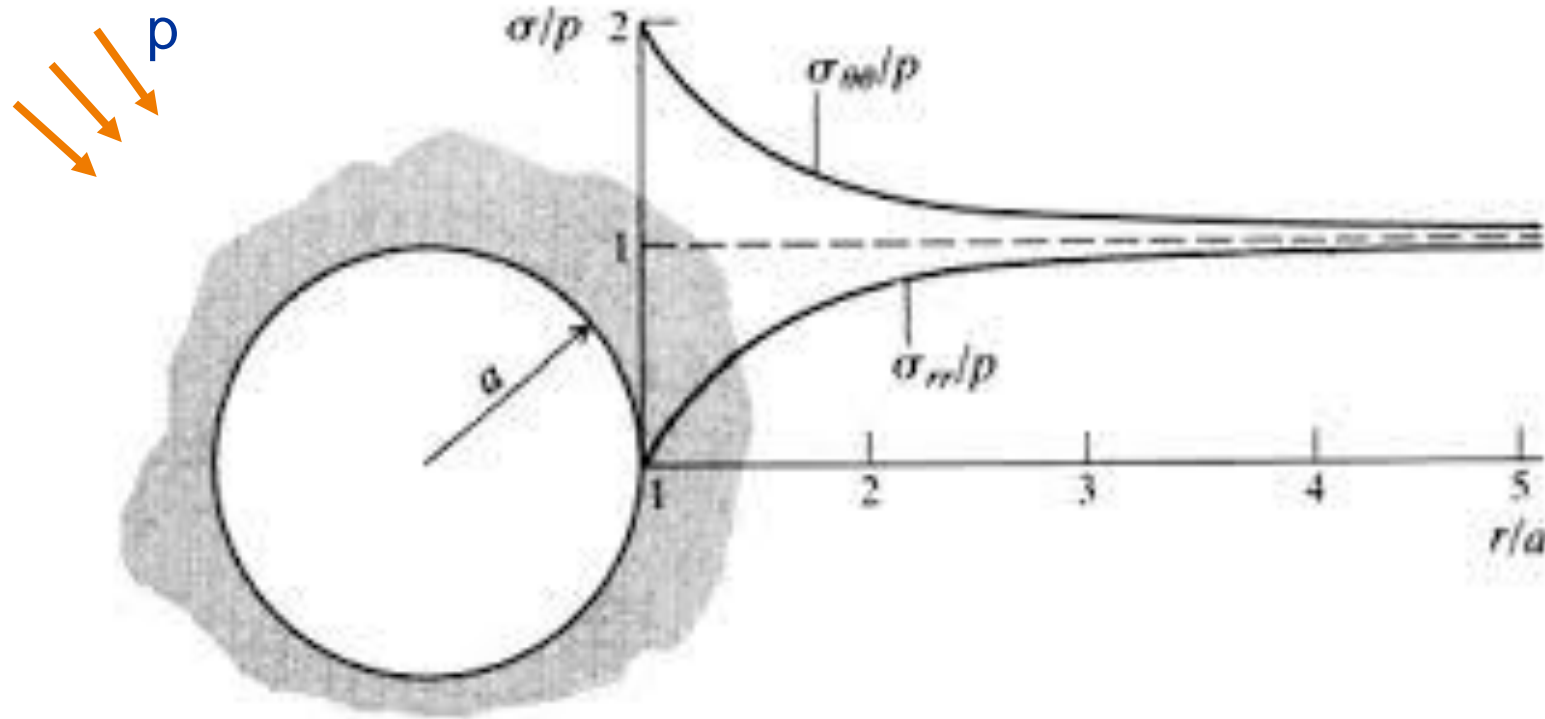
(Hoek and Brown, 1980)

Lo scavo di una galleria induce una perturbazione dello stato tensionale nell'ammasso

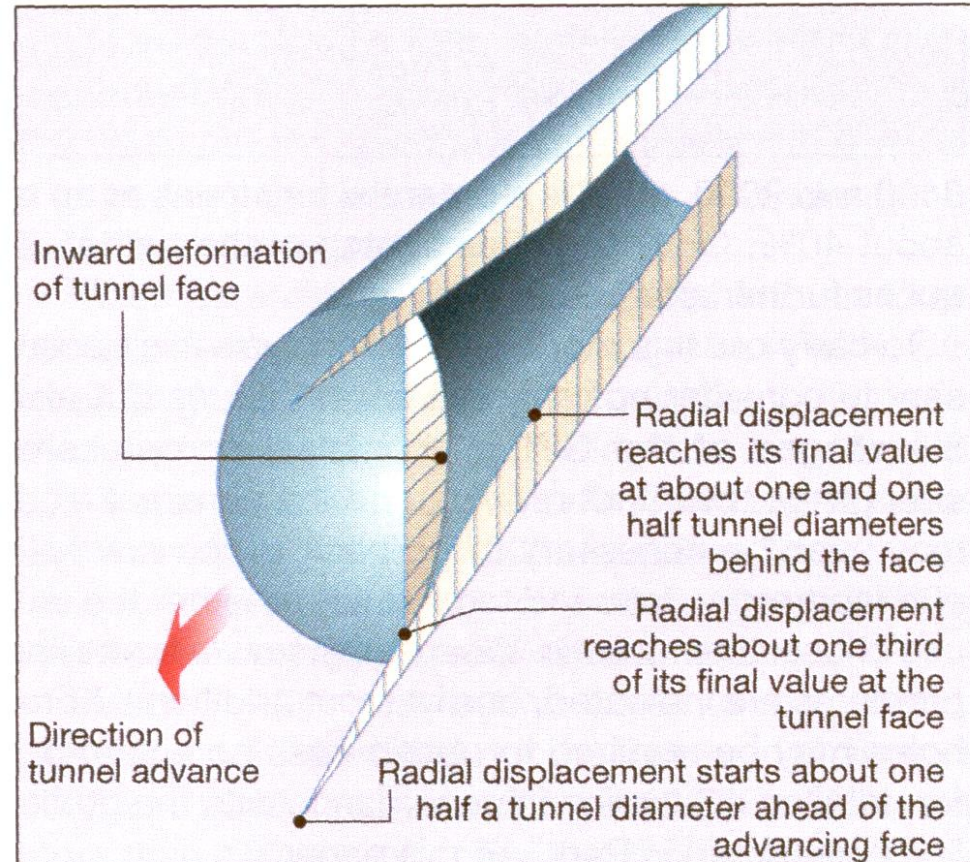
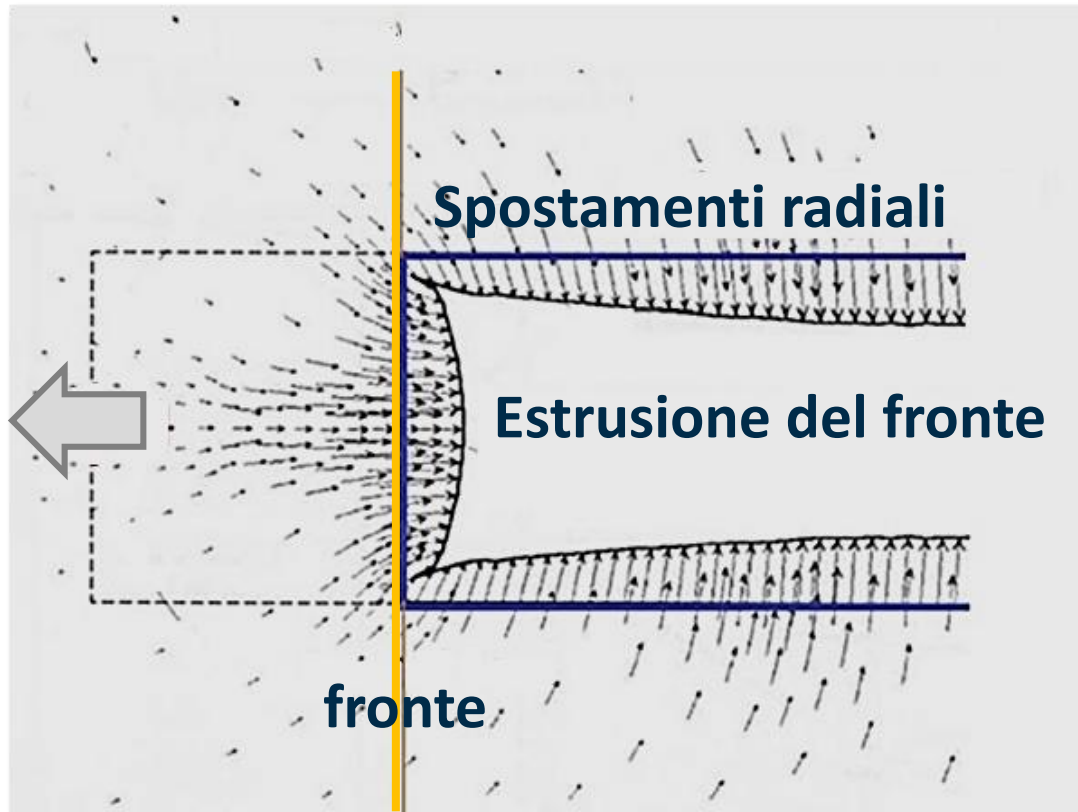


Cortesia Lunardi

Lo scavo di una galleria induce una perturbazione dello stato tensionale nell'ammasso

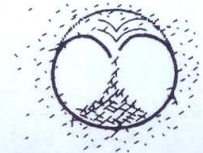
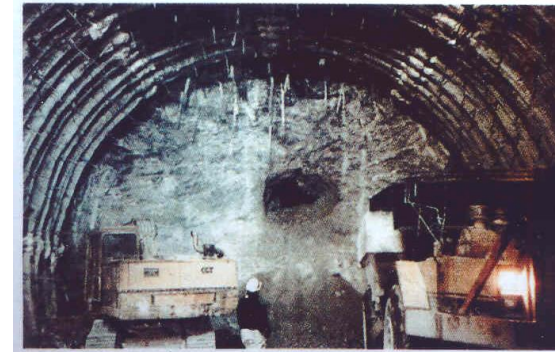
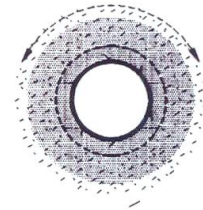
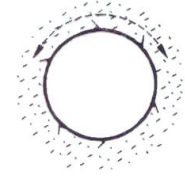
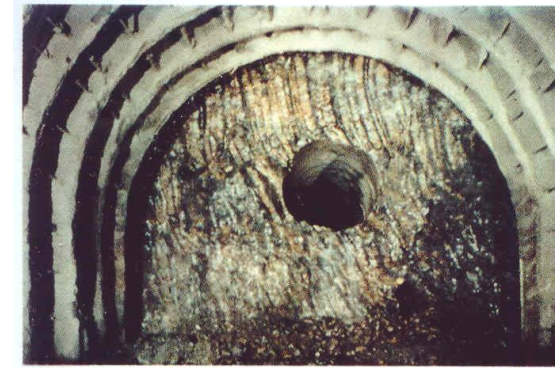


La geometria di una galleria durante lo scavo è tridimensionale e come tale deve essere studiata



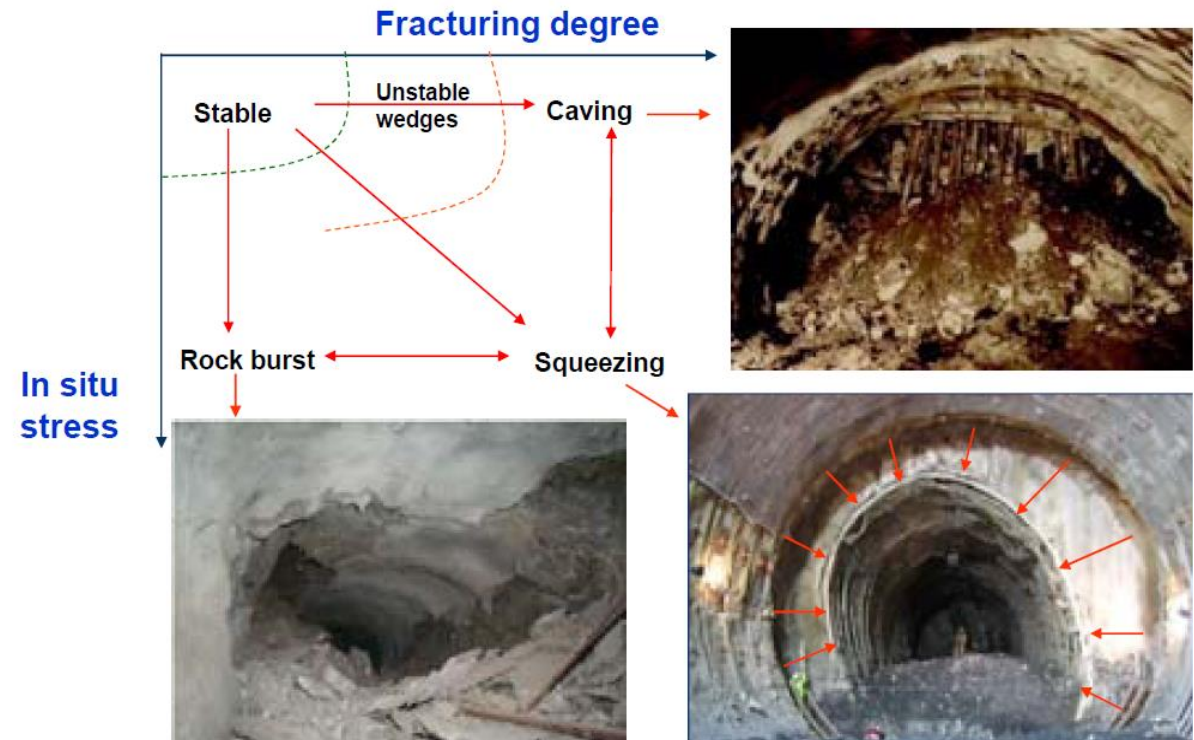
Hoek, 2002

Lo scavo di una galleria induce una perturbazione dello stato tensionale nell'ammasso che interagisce con l'ammasso il quale reagisce in relazione alle proprie caratteristiche di comportamento meccanico

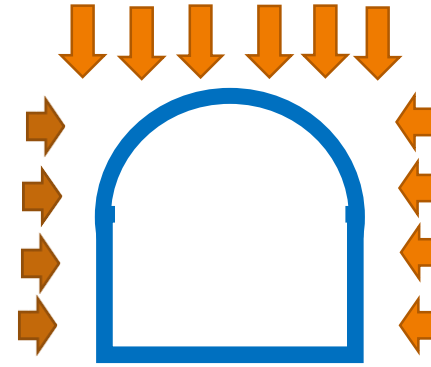
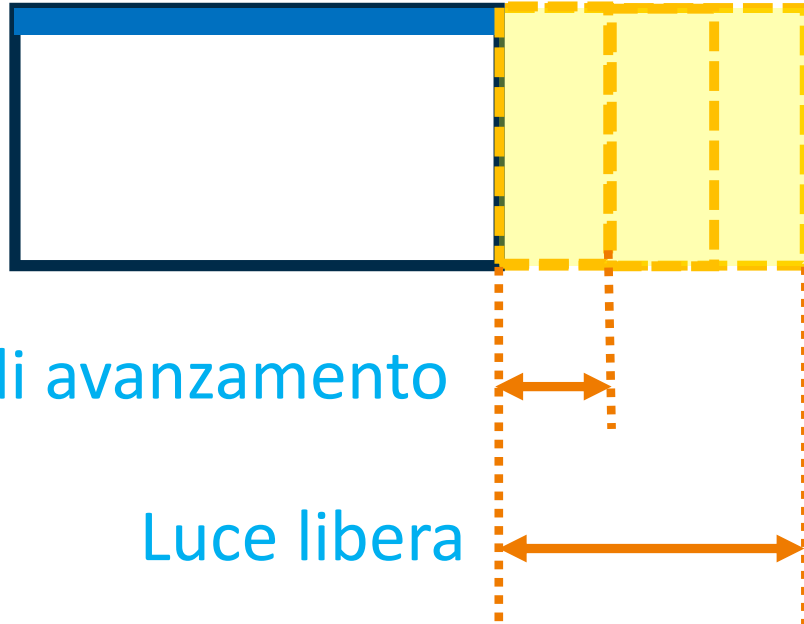


Lunardi, 2000

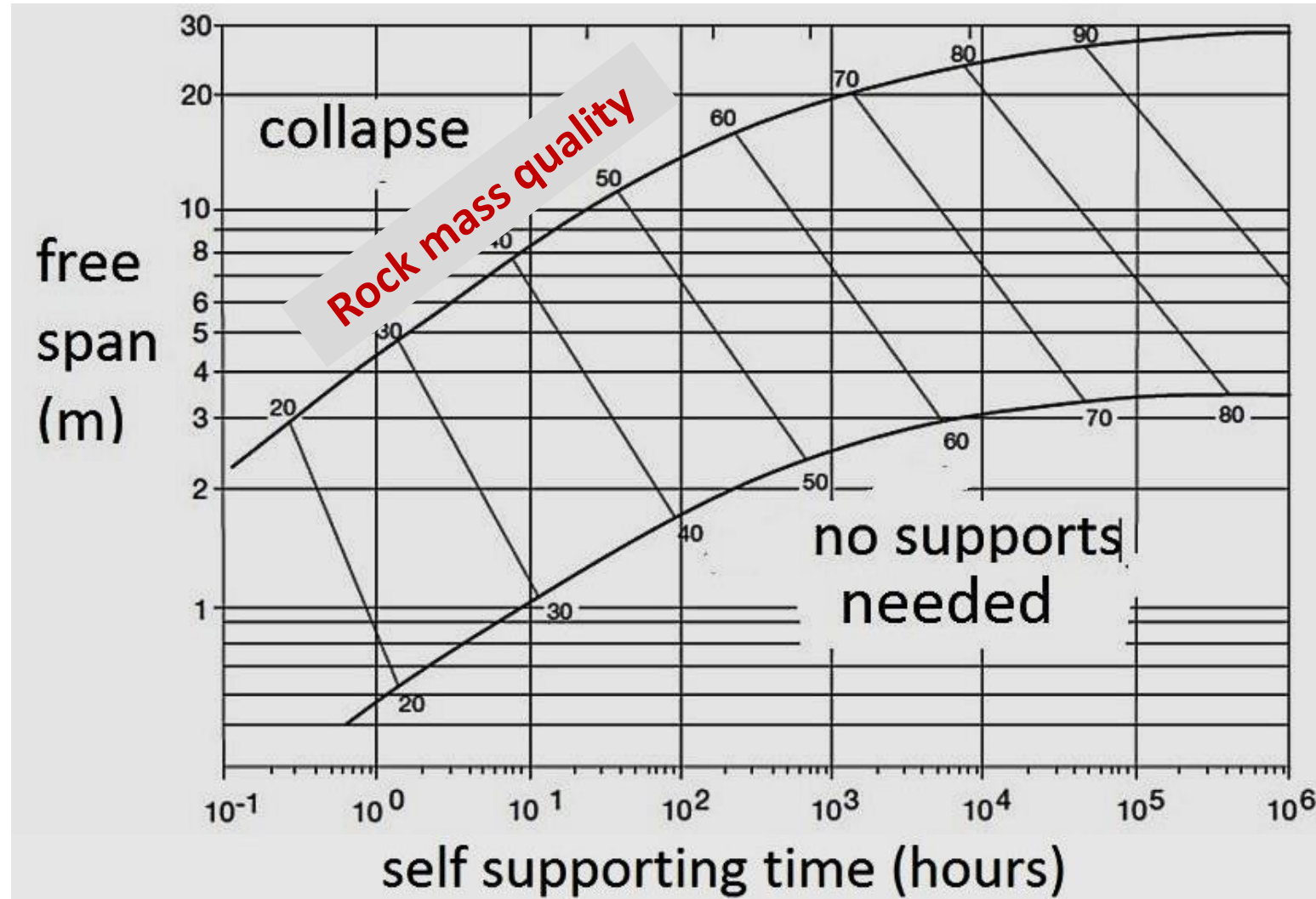
Le condizioni di instabilità che possono influenzare lo scavo di una galleria dipendono dal tipo di terreno e dello stato tensionale naturale pre-esistente



