NATIONAL TECHNICAL UNIVERSITY OF ATHENS

School of Civil Engineering – Geotechnical Department

Computational Methods in the Analysis of Underground Structures

Spring Term 2023 – 24

Lecture Series in Postgraduate Programs:

1. Analysis and Design of Structures (DSAK)
2. Design and Construction of Underground Structures (SKYE)

Instructor: Michael Kavvadas, Emer. Professor NTUA

LECTURE 4: Conventional tunnelling methods - NATM

31.07.2023

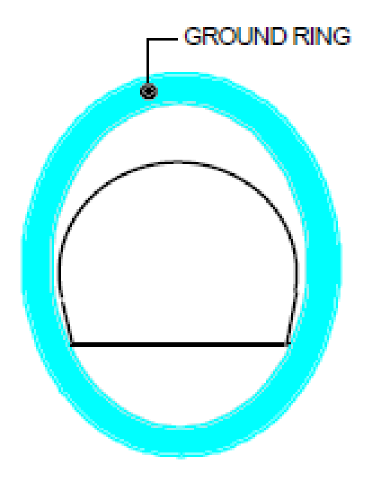
Conventional tunnelling methods - NATM

NATM = New Austrian Tunnelling Method

Beginning with late 1950's, the use of **rockbolts** and **shotcrete** for support, revolutionized tunnelling in difficult ground.

This technique, first gained attention in Austria, in the work of Rabcewicz, Müller and Pacher in 1957 (who named it "Shotcrete Method"). In 1964, Rabcewicz called it "New Austrian Tunnelling Method" (NATM).

Definition of NATM, according to the ITA (Int. Tunnelling Association), in 1980:
NATM is a tunnelling method based on a concept whereby the ground (rock or soil) surrounding a tunnel becomes a load bearing structural component, through activation of a ring-like body of supporting ground around the tunnel.

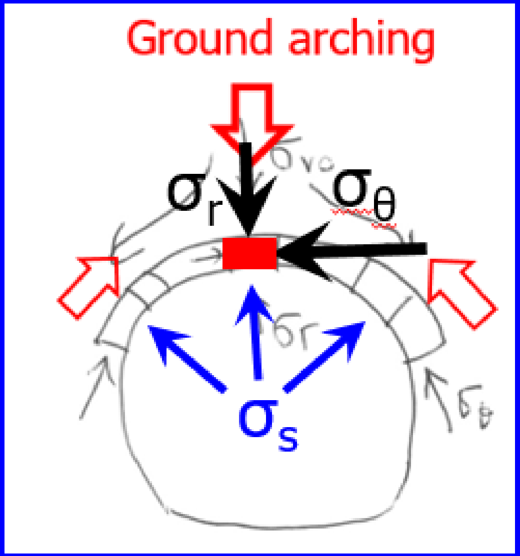


The above definition gives the impression that, instead of the ground exerting a load on the tunnel (as in traditional methods, like the Terzaghi loads), NATM makes the ground a "*load bearing structural component*" and thus there are savings in the required support, because NATM "creates" the ring-like body which supports the tunnel (reducing the need of actual support).

Conventional tunnelling methods - NATM

The definition of NATM is misleading, because it claims a beneficial factor (the arching effect of the ground ring to support the tunnel) as specific to NATM, while the arching effect is present in all types of tunnelling (regardless of using NATM).

NATM does not save in the required support by mobilising the ground strength, since all tunnelling methods do the same: the Terzaghi loads are the reduced ground loads on the tunnel support, after subtracting the ground loads undertaken by arching – arching develops by allowing the tunnel wall to converge inwards.



NATM simply interprets the support loads as the loads required to act on the ground ring to ensure that it can undertake the full ground loads.

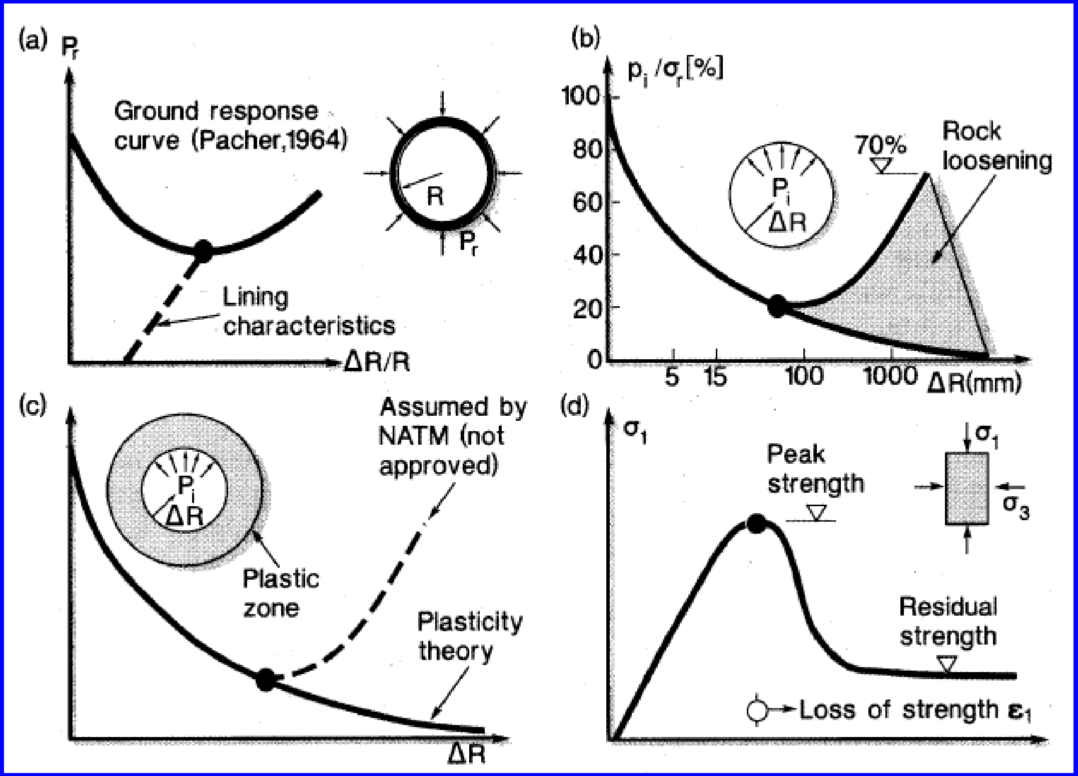
- Older tunnelling methods: (Geostatic loads) – (Ground arch loads) = (Support loads)
- NATM: (Geostatic loads) = (Ground arch loads), including arch strength increase due to the support) → NATM claims (misleadingly): the ground arch supports the ground