Concetti di luce libera e tempo di autoportanza

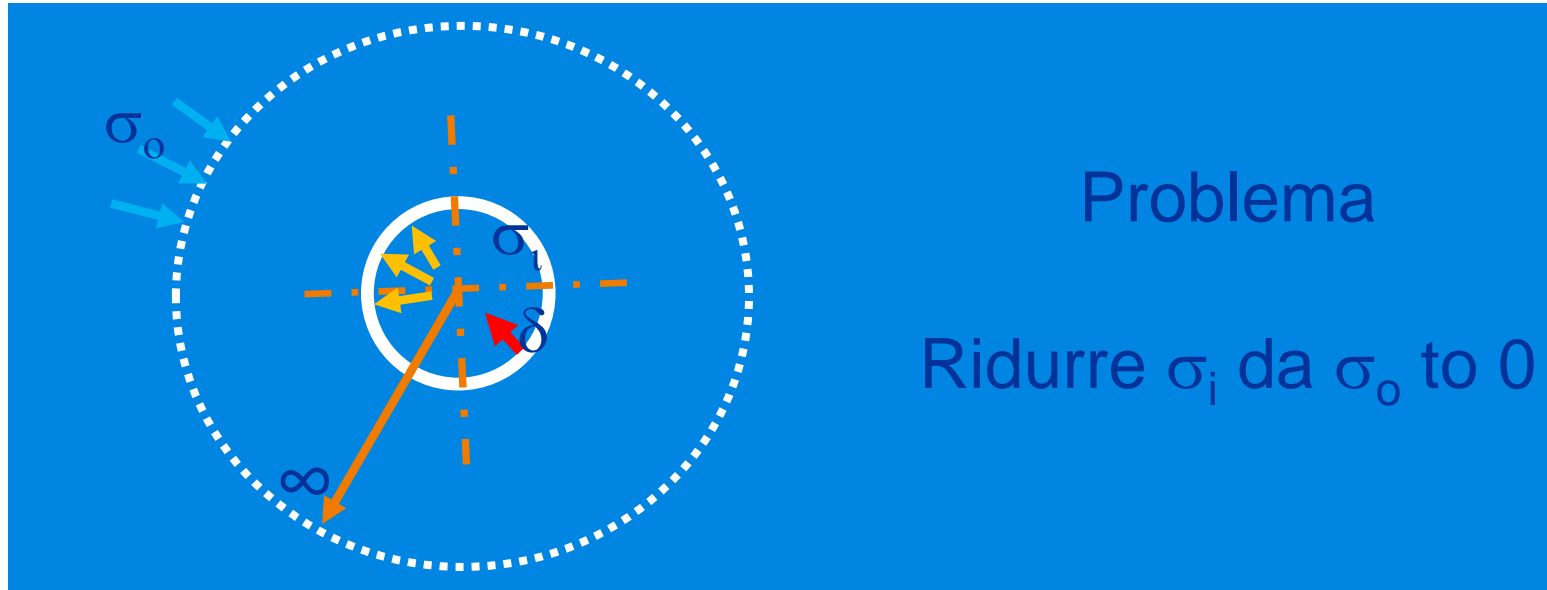


Concetti di luce libera e tempo di autoportanza



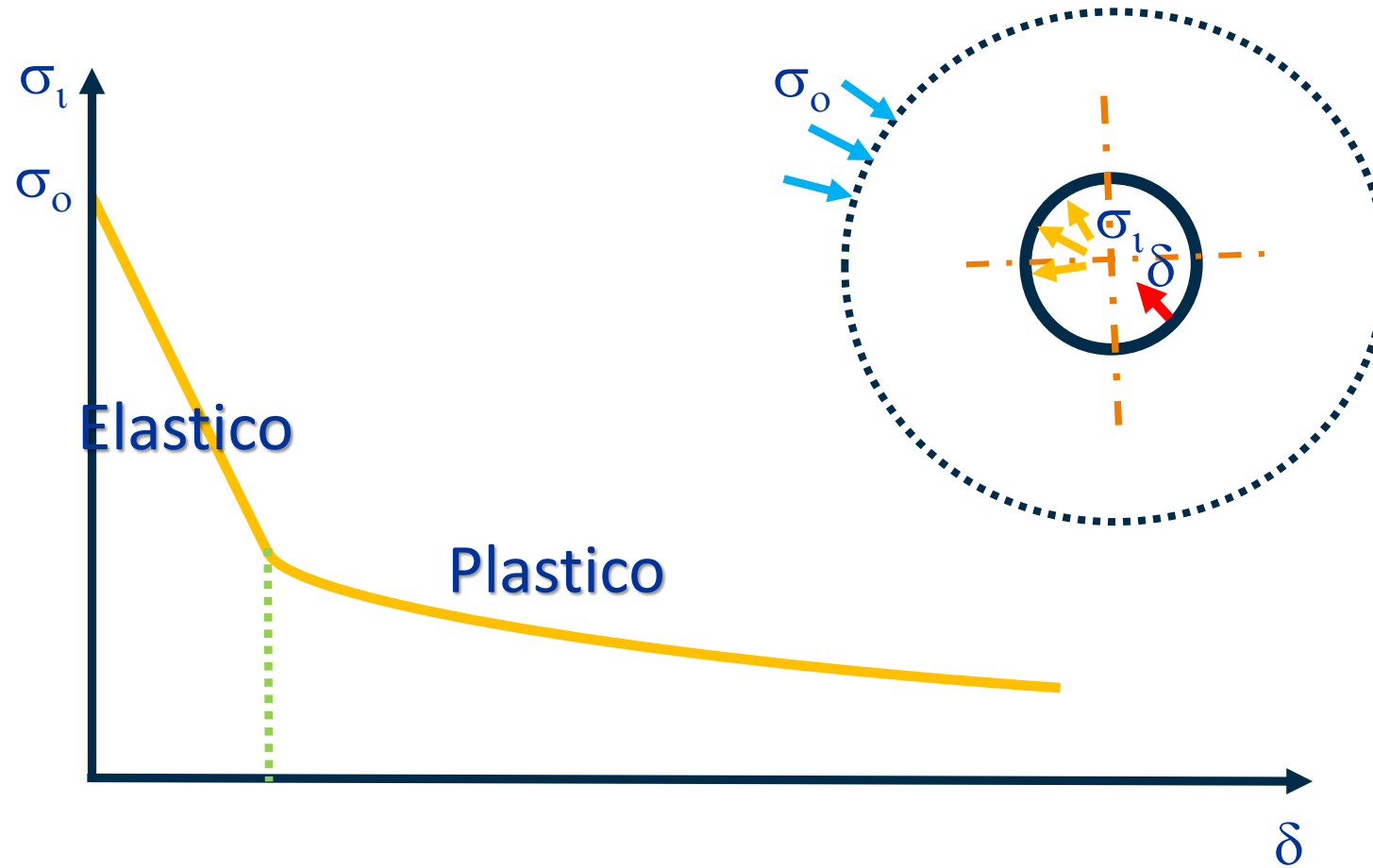
modified from Bieniawski, 1987

Concetto di curva caratteristica

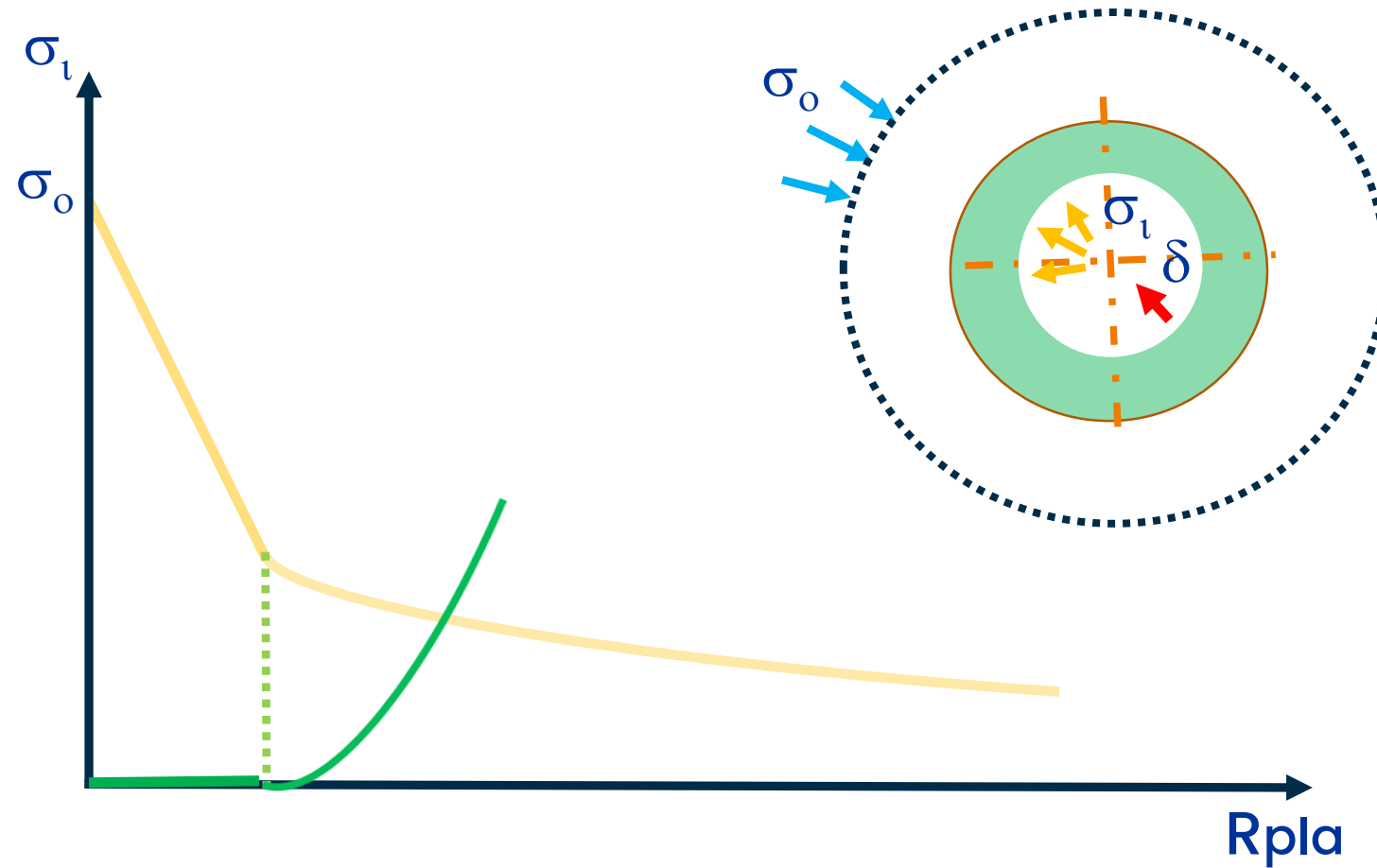


Ipotesi di base : 1) materiale omogeneo e isotropo;
2) stato di sforzo idrostatico, 3) geometria assialsimmetrica
La soluzione analitica si può trovare in Hoek and Brown (1980)

Concetto di curva caratteristica

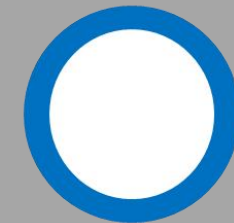
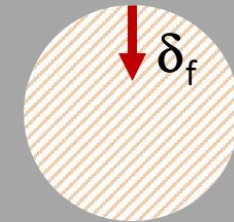
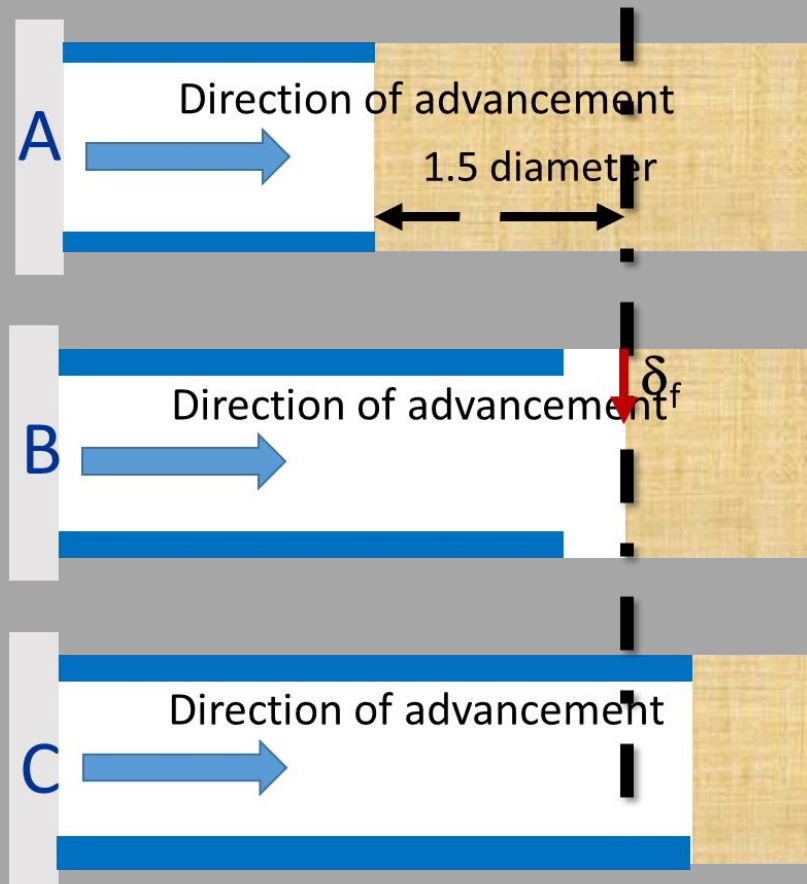
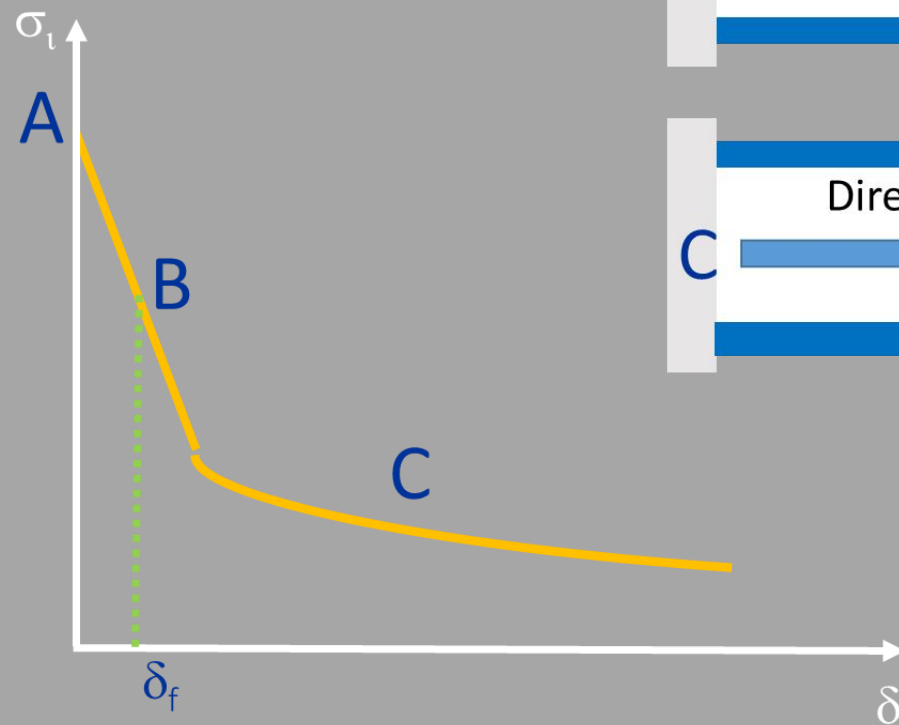


Concetto di curva caratteristica



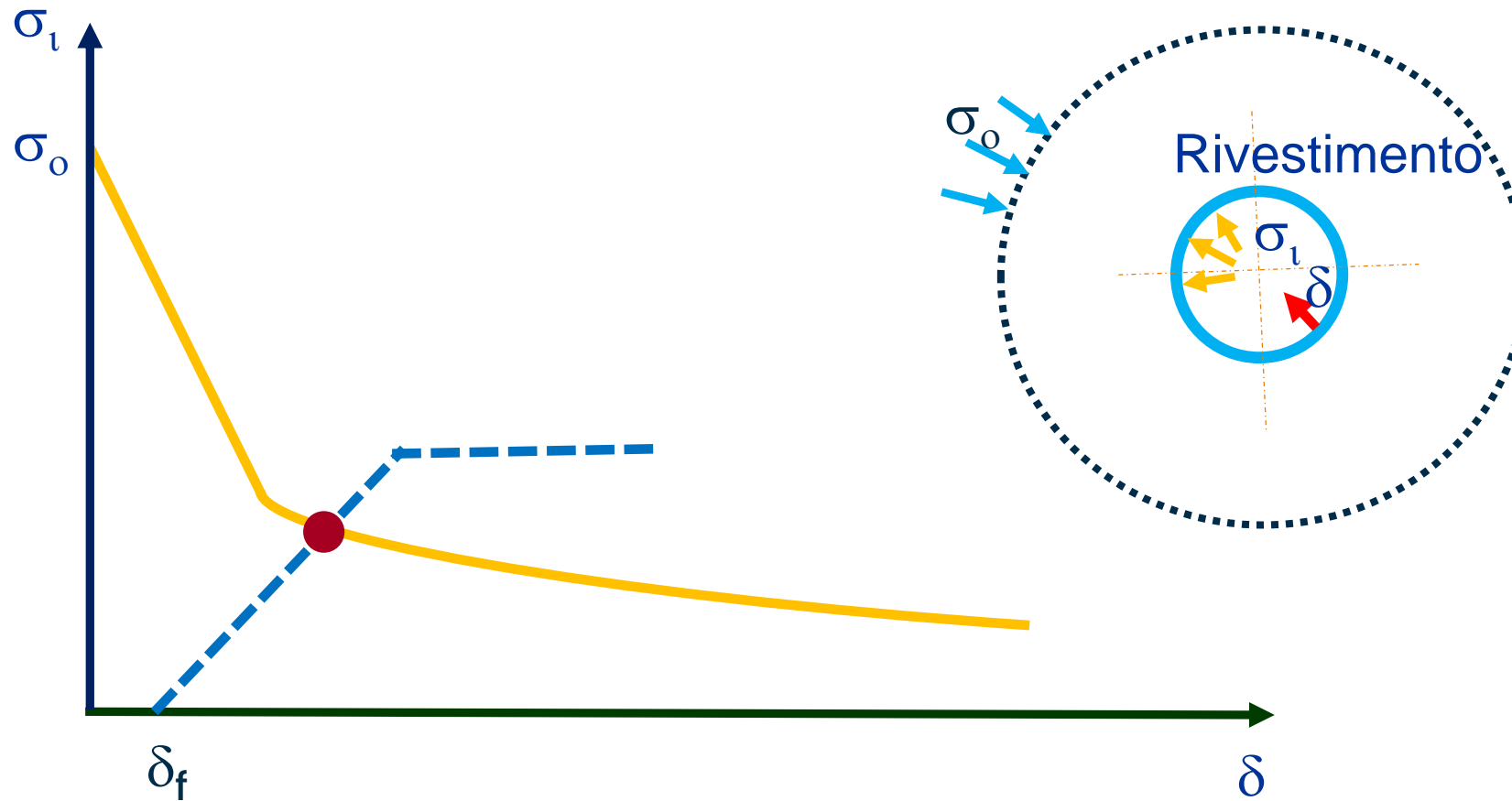
Sviluppo della zona plastica





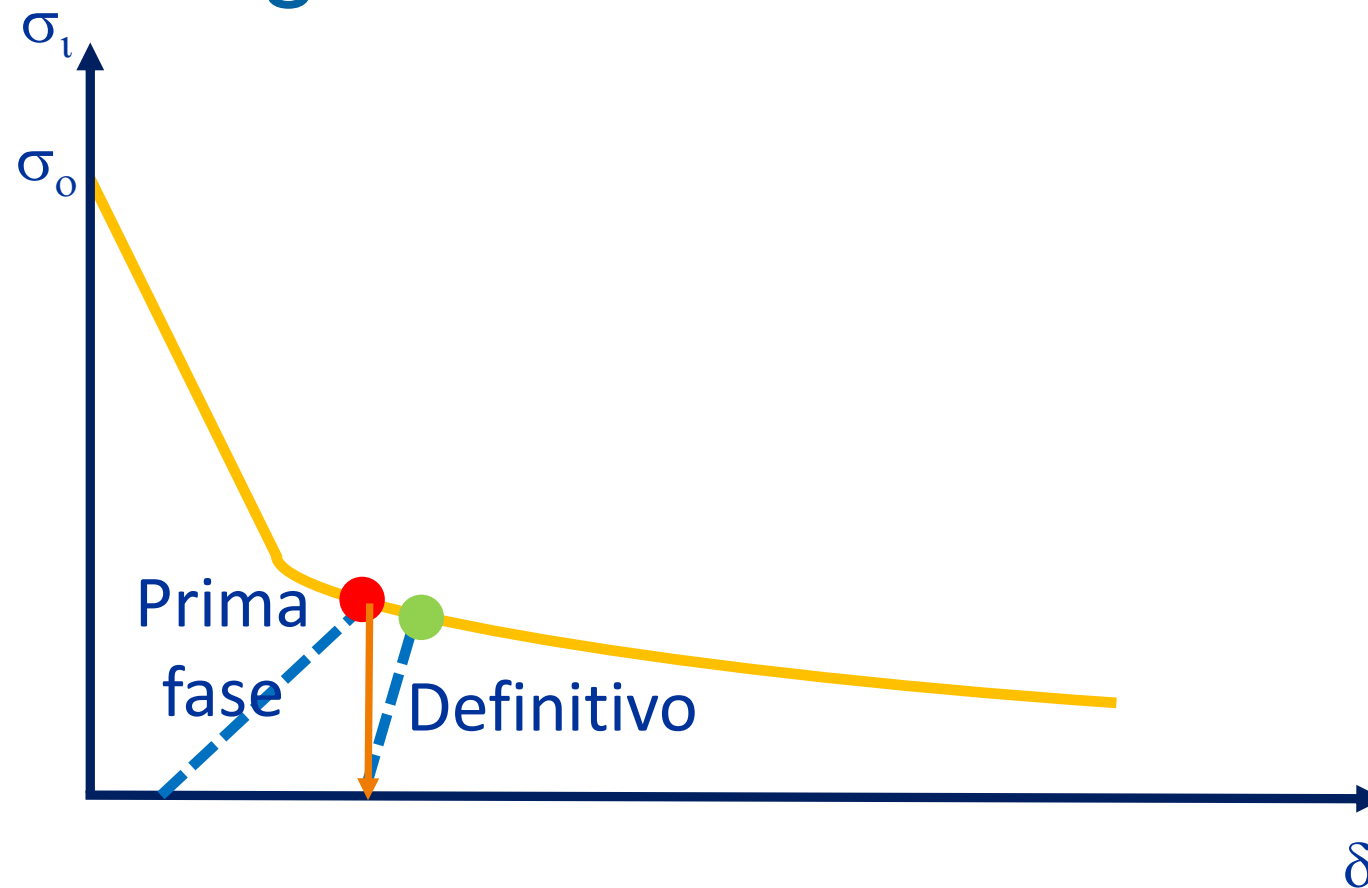
Concetto di curva caratteristica

Azione dei sostegni



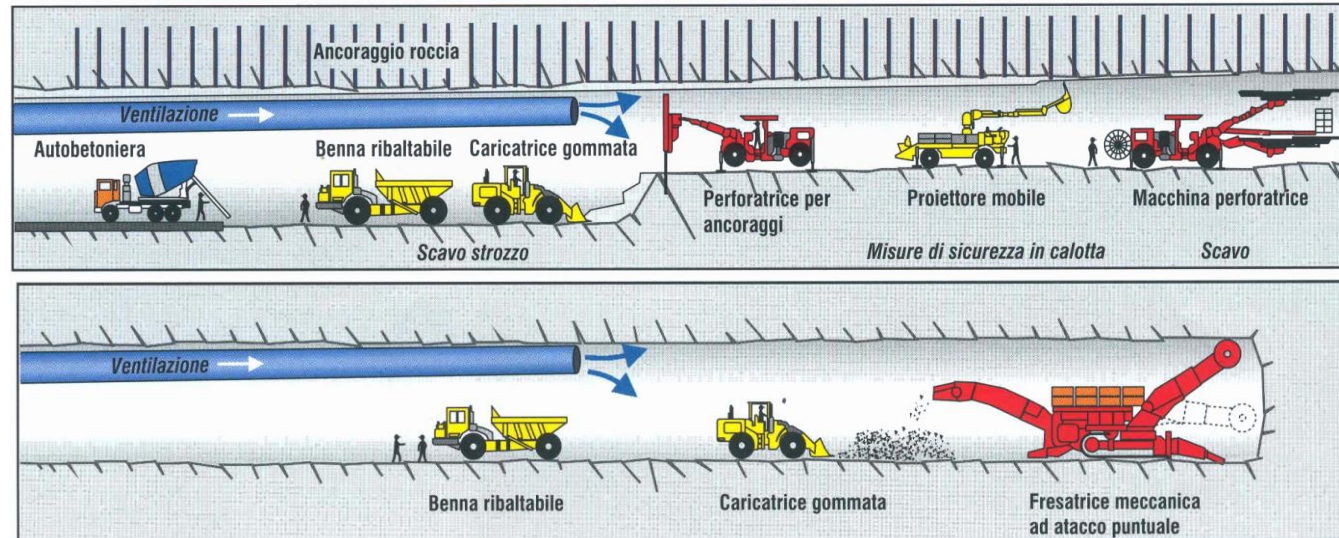
Concetto di curva caratteristica

Azione dei sostegni

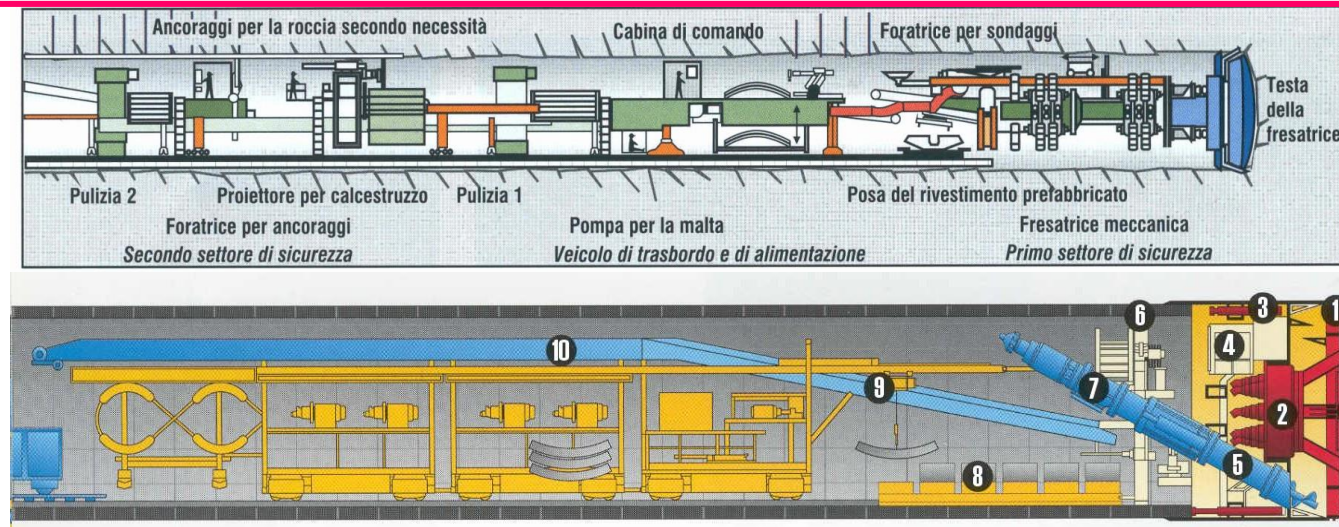


Sintesi dei metodi di scavo

CONVENZIONALE

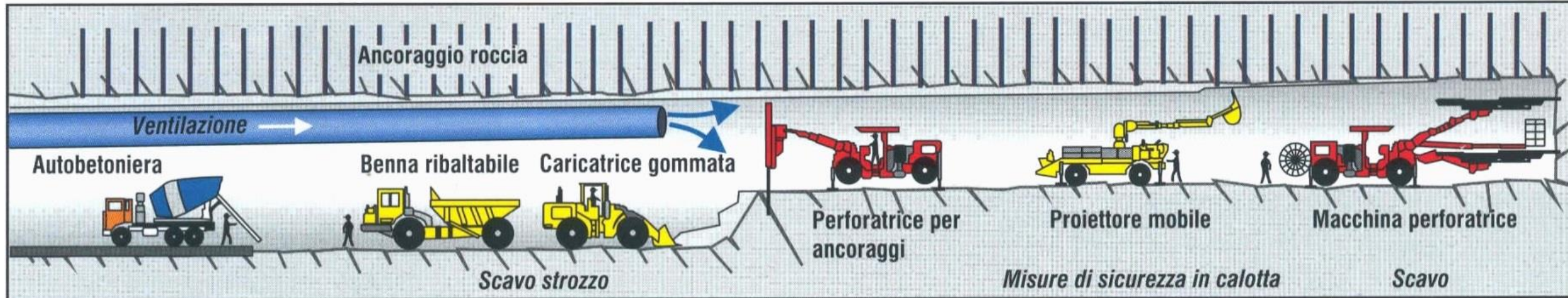


MECCANIZZATO INTEGRALE



Sintesi dei metodi di scavo

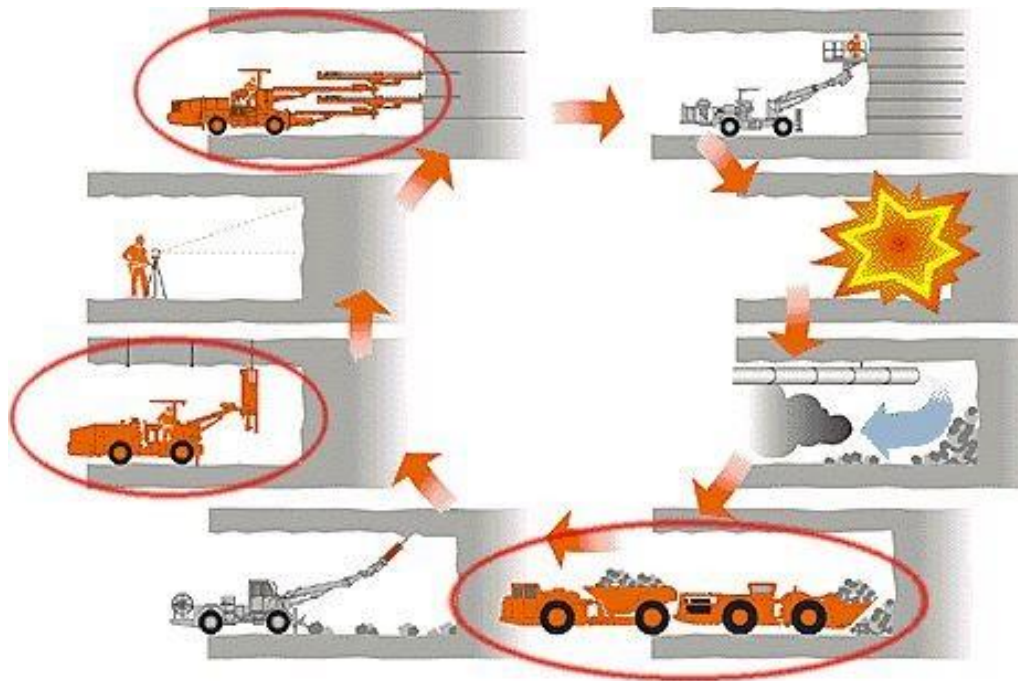
Scavo convenzionale con esplosivo (Drill & Blast)



Sintesi dei metodi di scavo

Scavo convenzionale con esplosivo (Drill & Blast)

Lo scavo può essere realizzato a piena sezione o a sezione parzializzata; con o senza consolidamenti o presostegni dell'ammasso roccioso. Lo scavo segue tipicamente un processo ciclico dove si alternano le fasi di abbattimento, di asportazione del materiale abbattuto (smarino) e di installazione di sostegni.



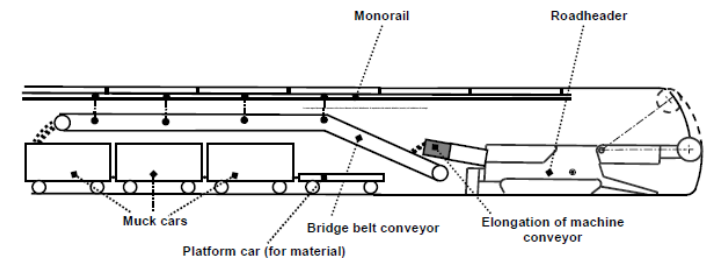
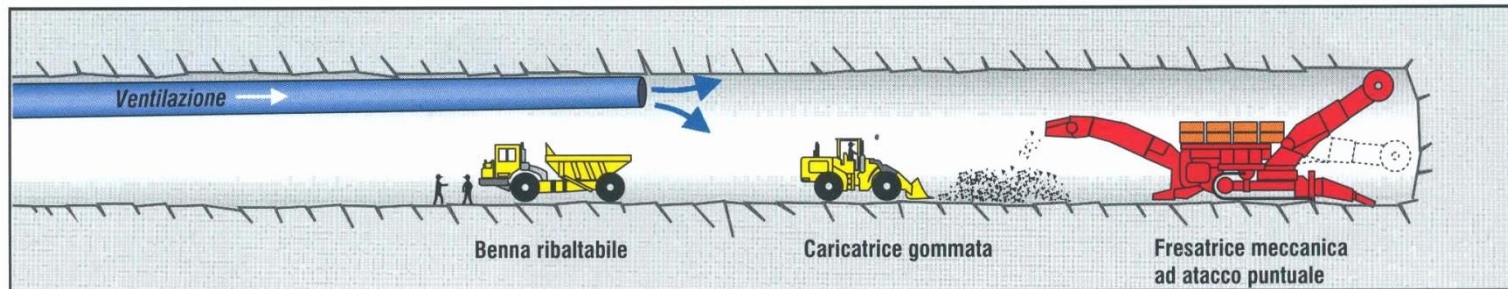
Sintesi dei metodi di scavo

Scavo convenzionale con metodi di scavo puntuali

Lo scavo può essere realizzato a piena sezione o a sezione parzializzata con o senza consolidamenti o presostegni dell'ammasso roccioso. . Lo scavo segue tipicamente un processo ciclico dove si alternano le fasi di abbattimento, di asportazione del materiale abbattuto (smarino) e di installazione di sostegni.

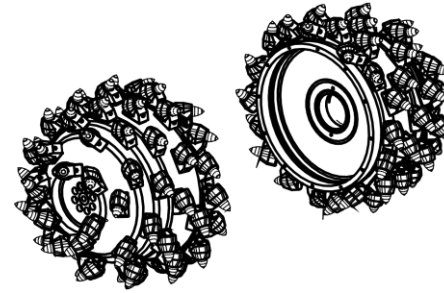
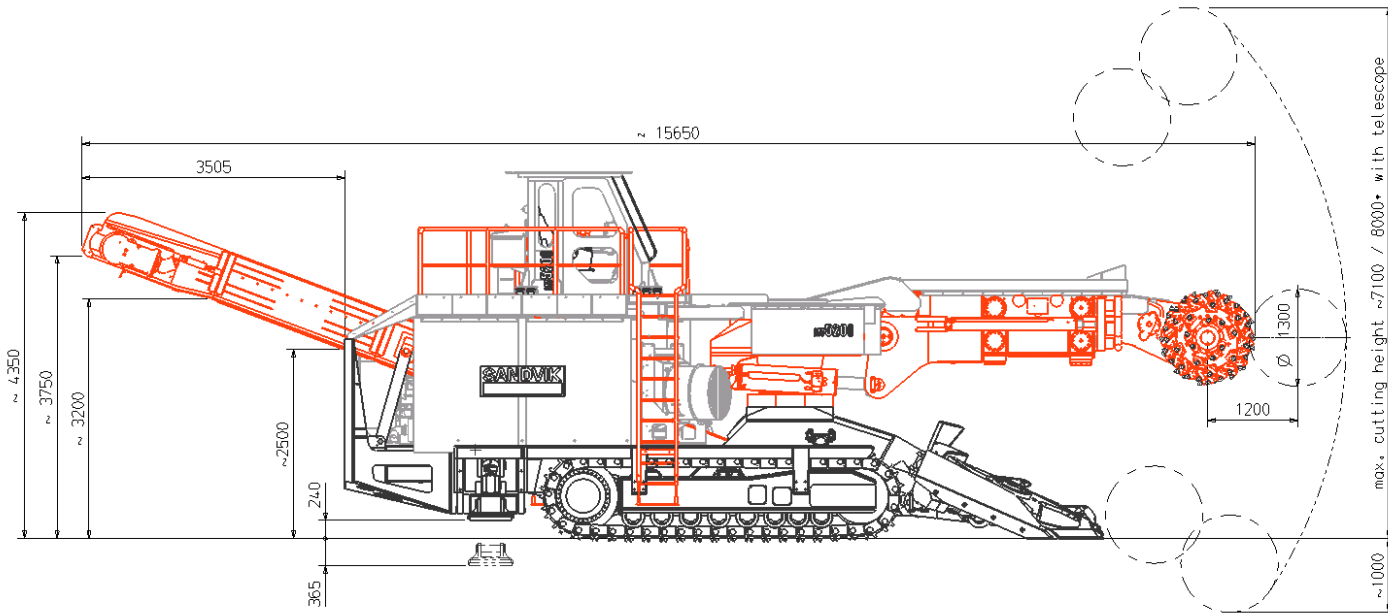
Lo scavo può essere eseguito con frese puntuali (roadheader), martelli ad alta energia d'urto (HEIH), escavatori con benna rovescia, tecnologie speciali (superwedge, ecc.).