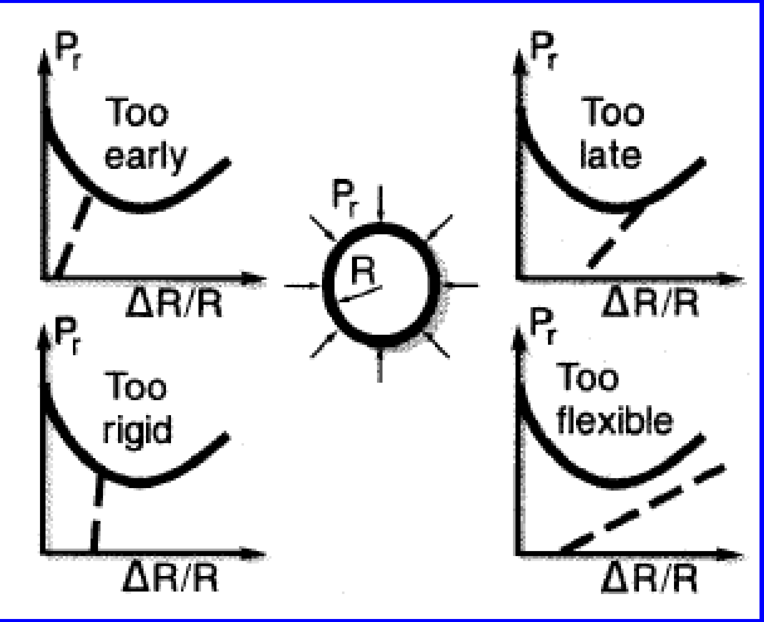
An analogy:

We propose a New Swimming Method (NSM) based on a concept that the swimmer stays afloat by activation of water uplift, and thus water becomes a supporting medium rather than a medium offering resistance to swimming.

Conventional tunnelling methods - NATM

Another misleading claim of NATM is that the amount of support can be optimized using wall convergence measurement:





Time of support installation and stiffness of support

The ground reaction curve does not turn upwards and when it does (if rock blocks lose contact), we cannot predict when it happens. So, when the minimum point of the ground reaction curve does not exist or cannot be predicted, the method cannot be used in optimising support.

So, the amount and the time of support installation remains a challenging problem, and NATM does not help in solving it (other than the well known principle: not too little, not late and not too stiff).

Conventional tunnelling methods - NATM

NATM principles are usually meaningless and trivial, e.g.:

- “Stabilize the rock with anchors, except for the case the rock stabilizes by itself”
- “Construct the lining not too early or too late, and not too rigid or too flexible”,
- “Perform full-face excavation since multi-phase tunnelling damages the ground, whenever possible” (usually NATM exploits multi-phase excavation)

Conclusion:

NATM is not a “method” because it does not the characteristics of a method:

- Specific differences from other methods
- Specified and measurable way of application

NATM is just a collection of <u>support technology</u> (use of shotcrete and rockbolts) and <u>empirical skills</u> in selecting the quantity of support based on experience and measurements (although there are no specific guidelines on the use of measurements in optimizing support requirements).

Since everybody uses these techniques today, …. everybody uses NATM

So, the common terminology is to (erroneously) call NATM any tunnelling method that does not use a Tunnel Boring Machine (TBM), i.e., tunnelling with:

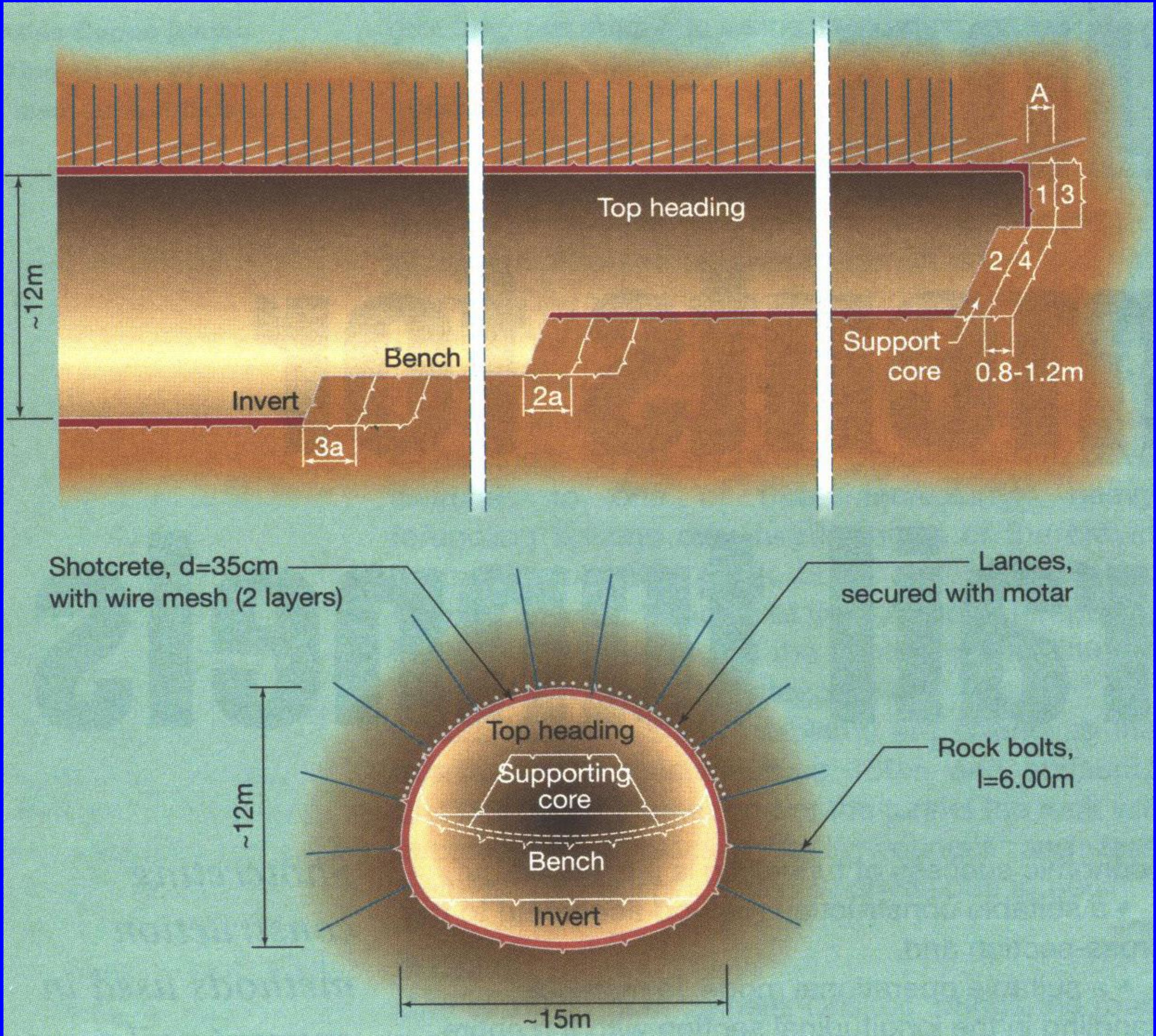
- Conventional excavation (not TBM), possibly with multiple excavation stages
- Immediate support with shotcrete and rockbolts (plus steel sets, FG nails, etc). The required support is usually designed with finite element analyses
- Final lining constructed at a later stage (separate design)

Conventional tunnelling methods - NATM

Comparison of NATM and TBM tunnelling:

- NATM is more adaptable in variable ground conditions, while TBM machines operate effectively in a specific type of ground (there are TBM machines for various ground conditions, but each machine has a limited range for optimal operation)
- TBM tunnelling has significantly faster advance rates in ground conditions suitable for the specific TBM, but can have long down times under adverse ground conditions. NATM is usually slower, but down times are usually shorter than in TBM tunnelling.
- NATM is more favourable in short tunnels (shorter than about 2000m), since TBM requires high initial investment
- TBM can better control issues of face instability (e.g. in very weak ground, cohesionless soils, presence of groundwater seepage, etc).
- NATM is more favourable than TBM in squeezing conditions and swelling ground, because TBM has the risk of getting stuck if its advance rate reduces or stops (e.g. due to maintenance or break down)
- NATM is more favourable than TBM in very large tunnel sections (>12m), since the cost of TBMs (per unit length of tunnel) increases much faster with the diameter
- NATM is more adaptable in variable tunnel sections (TBM can excavate a circular section with constant diameter) and strongly non-circular sections
- NATM permits sealing of the tunnel with synthetic membrane. TBM tunnelling with precast segmental lining has to rely on gasket sealing between segments