Nel caso di scavo con frese puntuali l'asportazione dell'abbattuto sono usualmente contestuali.



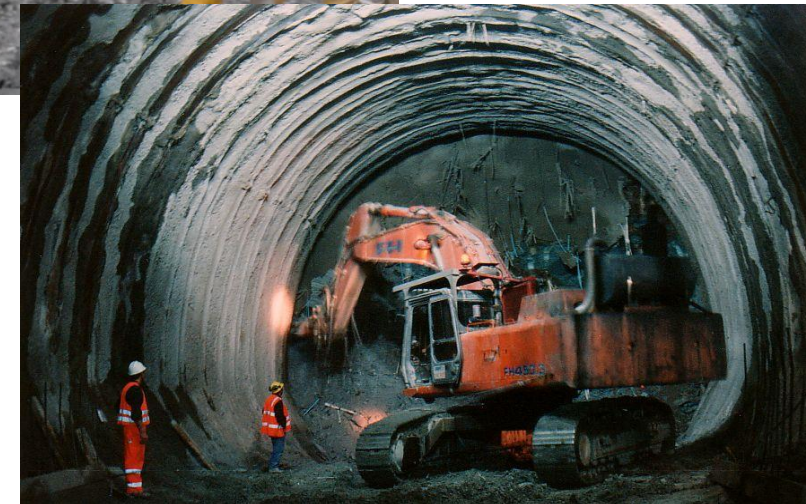
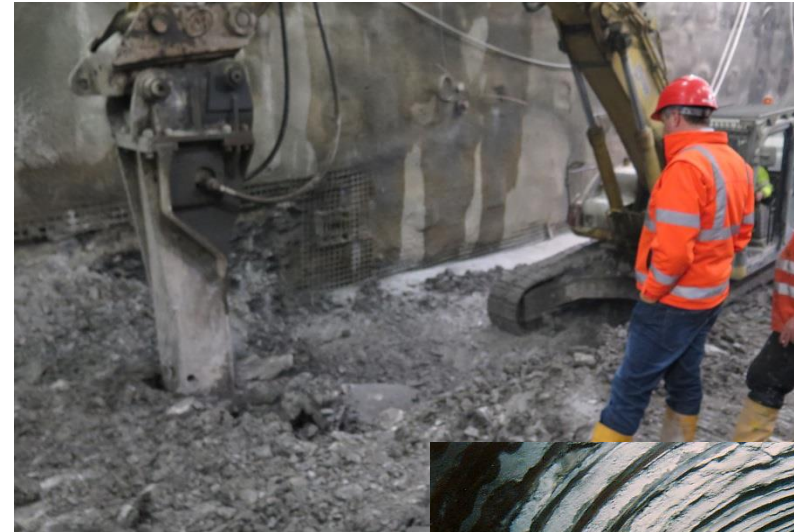
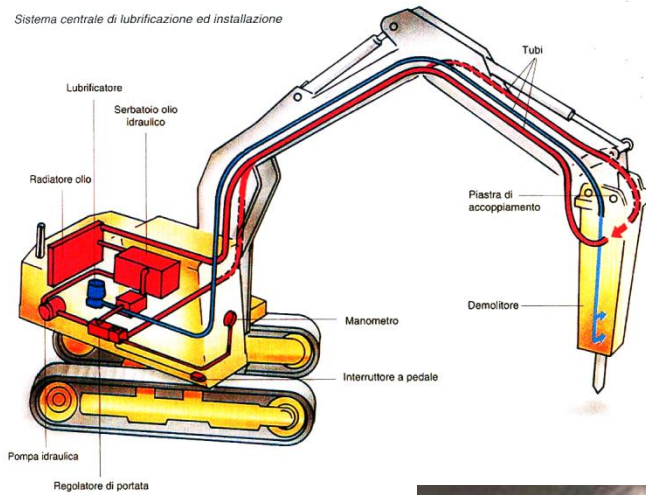
Sintesi dei metodi di scavo

Scavo convenzionale con metodi di scavo puntuali: roadheader



Sintesi dei metodi di scavo

Scavo convenzionale con metodi di scavo puntuali: martello ad alta energia d'urto



Sintesi dei metodi di scavo

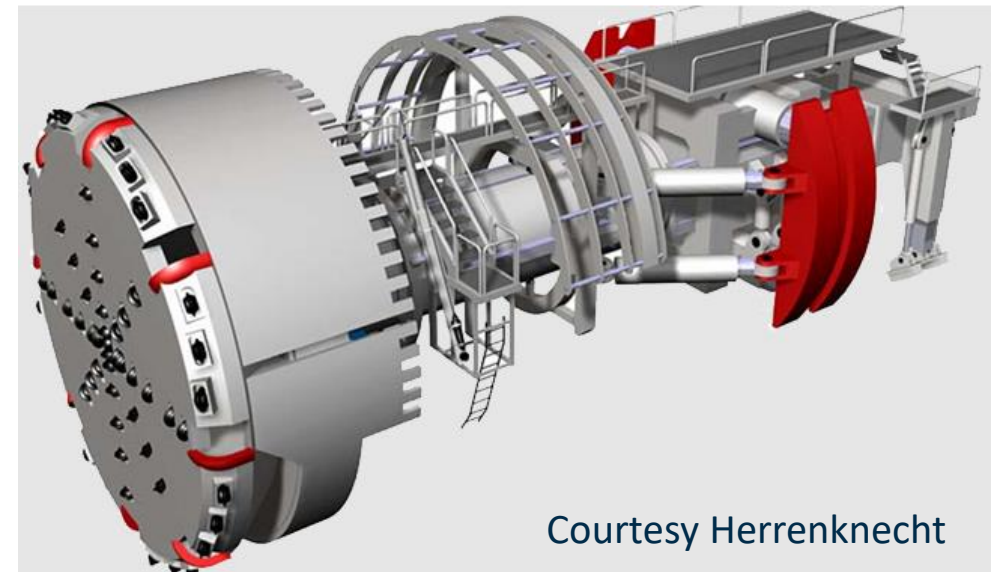
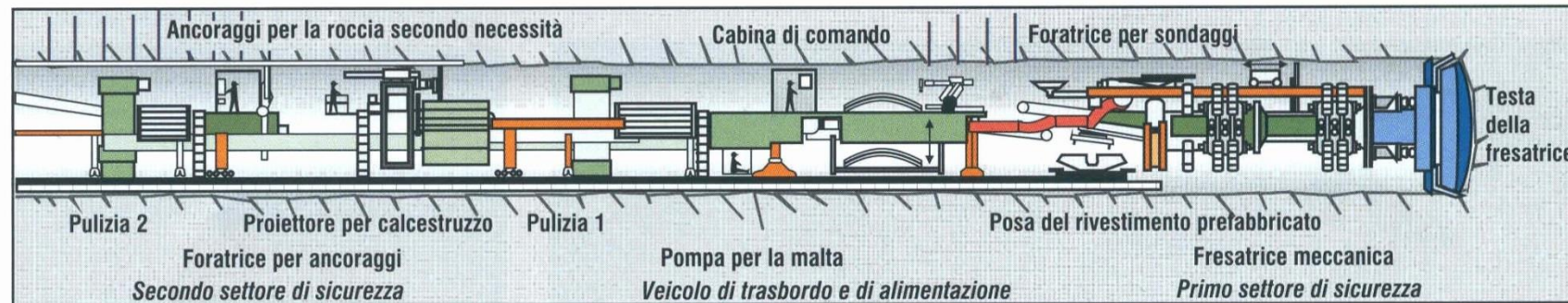
Scavo convenzionale con metodi di scavo puntuali: escavatore



Sintesi dei metodi di scavo

Scavo meccanizzato a piena sezione in roccia

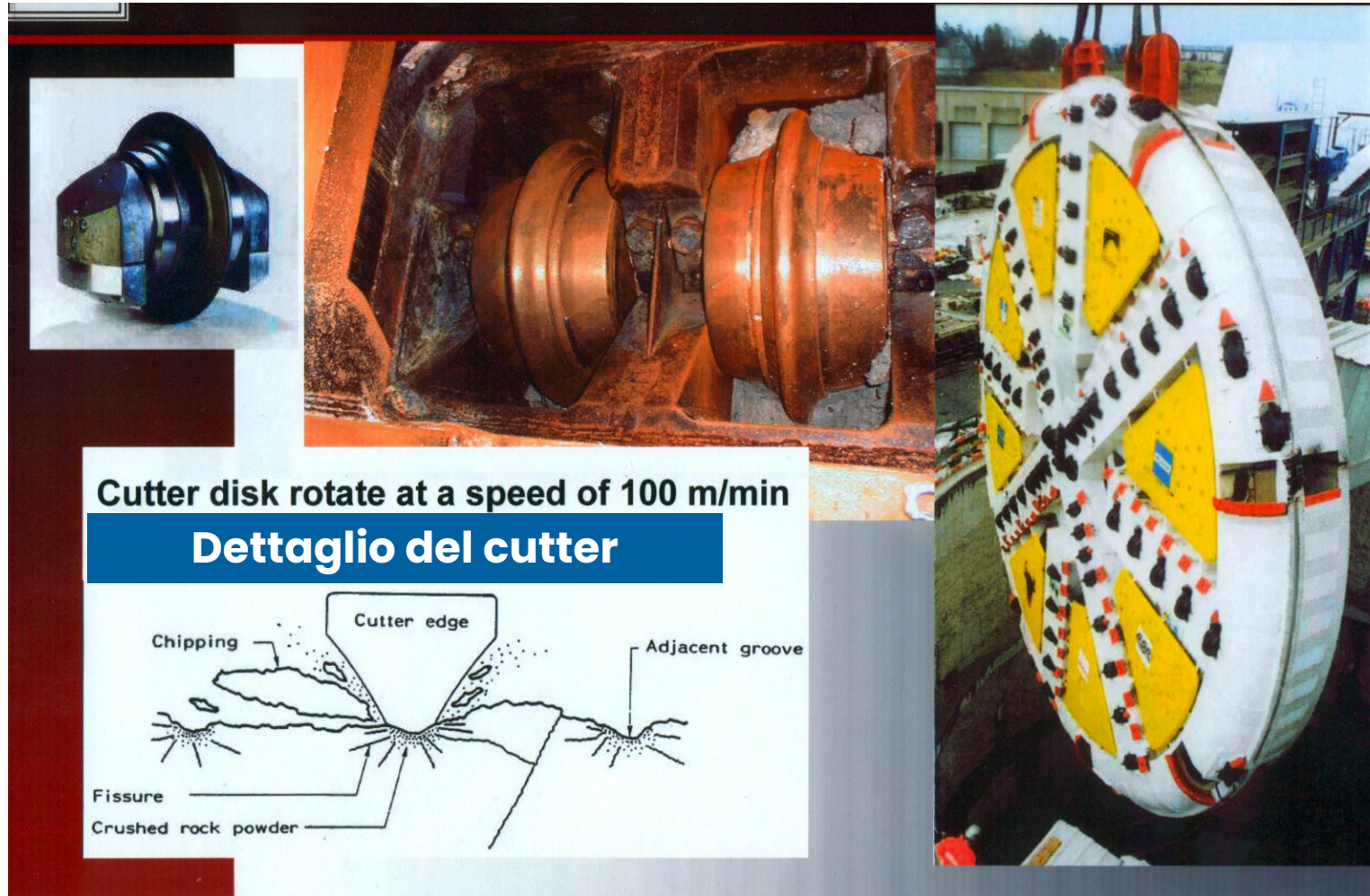
Le macchine devono essere in grado di demolire la roccia grazie all'azione di utensili (cutter)



Courtesy Herrenknecht

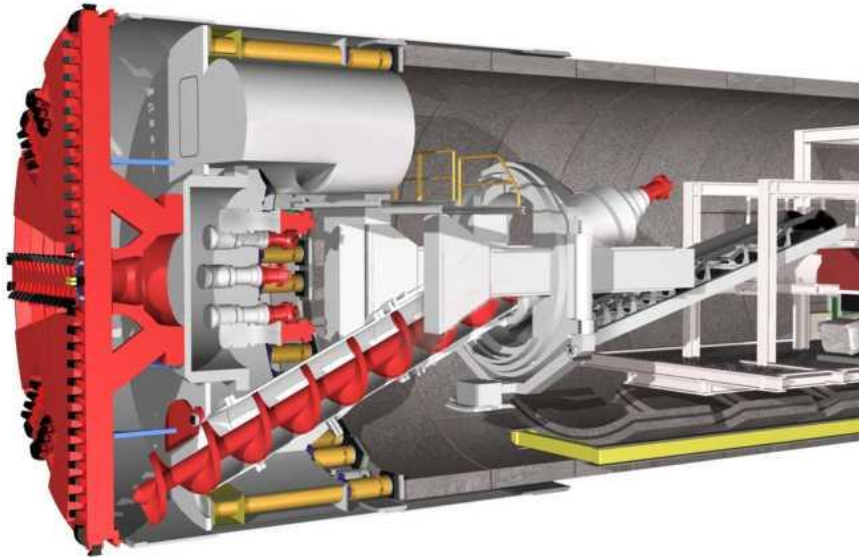
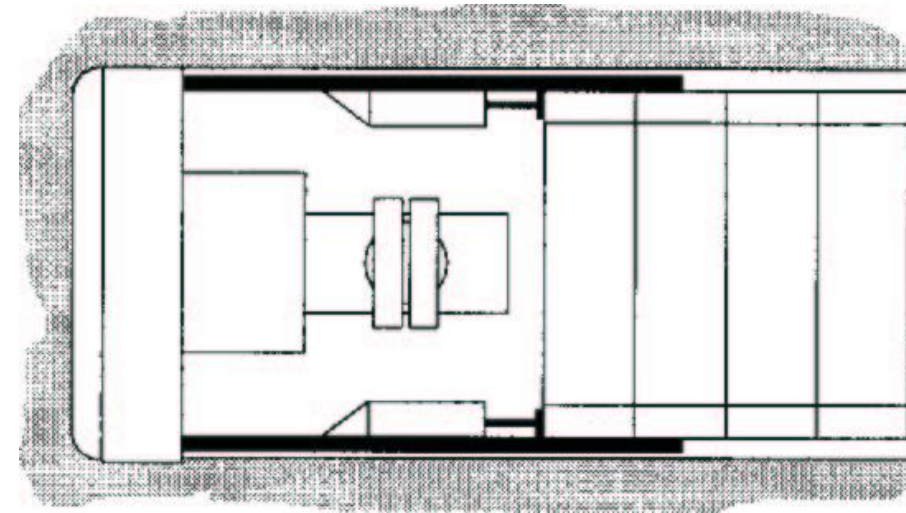
Sintesi dei metodi di scavo

Scavo meccanizzato a piena sezione in roccia

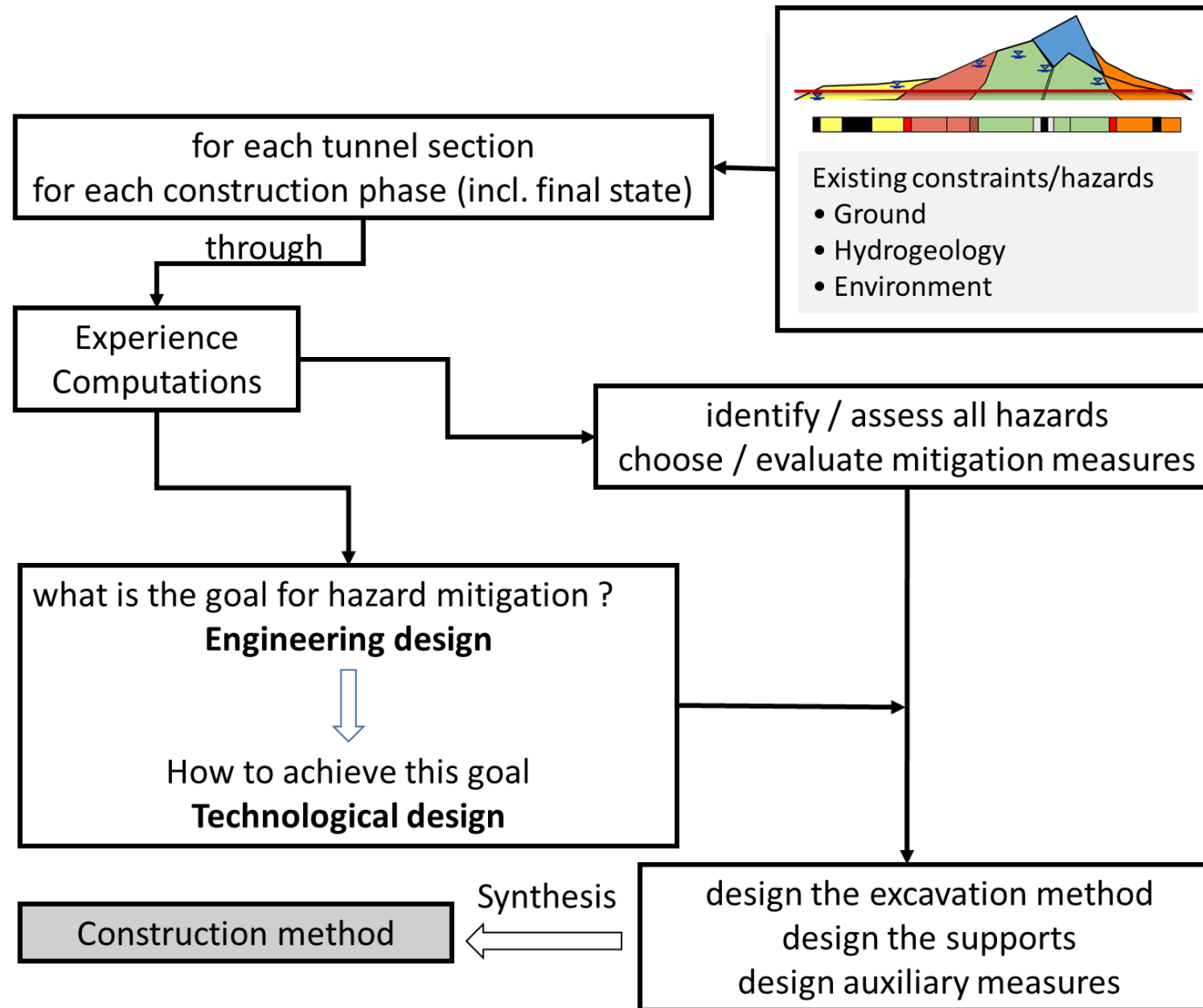


Sintesi dei metodi di scavo

Scavo meccanico a piena sezione in terreno: scudi



Base concettuale per la progettazione

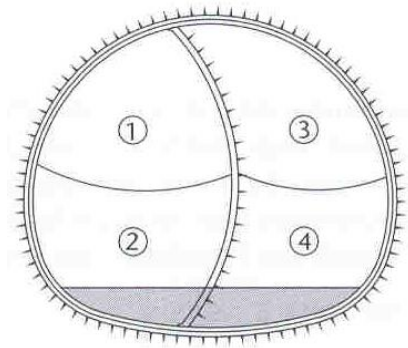
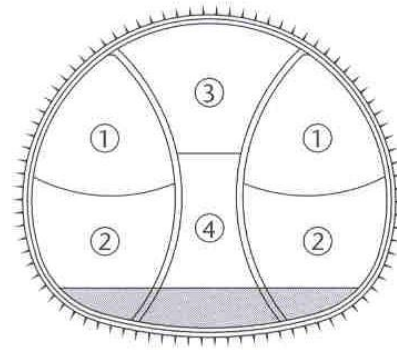
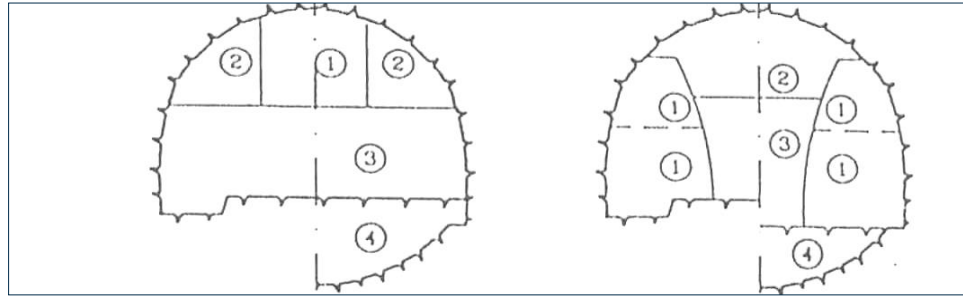
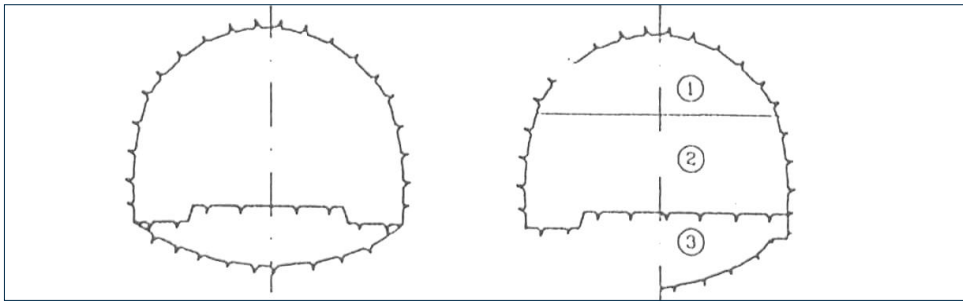


Base concettuale per la progettazione

Quando la luce libera è troppo corta ed il tempo di autoportanza è eccessivamente breve per garantire un'installazione sicura dei sostegni

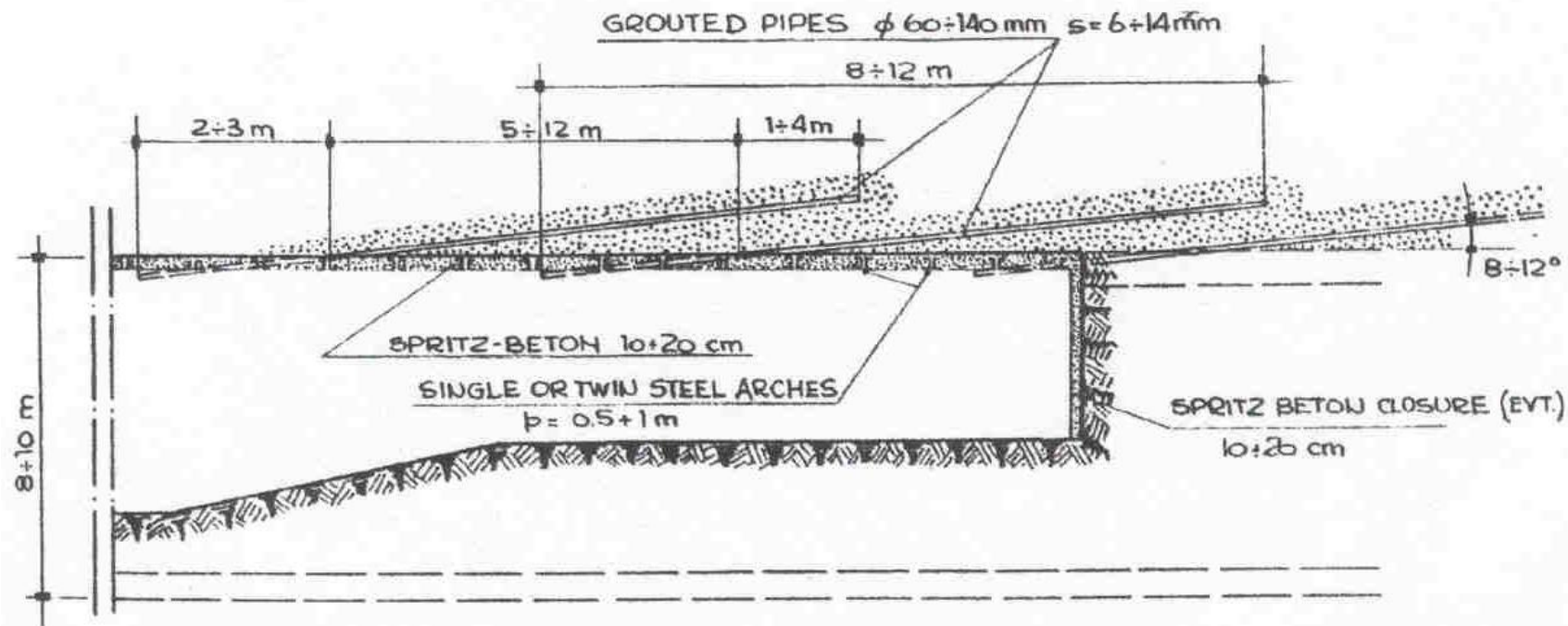
Il progettista ha quattro opzioni fondamentali

- 1) Ridurre la sezione di scavo a valori più piccoli (sezione parzializzata);**
- 2) Usare presostegni o miglioramenti della massa rocciosa davanti al fronte**
- 3) Migliorare la proprietà meccaniche dei terreni**
- 4) Applicare una contropressione al fronte**



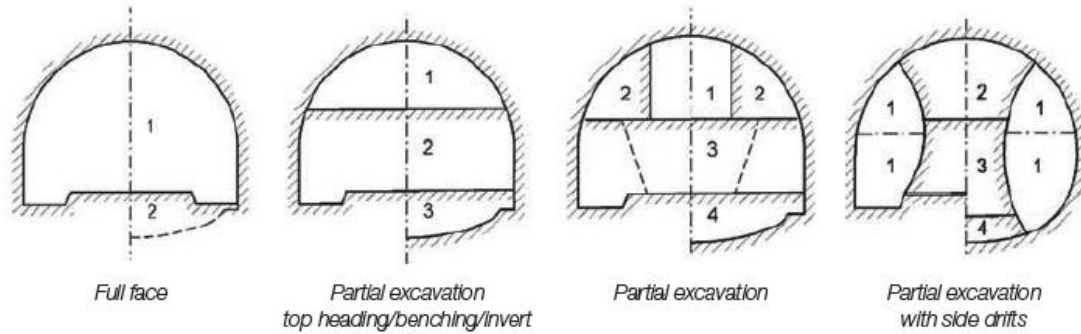
LONGITUDINAL SECTION (MEDIUM WEIGHT SUPPORT TYPE)

HALF SECTION OR FULL SECTION DRIVAGE



Scavo a sezione parzializzata calotta e ribasso + ombrello di tubi

Scavo in convenzionale a sezione piena o a sezione parzializzata ?



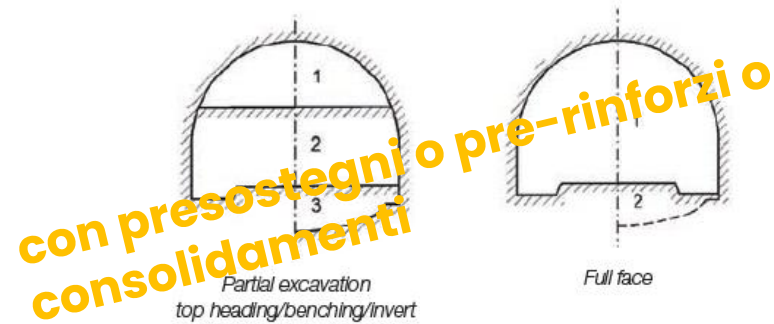
Riduzione delle proprietà meccaniche dei terreni e quindi tempi di autoportanza brevi e luci libere corte



Partial excavation



Top heading





BO-FI High speed railway line (Italy) - CAVET
Brossure

	PROFILO LONGITUDINALE	IN FASE D'AVANZAMENTO	CON RIVESTIMENTO DEFINITIVO
TIPO C1			
TIPO C2			
TIPO C3			

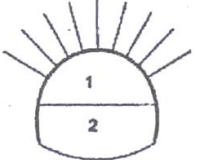
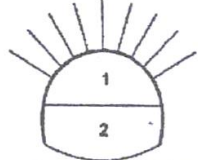
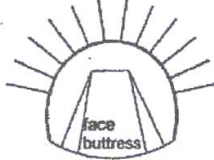
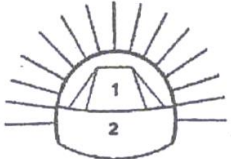
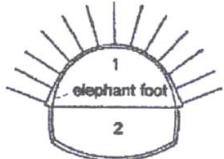
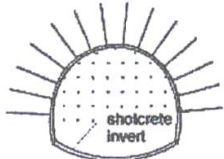
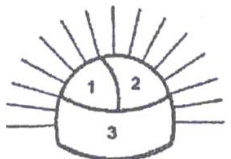
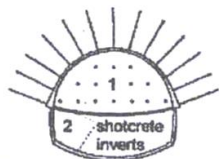
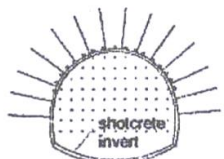

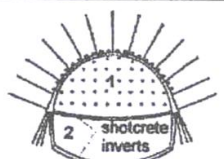
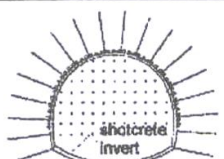
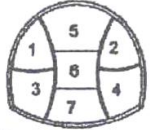
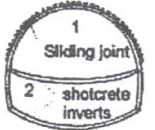
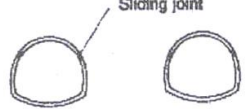
Esempio di sezioni parzializzate in grandi sezioni di scavo



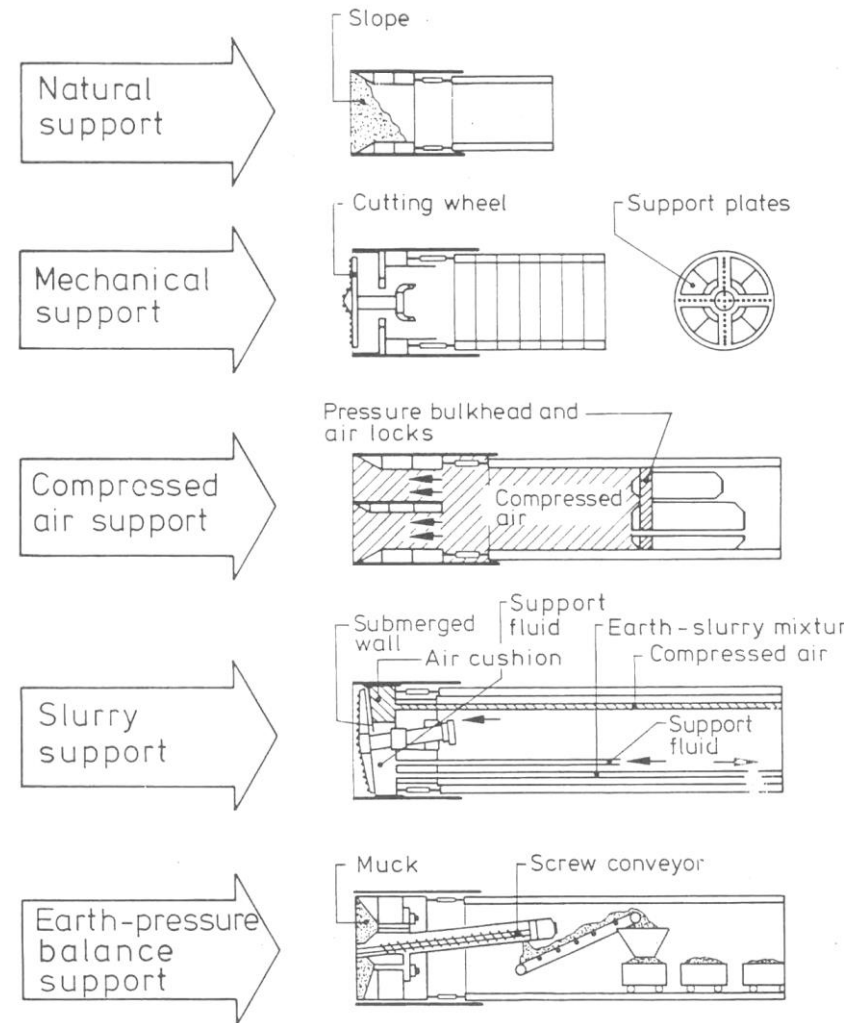
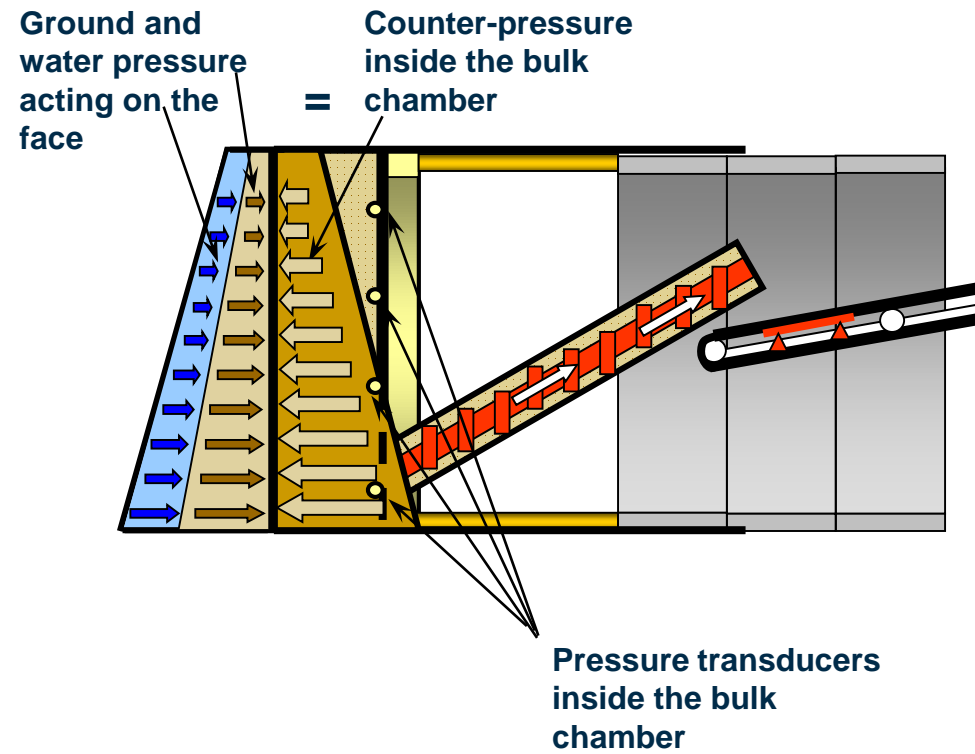
Caverna Borzoli –cortesia Geodata SpA



Esempio dello scavo del “Camerone C GN13” linea Av tra Genova e Milano (cortesia Italferr SpA).

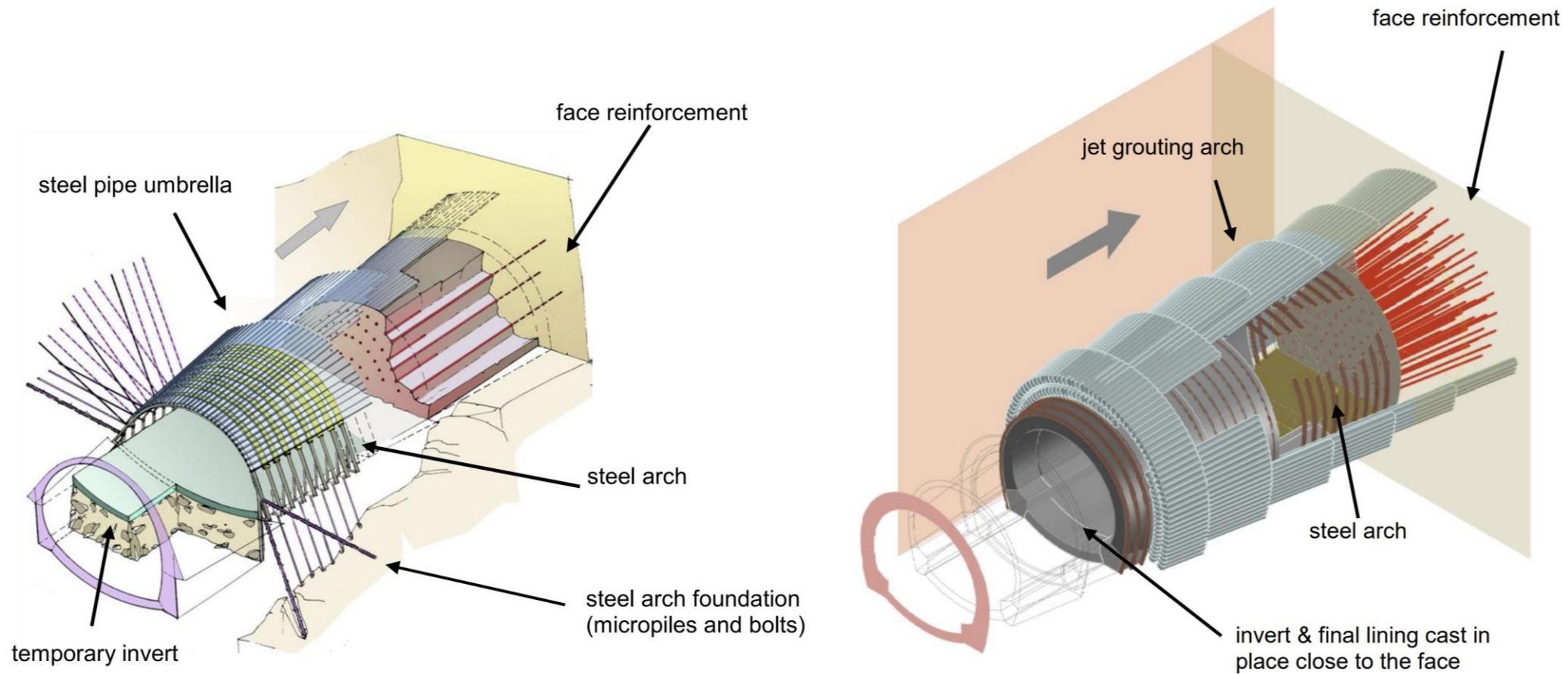
	MULTIPLE HEADINGS	TOP HEADING AND BENCH	FULL FACE EXCAVATION
NO SQUEEZING	 <p>Safety rockbolts in crown with 50 mm thick shotcrete</p>	 <p>Safety rockbolts in crown with 50 mm thick shotcrete</p>	 <p>Safety rockbolts, 50 mm thick shotcrete and face buttress</p>
MINOR SQUEEZING	 <p>Rockbolts, 100 mm thick shotcrete and face buttress</p>	 <p>Steel sets in shotcrete with elephant foot and invert lining</p>	 <p>Lattice girders, shotcrete, fiber-glass dowels grouted in face</p>
SEVERE SQUEEZING	 <p>Partial face excavation, 150 mm thick shotcrete lining and invert</p>	 <p>Steel sets in shotcrete, grouted fiberglass dowels in face</p>	 <p>Forepoles, steel sets, grouted fiberglass dowels in face</p>
V. SEVERE SQUEEZING	 <p>200 mm thick shotcrete linings, self-drilling rockbolts</p>	 <p>Forepoles, fiberglass dowels, micropile foundations for sets</p>	 <p>Dense forepole or jet grout umbrella and face support</p>
EXTREME SQUEEZING	 <p>Central pillar, lattice girders embedded in 250 mm thick shotcrete lining, no rockbolts</p>	 <p>Forepole umbrella, steel sets with sliding joints, close temporary and final inverts</p>	 <p>Split into two smaller tunnels and use steel sets with sliding joints in 250 mm shotcrete</p>