Conventional tunnelling methods - NATM



Conventional tunnelling methods - NATM

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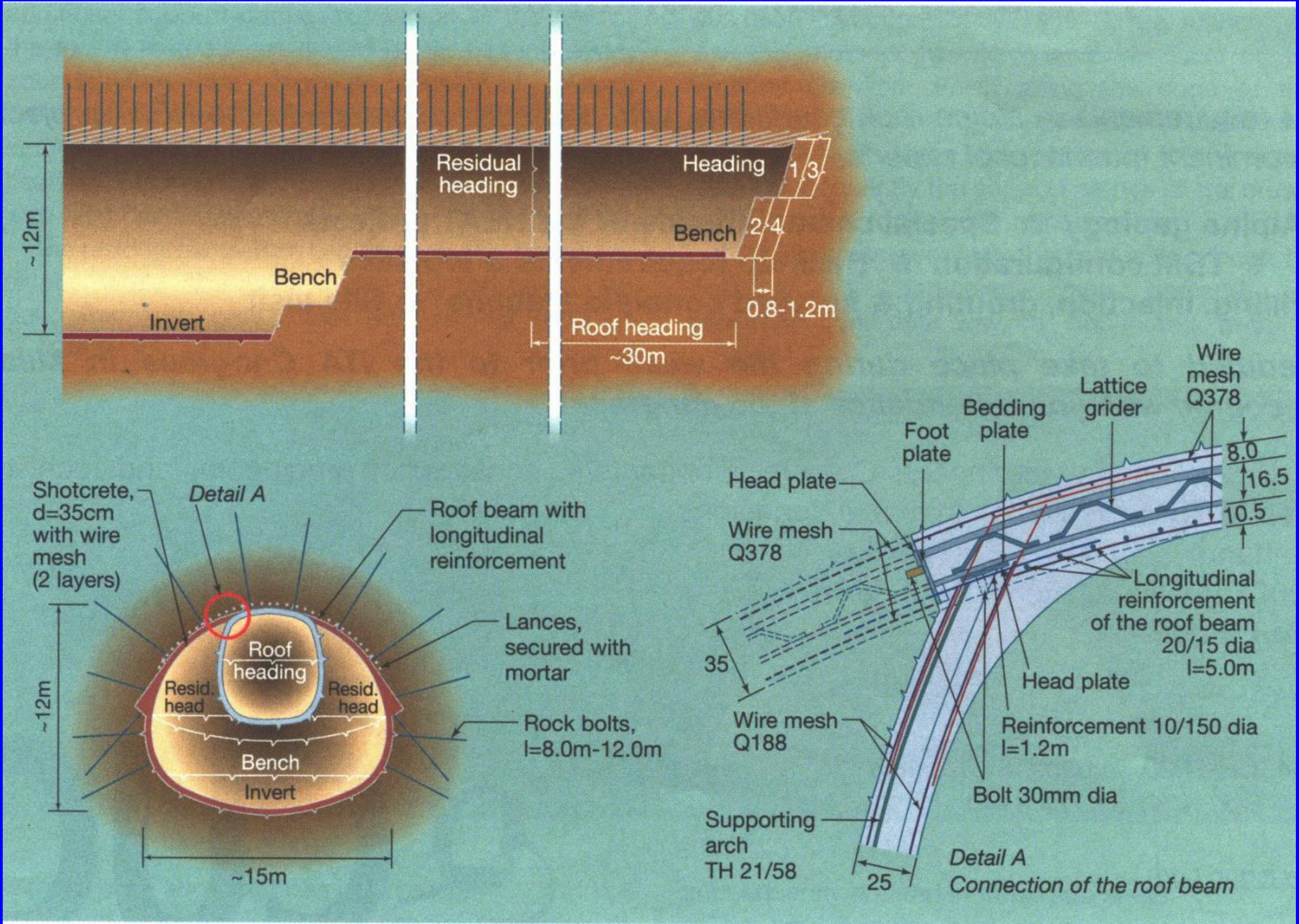
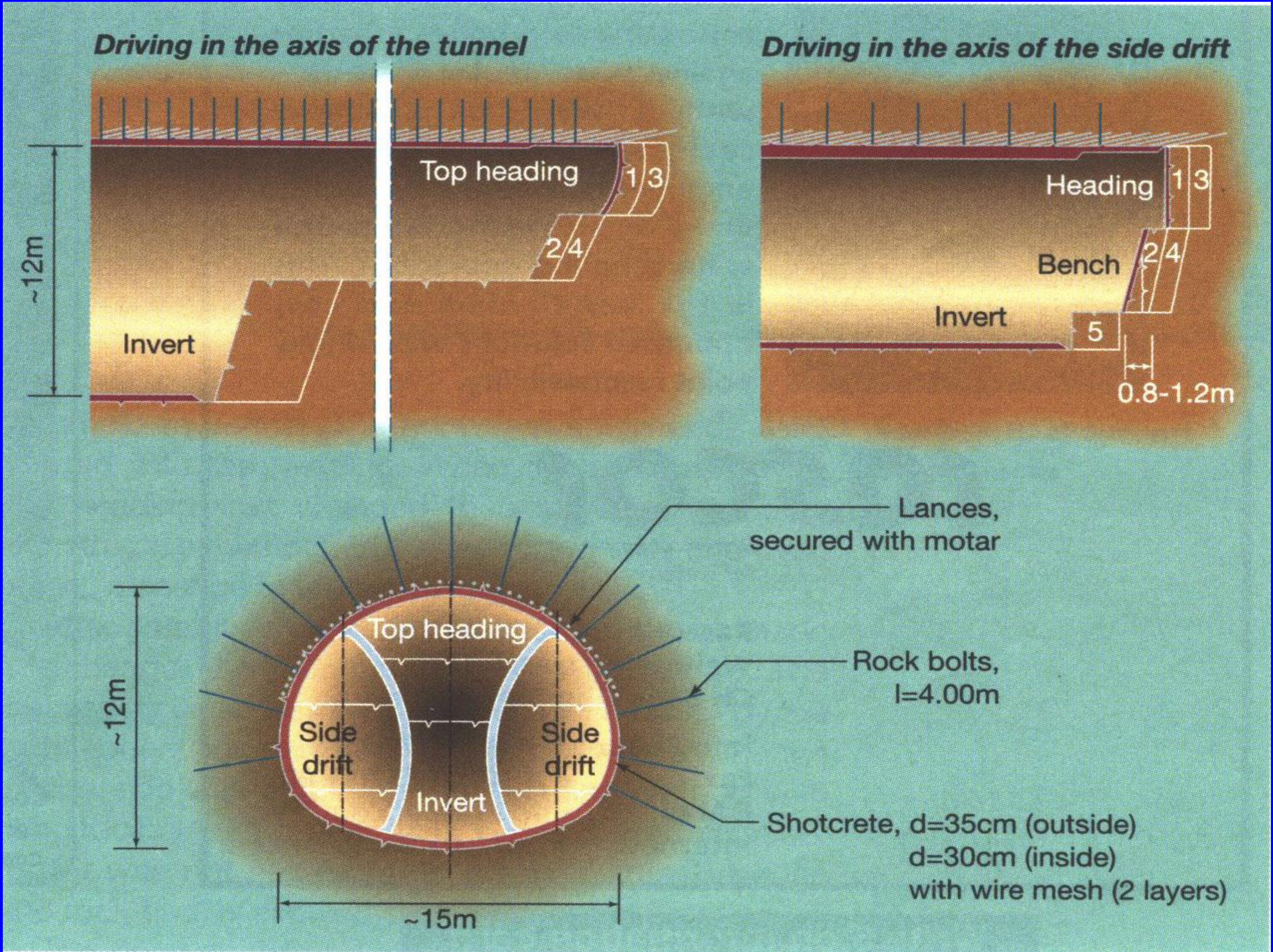
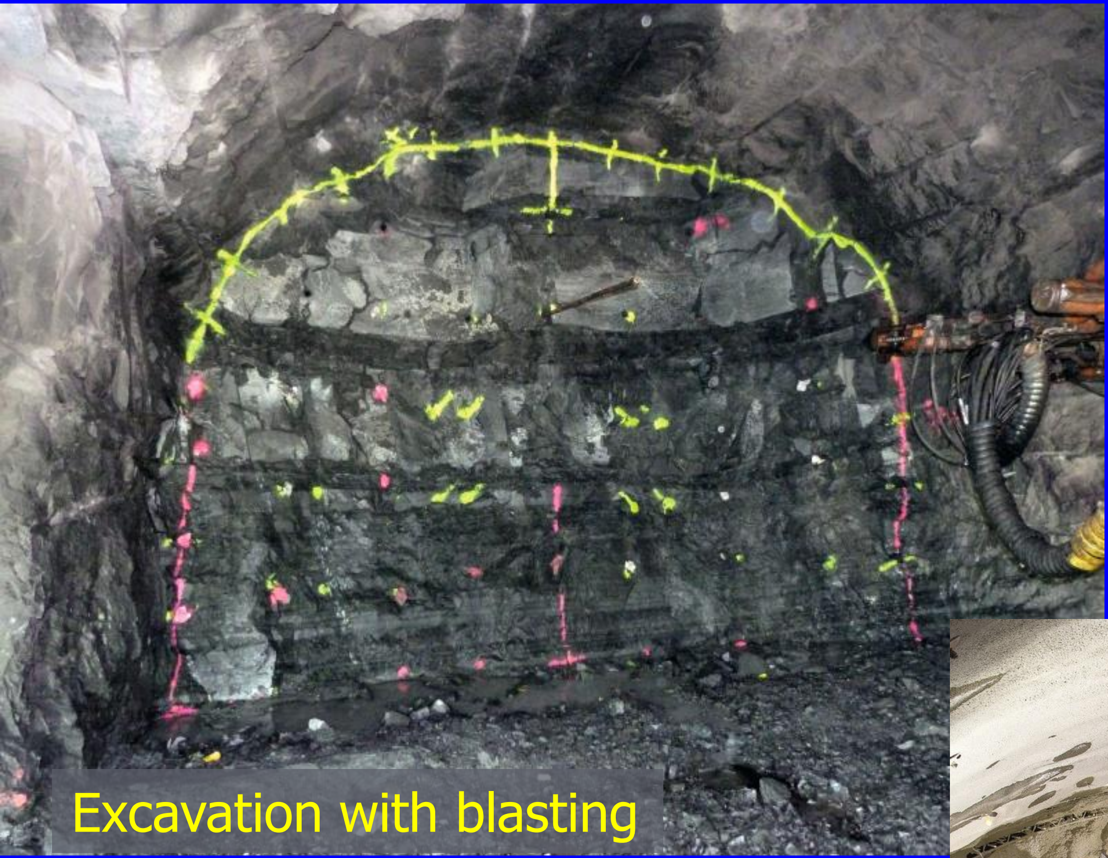