Hoek, 2000



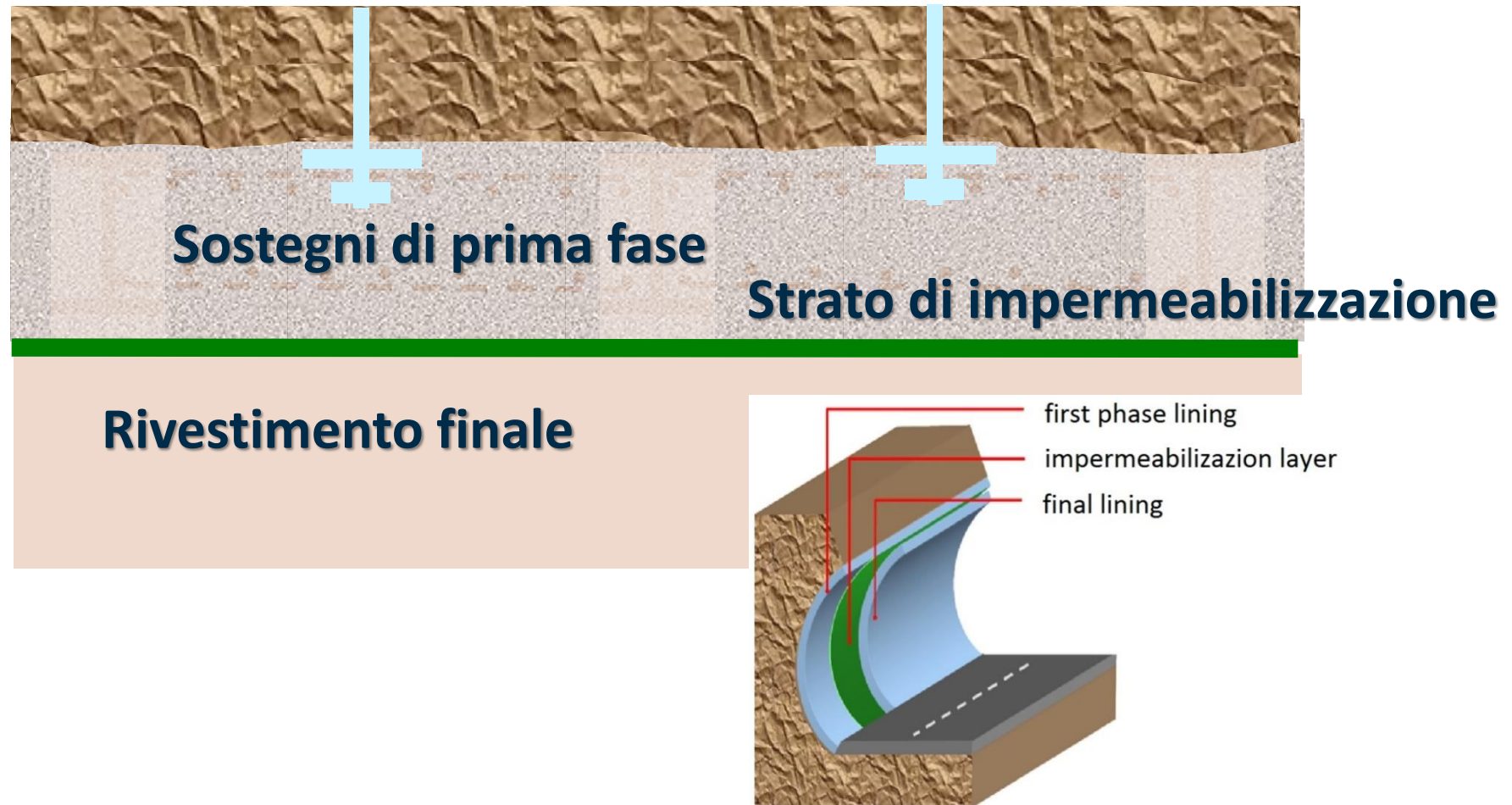
Maidl et al., 1994

Pre-sostegni e consolidamenti

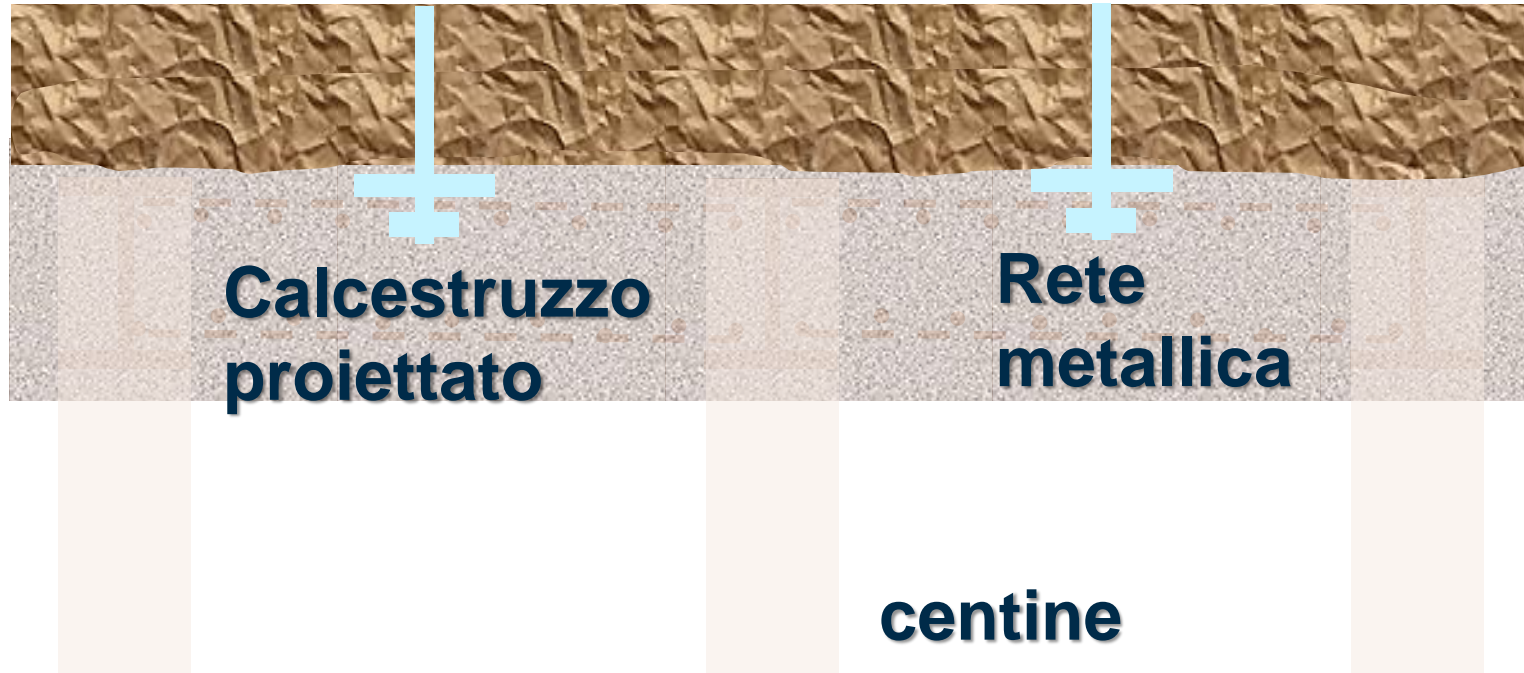


Tratte da: Handbook of Tunnels and Underground Works (2022)

Sostegni – Scavo convenzionale



Bulloni



Sostegni – Scavo convenzionale

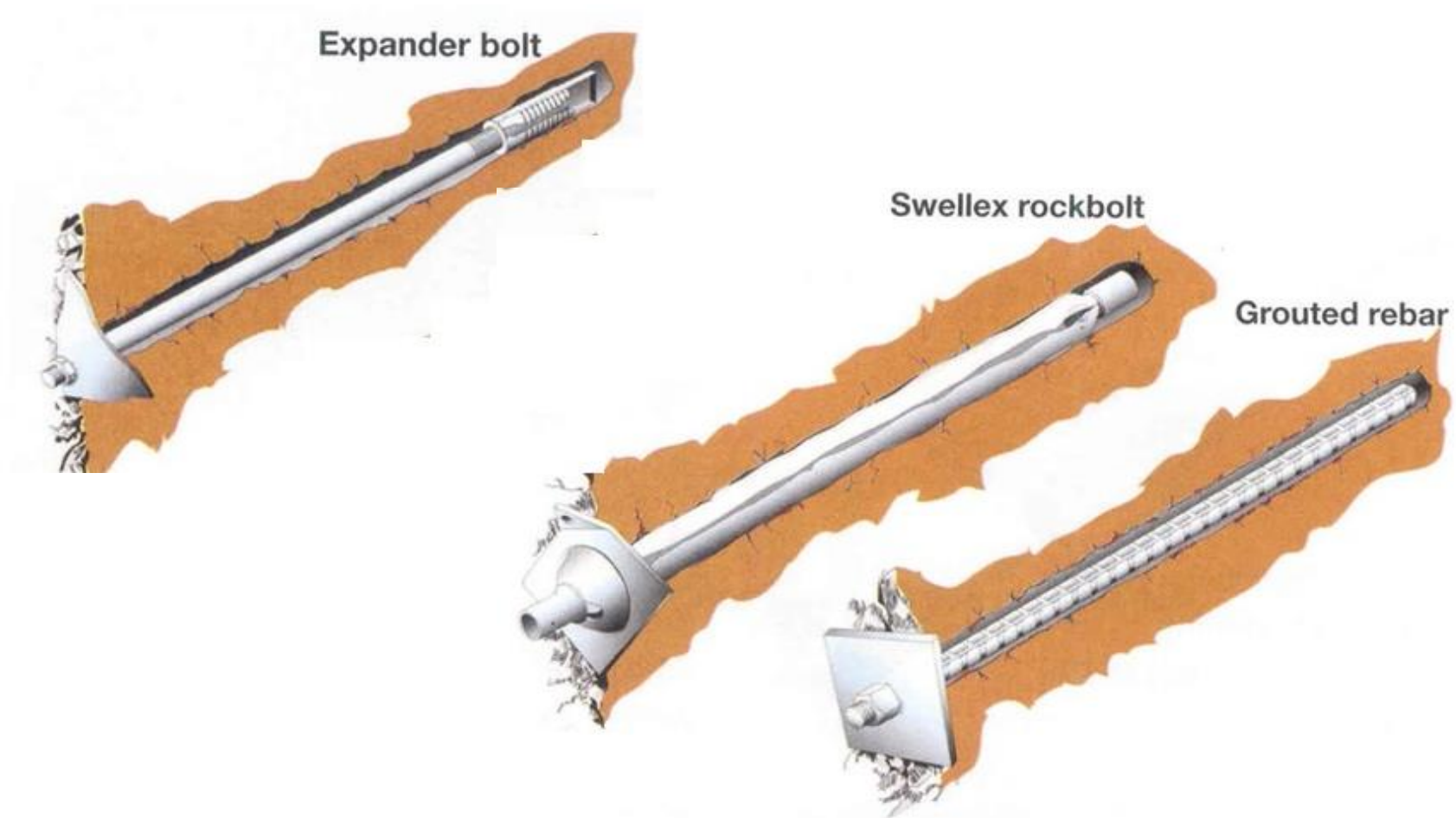
Bulloni



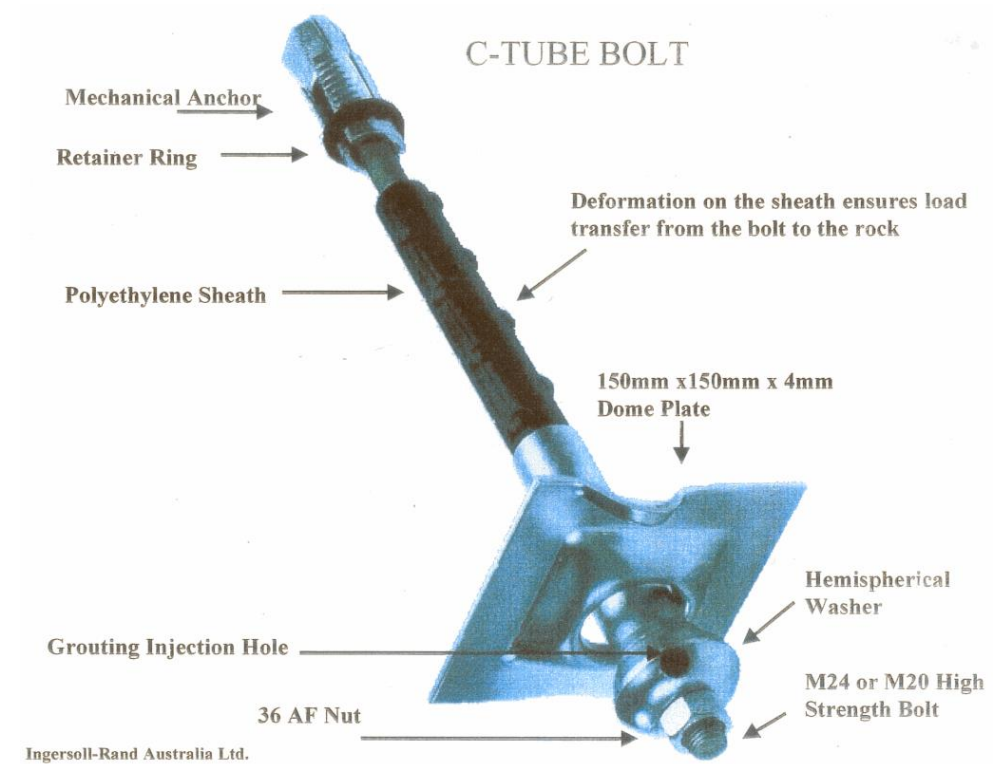
Rete metallica o fibre metalliche



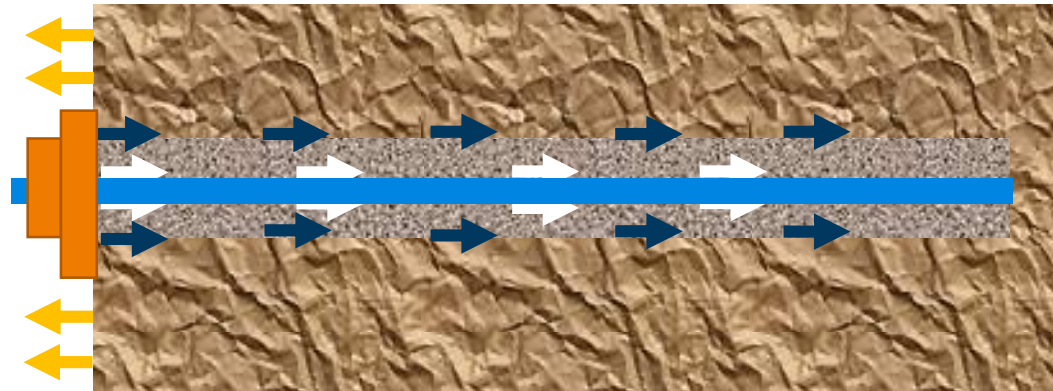
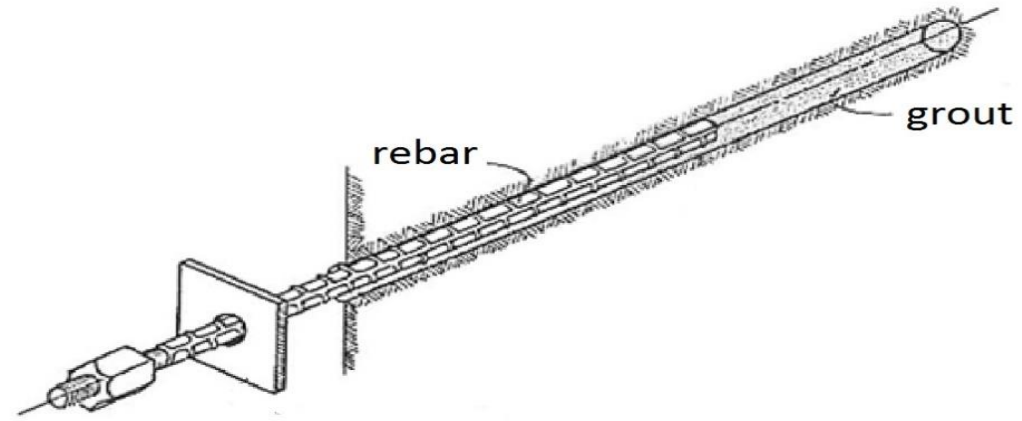
Bulloni



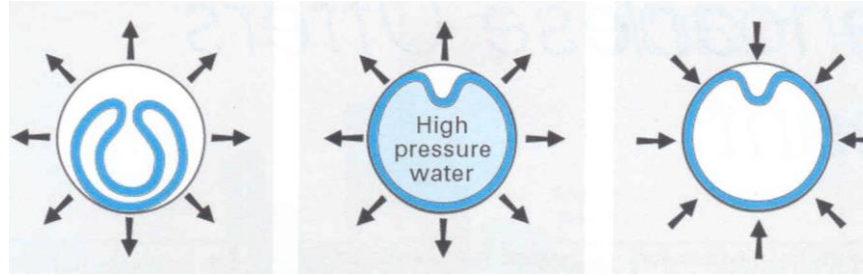
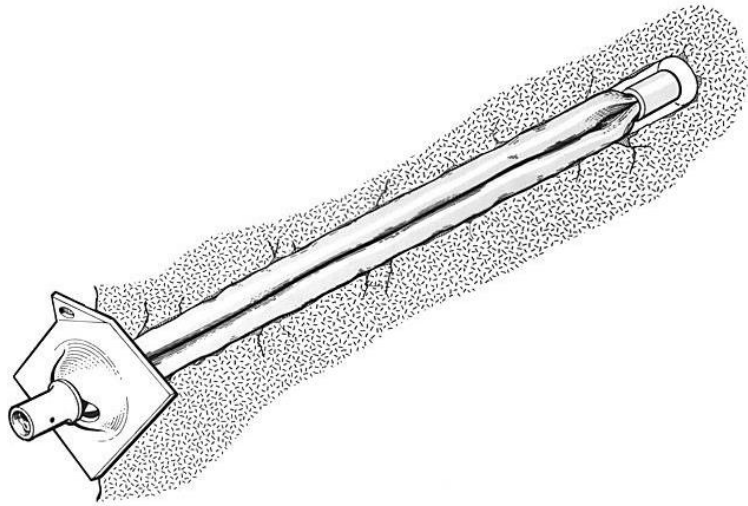
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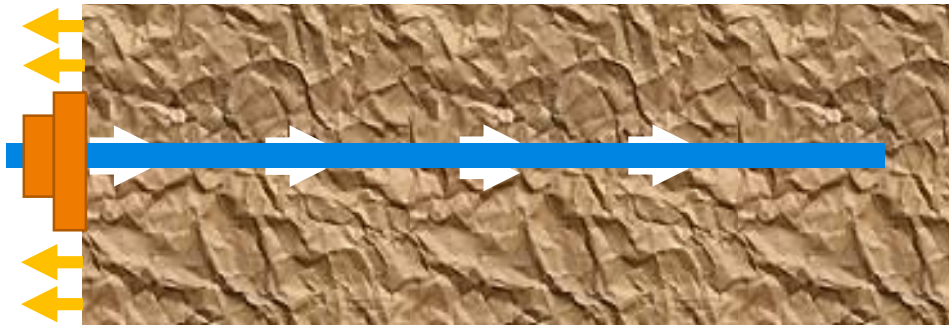
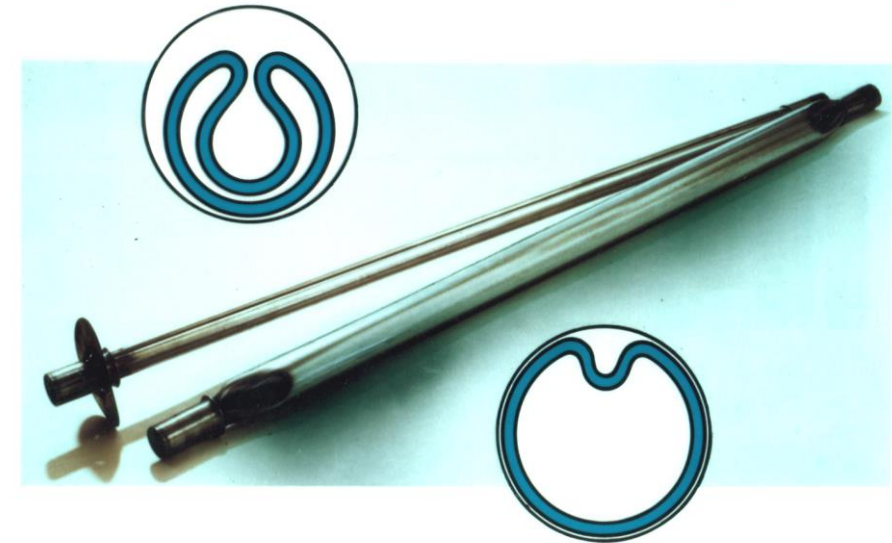
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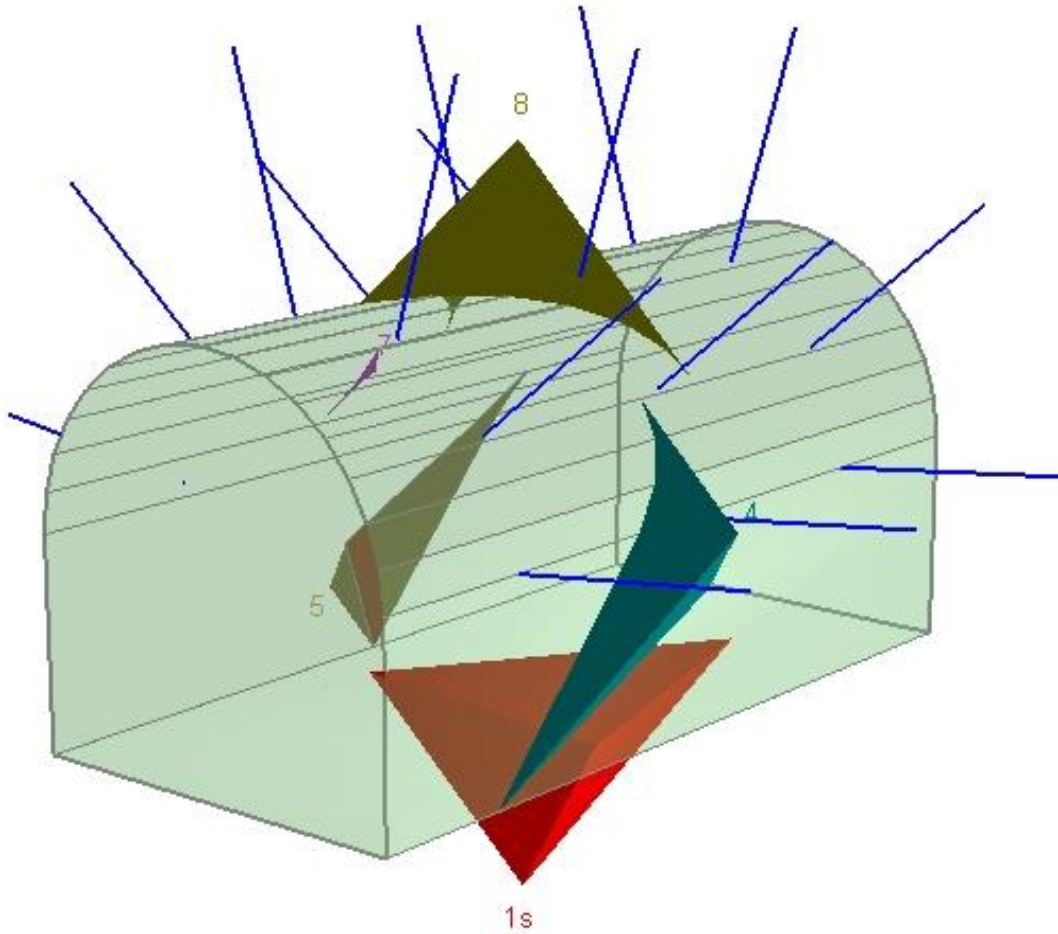
Bulloni



The principle of the Swellex system



Bulloni Swellex



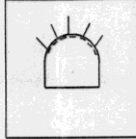
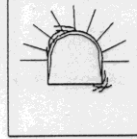
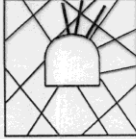
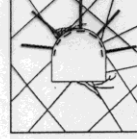
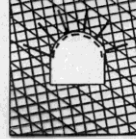
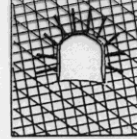
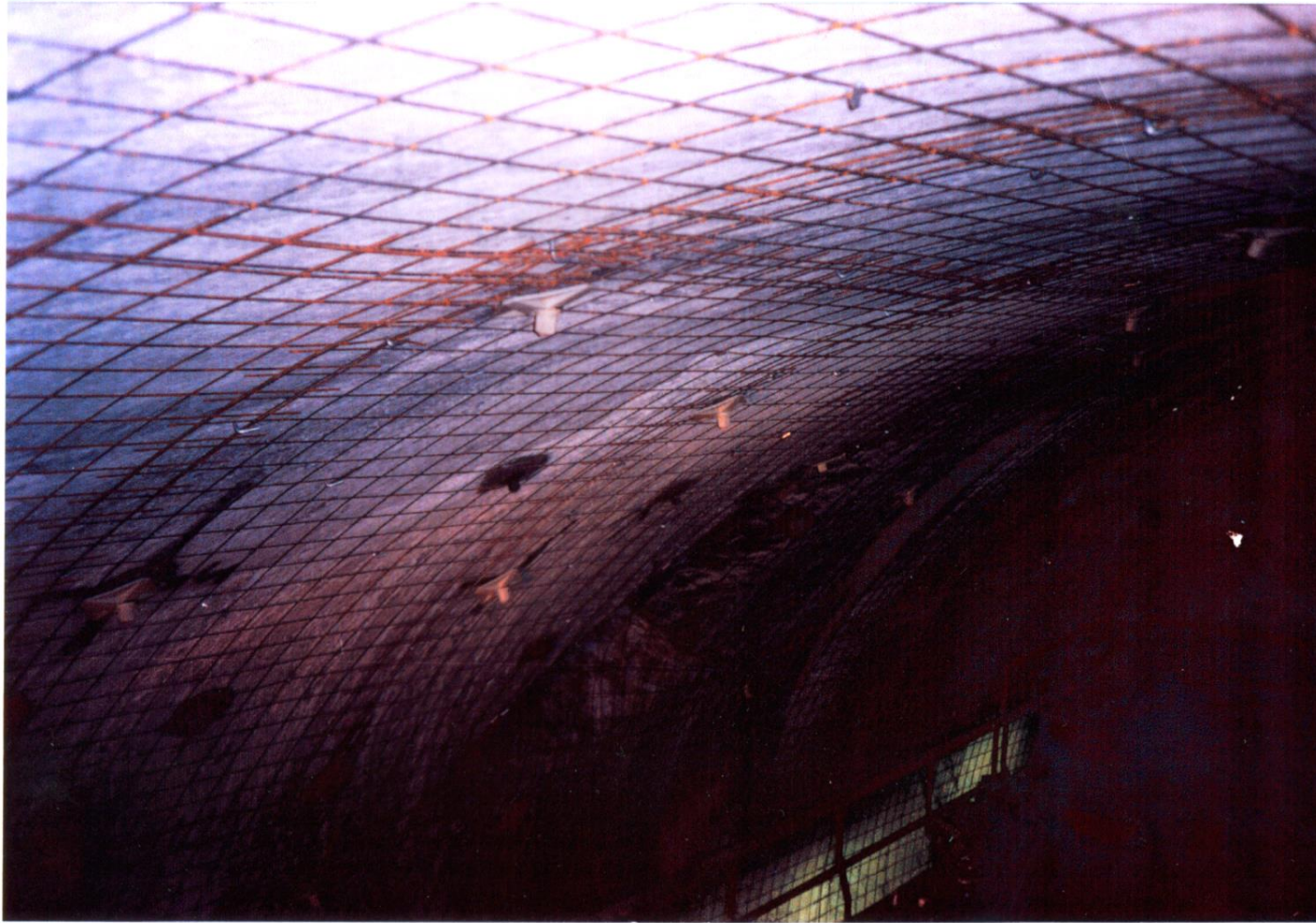
	Low stress levels	High stress levels
Massive rock	 <p>Massive rock subjected to low in situ stress levels. No support or 'safety bolts' or dowels and mesh.</p>	 <p>Massive rock subjected to high in situ stress levels. Pattern rockbolts or dowels with mesh or shotcrete to inhibit fracturing and to keep broken rock in place.</p>
Jointed rock	 <p>Massive rock with relatively few discontinuities subjected to low in situ stress conditions. 'Spot' bolts located to prevent failure of individual blocks and wedges. Bolts must be tensioned.</p>	 <p>Massive rock with relatively few discontinuities subjected to high in situ stress conditions. Heavy bolts or dowels, inclined to cross rock structure, with mesh or steel fibre reinforced shotcrete on roof and side-walls.</p>
Heavily jointed rock	 <p>Heavily jointed rock subjected to low in situ stress conditions. Light pattern bolts with mesh and/or shotcrete will control ravelling of near surface rock pieces.</p>	 <p>Heavily jointed rock subjected to high in situ stress conditions. Heavy rockbolt or dowel pattern with steel fibre reinforced shotcrete. In extreme cases, steel sets with sliding joints may be required. Invert struts or concrete floor slabs may be required to control floor heave.</p>

Figure 12.1: Typical rockbolt and dowel applications to control different types of rock mass failure.