Conventional tunnelling methods - NATM

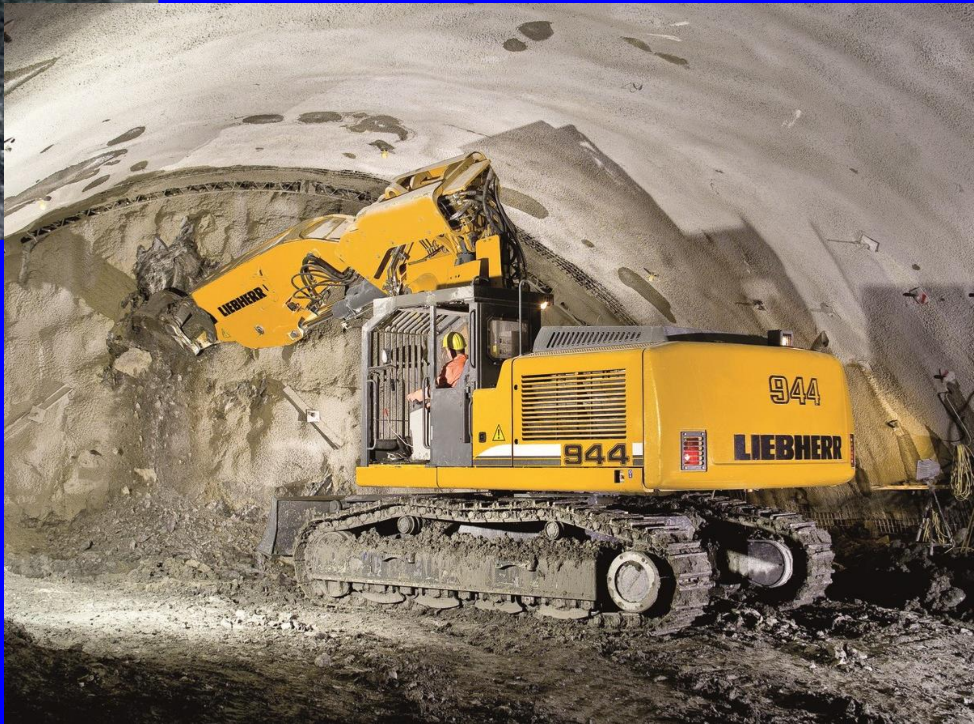


Conventional tunnelling methods - NATM



Excavation with blasting

Excavation with blasting



Mechanical excavation

Conventional tunnelling methods - NATM

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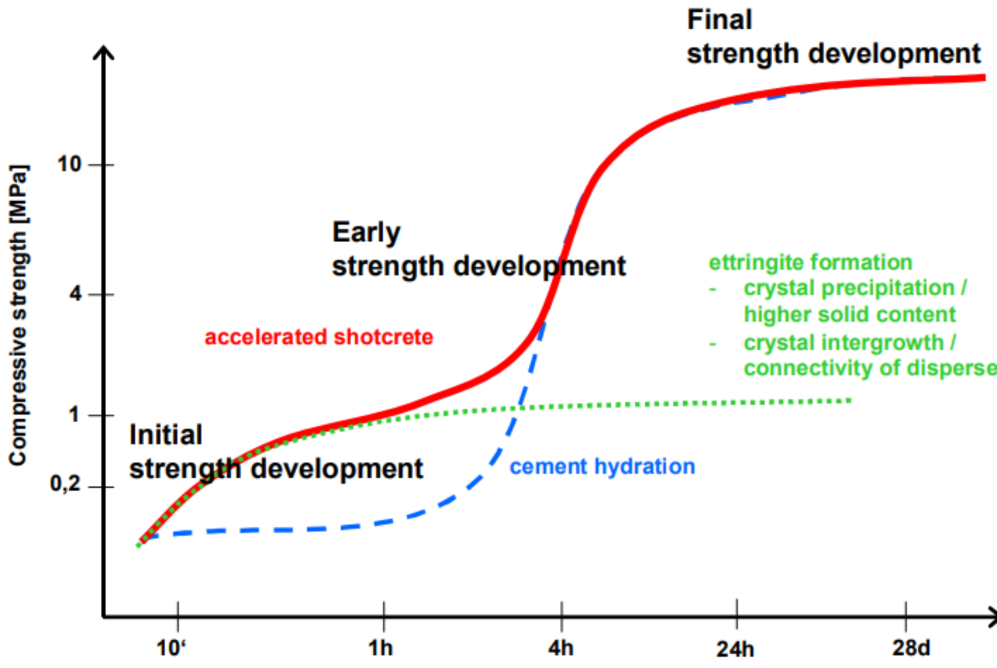
Conventional tunnelling methods - NATM

Shotcrete (sprayed concrete)

- Consists of cement, water and aggregates (up to 10mm). The mix is sprayed with a nozzle under high air pressure
- Cement and aggregates are either mixed dry (dry mix) with water added at the nozzle during spraying, or as wet mix of all ingredients (water is added in the mixer)
- Wet mix is used in cases where large quantities of shotcrete are required
- Constituents for 1m^3 wet-mix shotcrete (2250-2350 kg) – 28 day strength = 48 MPa:
  - ∗ Cement: 400 kg
  - ∗ Fly ash (up to 30%, replaces cement)
  - ∗ Silica fume (10% of cement): 40 kg
  - ∗ Fine aggregate (up to 2mm): 1110 kg
  - ∗ Coarse aggregate (2-10mm): 460 kg
  - ∗ Water (W/C ratio = 0.45): 180 kg
  - ∗ Water reducing admixture: 1.5 litres
  - ∗ Superplasticizer: 5 litres
  - ∗ Air entraining admixture: 2.5 litres
  - ∗ Steel fibers (50 kg) may be added as reinforcement



Fly ash reduces rebound. Silica fume reacts with calcium hydroxide ($Ca(OH)_2$) produced when cement is hydrated causing increase of concrete strength and reduction of its permeability.

Conventional tunnelling methods - NATM
Shotcrete (sprayed concrete)

Figure 5.4.1: Recommended aggregate gradation zone

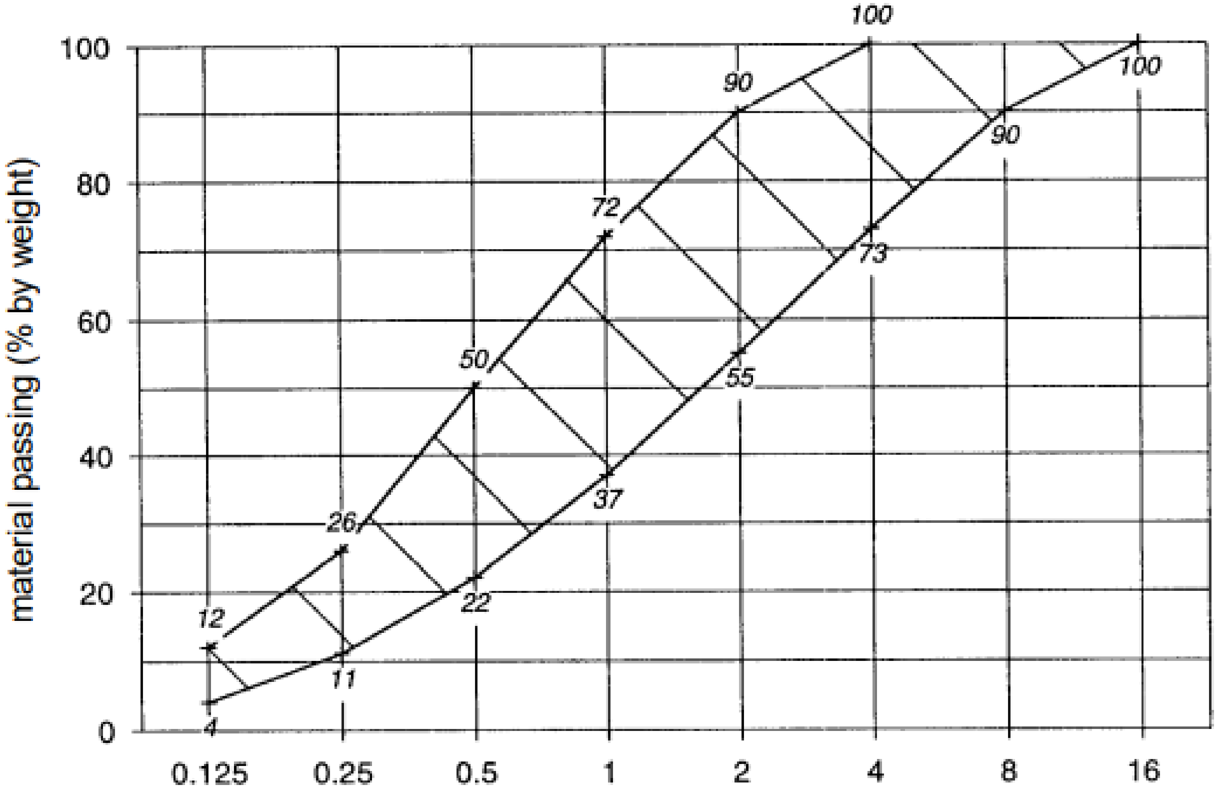
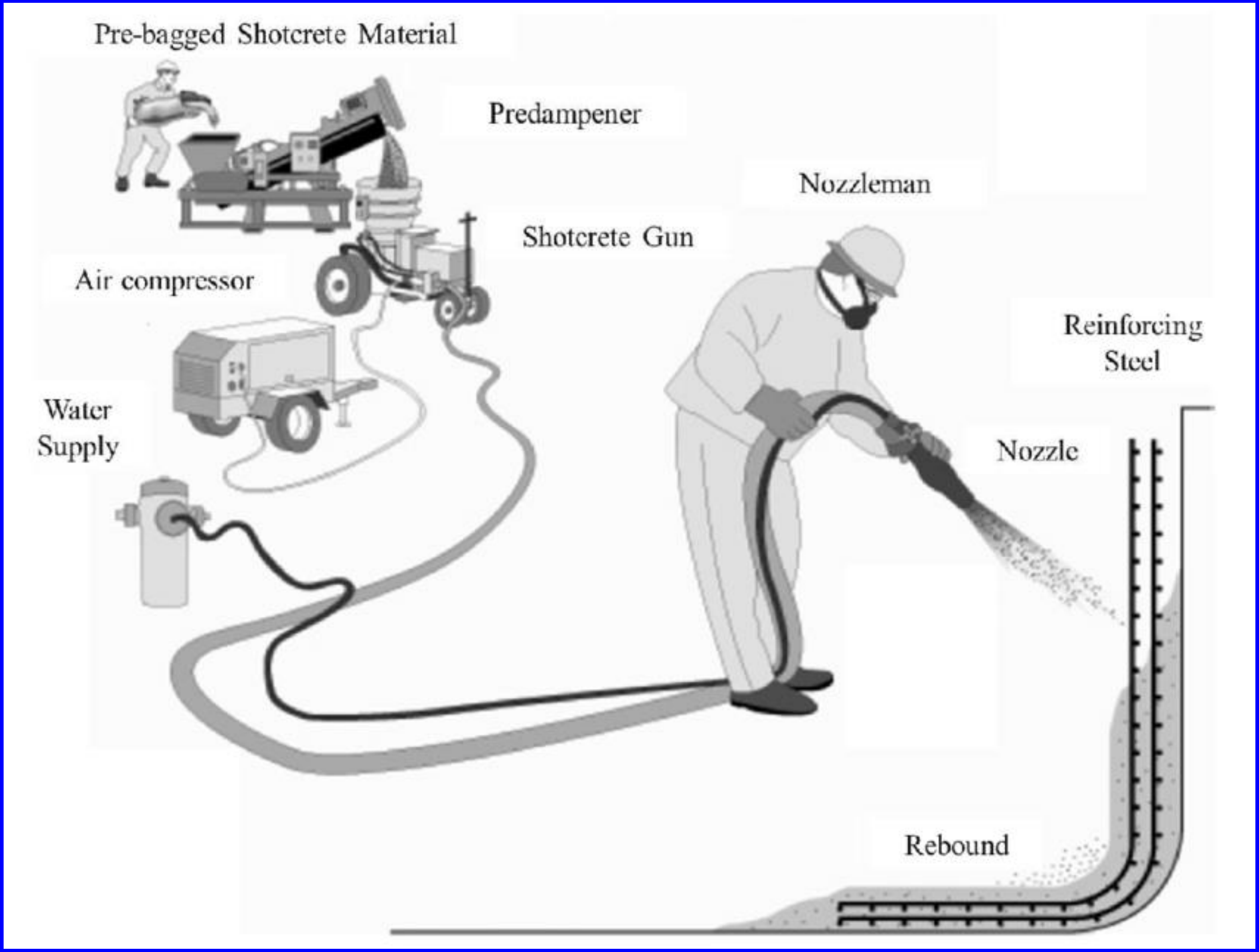