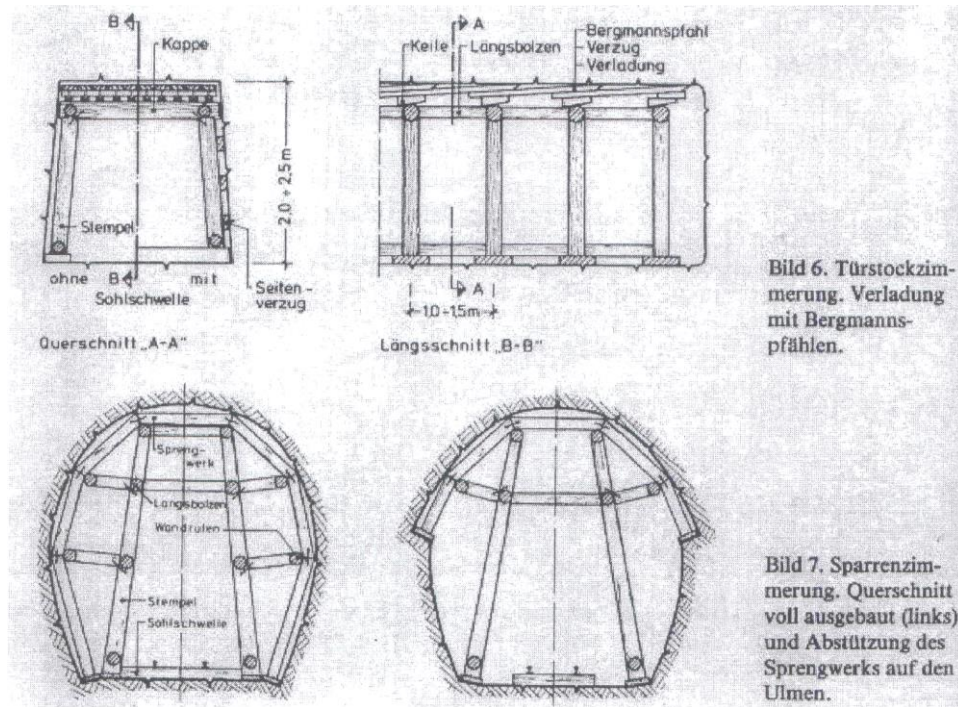
Bulloni



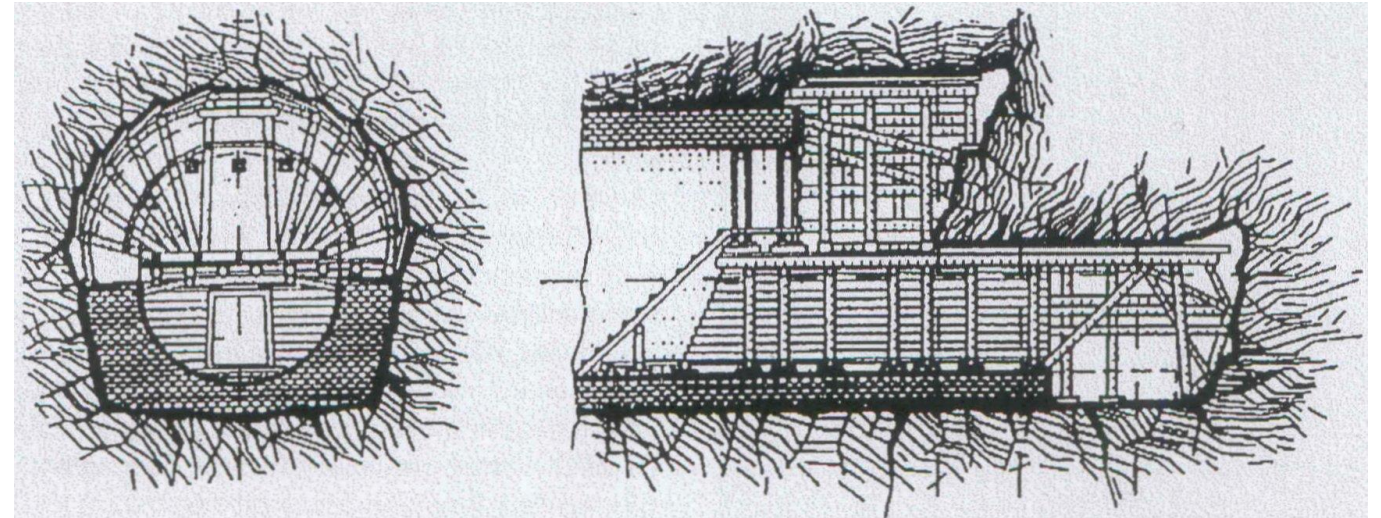
Centine



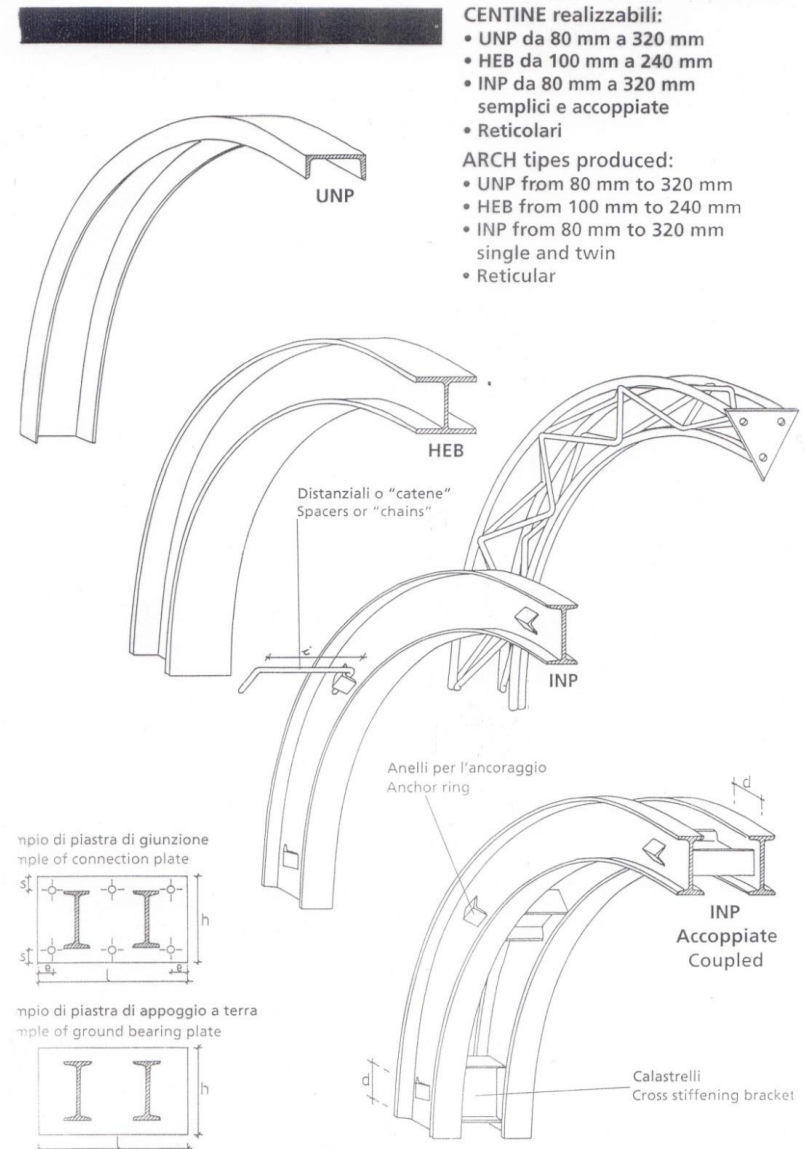
Centine

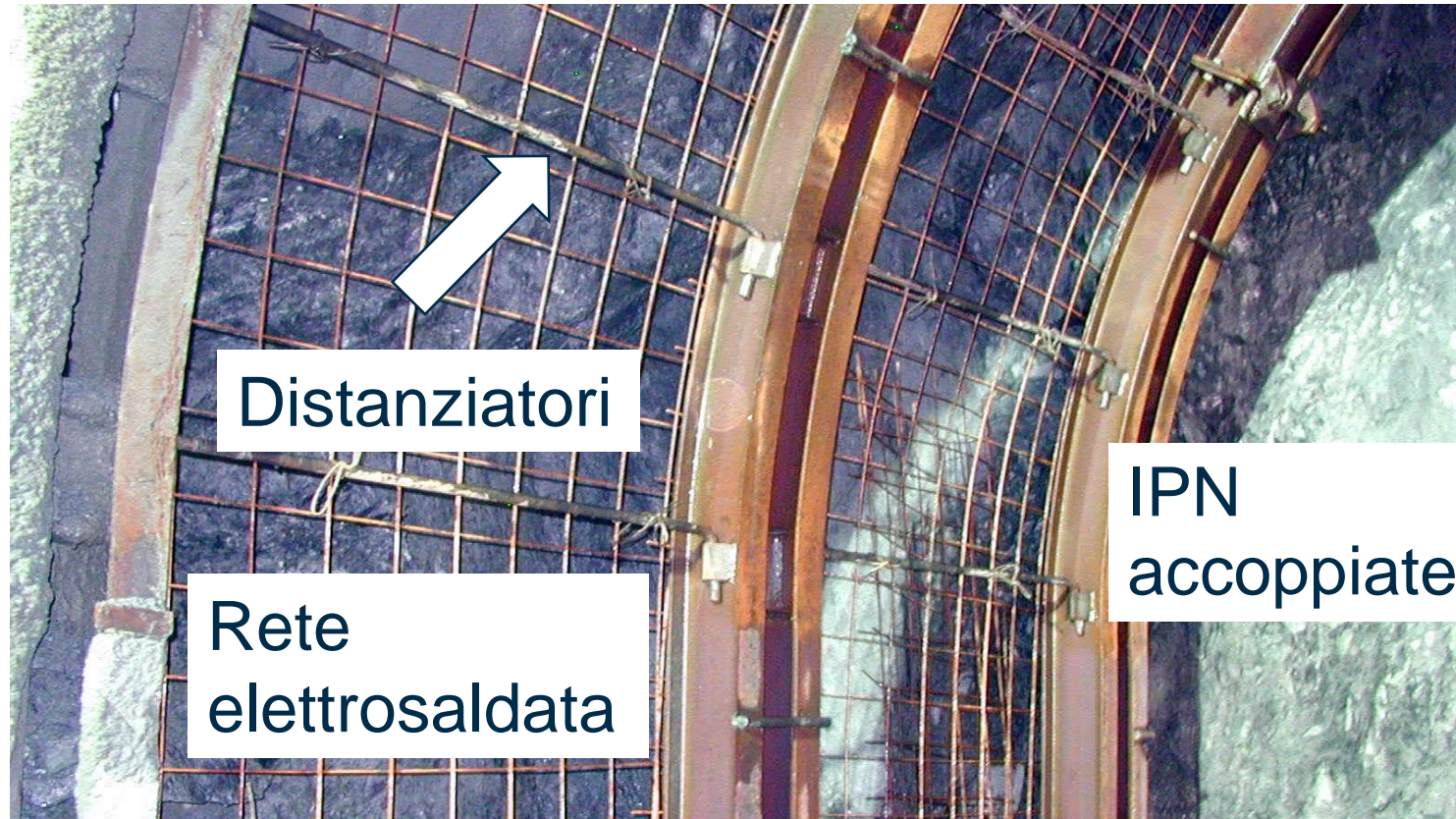


Nel passato : centine in legname

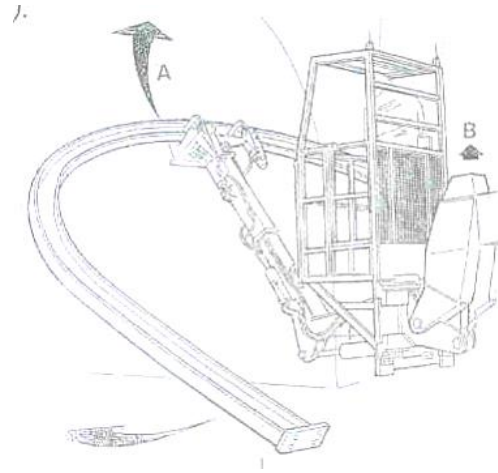


A sketch of the Italian method of excavating and supporting a tunnel in difficult ground conditions applied in the Cristina tunnel





Centine – montaggio



Calcestruzzo proiettato



Calcestruzzo proiettato

Cemento (42.5)

Inerti (0-8)

Accelleranti

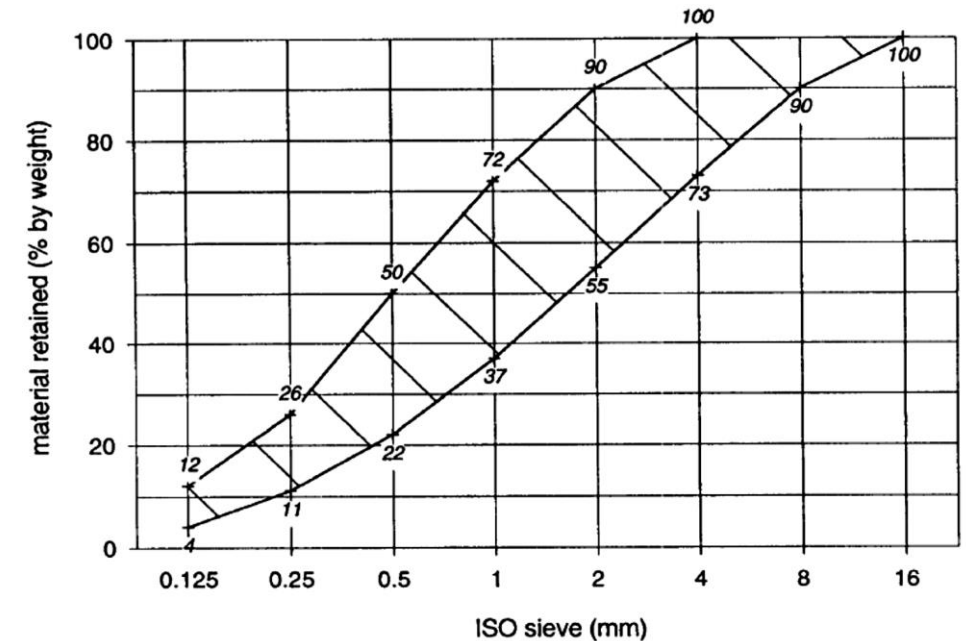
Rapporto acqua cemento

350 - 500 kg/m³

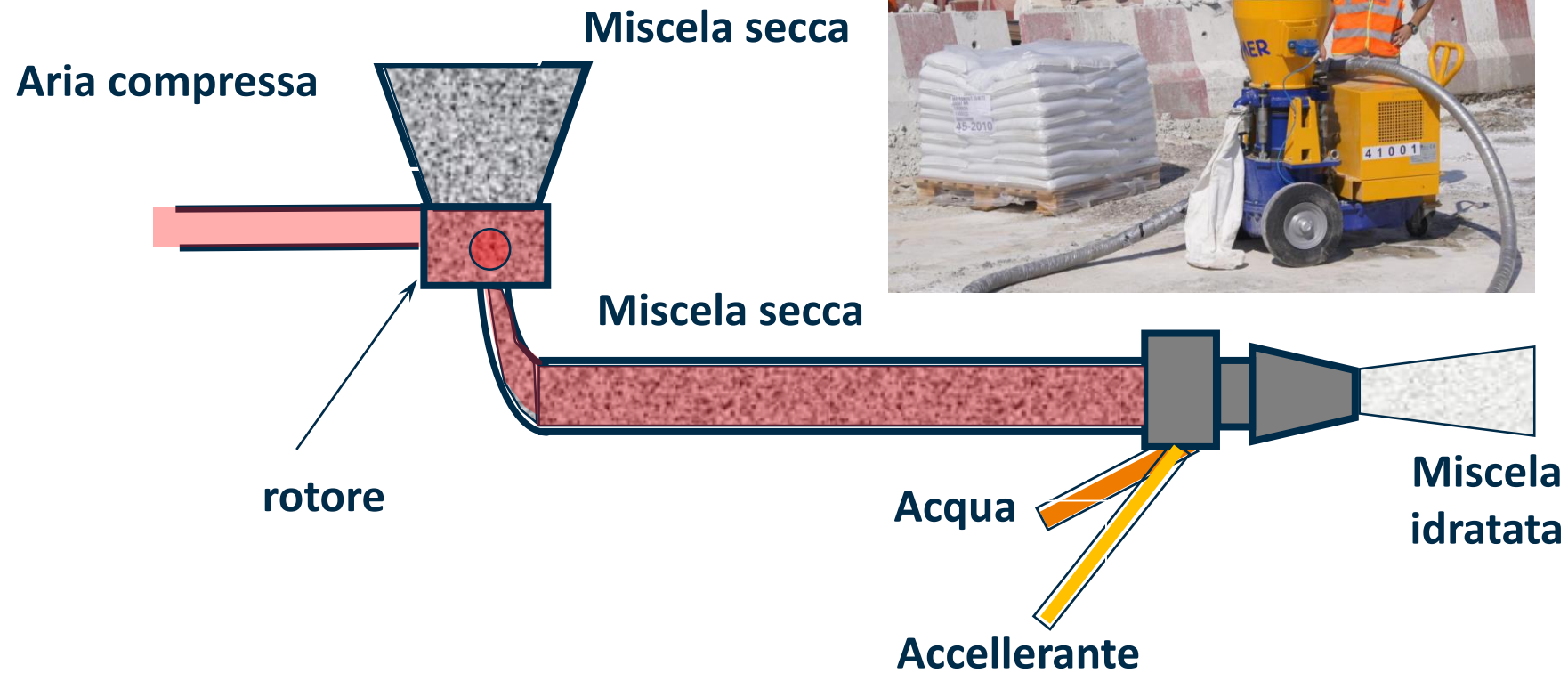
~ 1700 kg/m³

4 - 6 %

0.4 - 0.55



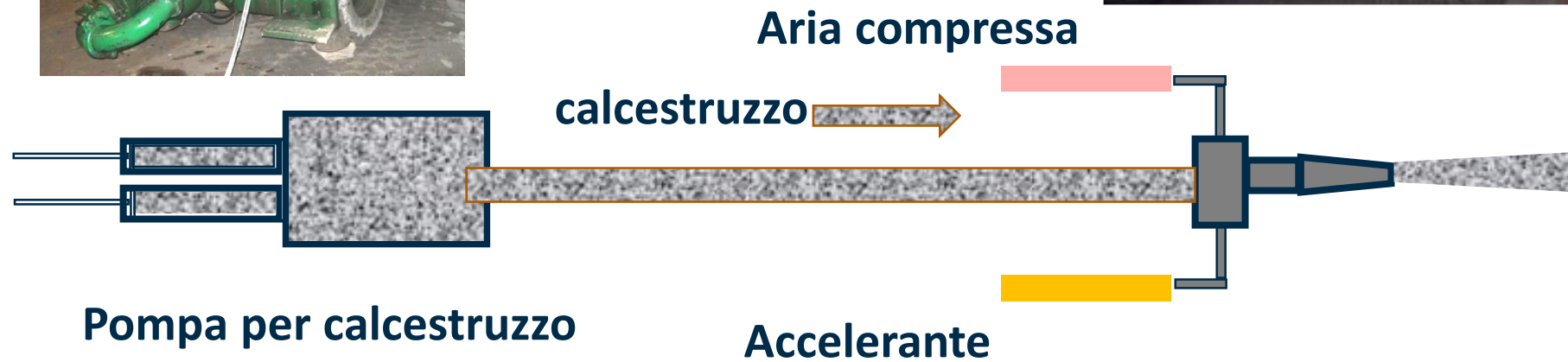
Calcestruzzo proiettato – proiezione a secco



Cortesia Dal Negro

Calcestruzzo proiettato – proiezione a umido

Calcestruzzo preparato
in un impianto di miscelazione



Cortesia Dal Negro

Calcestruzzo proiettato – fibre



Steel fibers



Steel fibers packed



PP structural fibers



Glass fibers



PP anti spalling fibers



Fibre metalliche (dosaggio usuale) $\geq 30 \text{ kg/m}^3$

Calcestruzzo gettato in opera

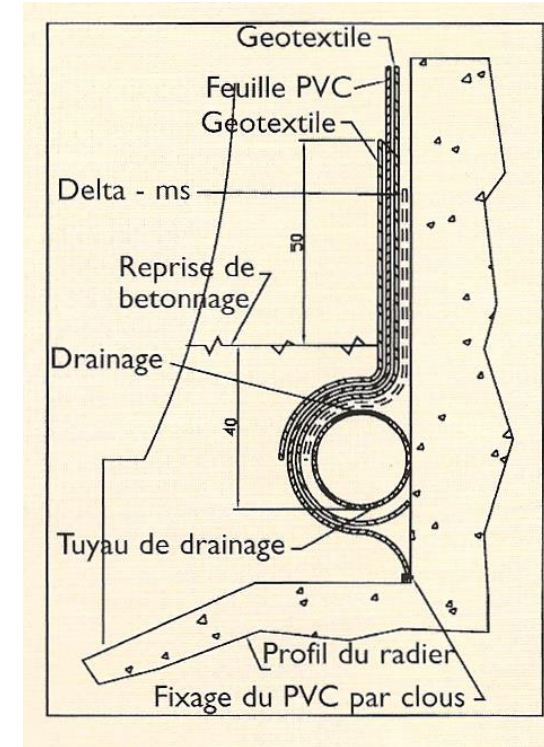
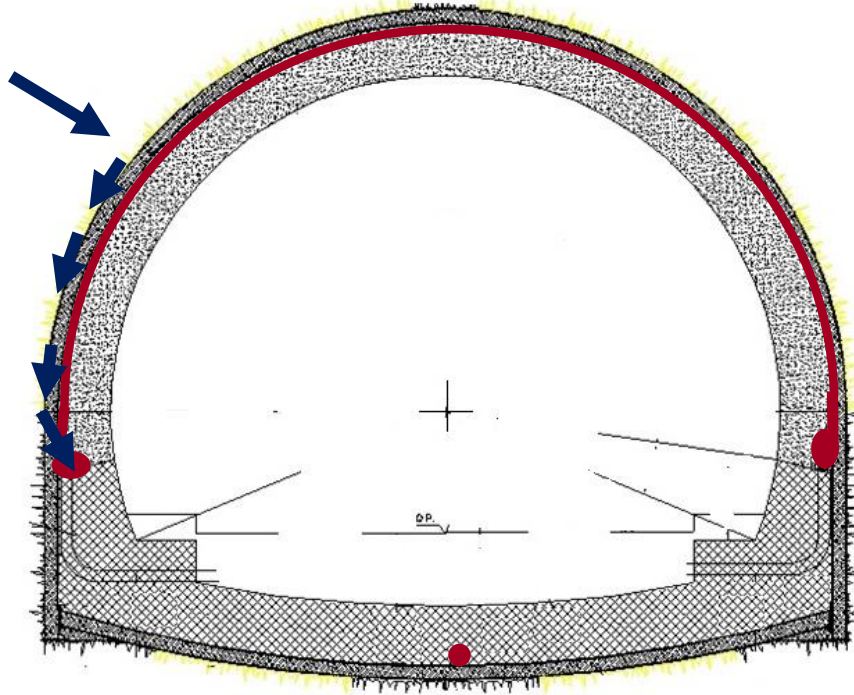


Esempio di cassero

Calcestruzzo gettato in opera



Impermeabilizzazione



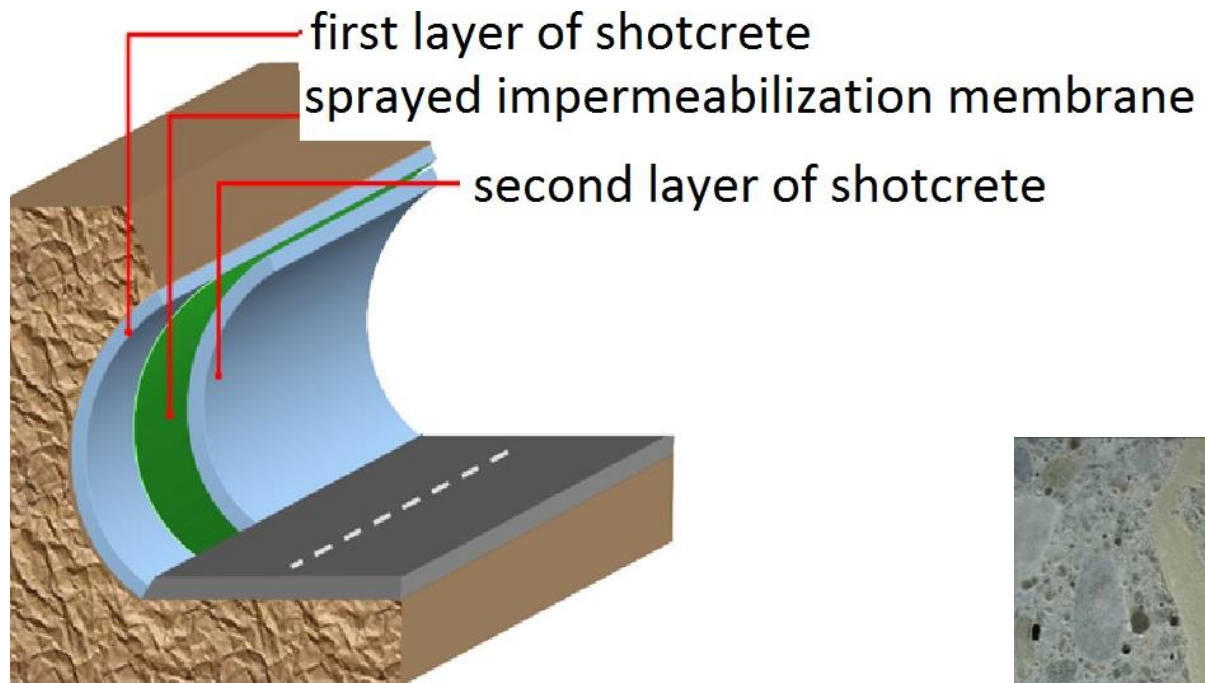
Impermeabilizzazione



Impermeabilizzazione



Impermeabilizzazione – membrane a spruzzo





**Politecnico
di Torino**