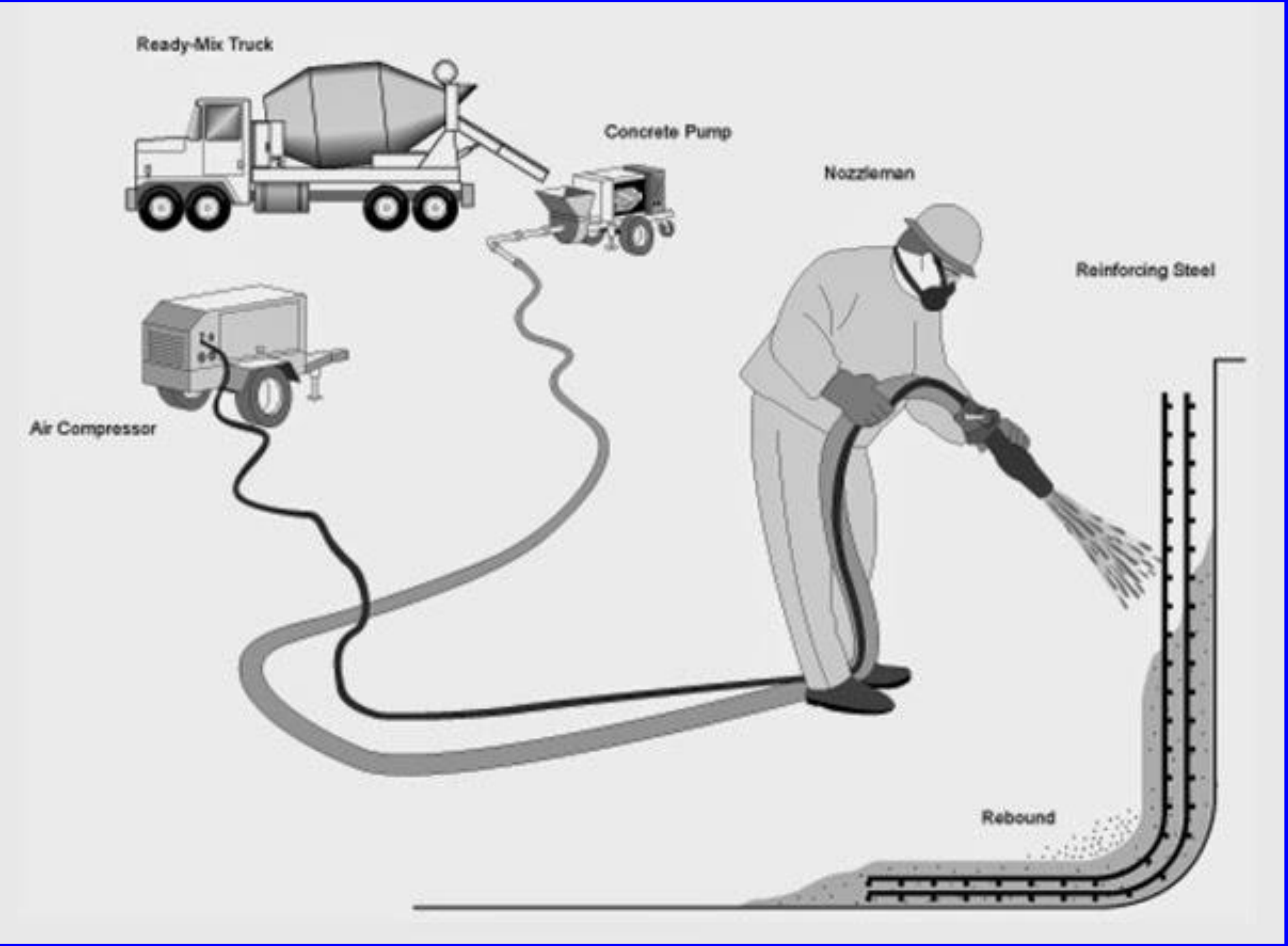
Table 9.1.1: Compressive strength classes for sprayed concrete (EN 206)

Characteristic strength (MPa)							
STRENGTH CLASS	C24/30	C28/35	C32/40	C36/45	C40/50	C44/55	C48/60
Cylinder	24	28	32	36	40	44	48
Cube	30	35	40	45	50	55	60

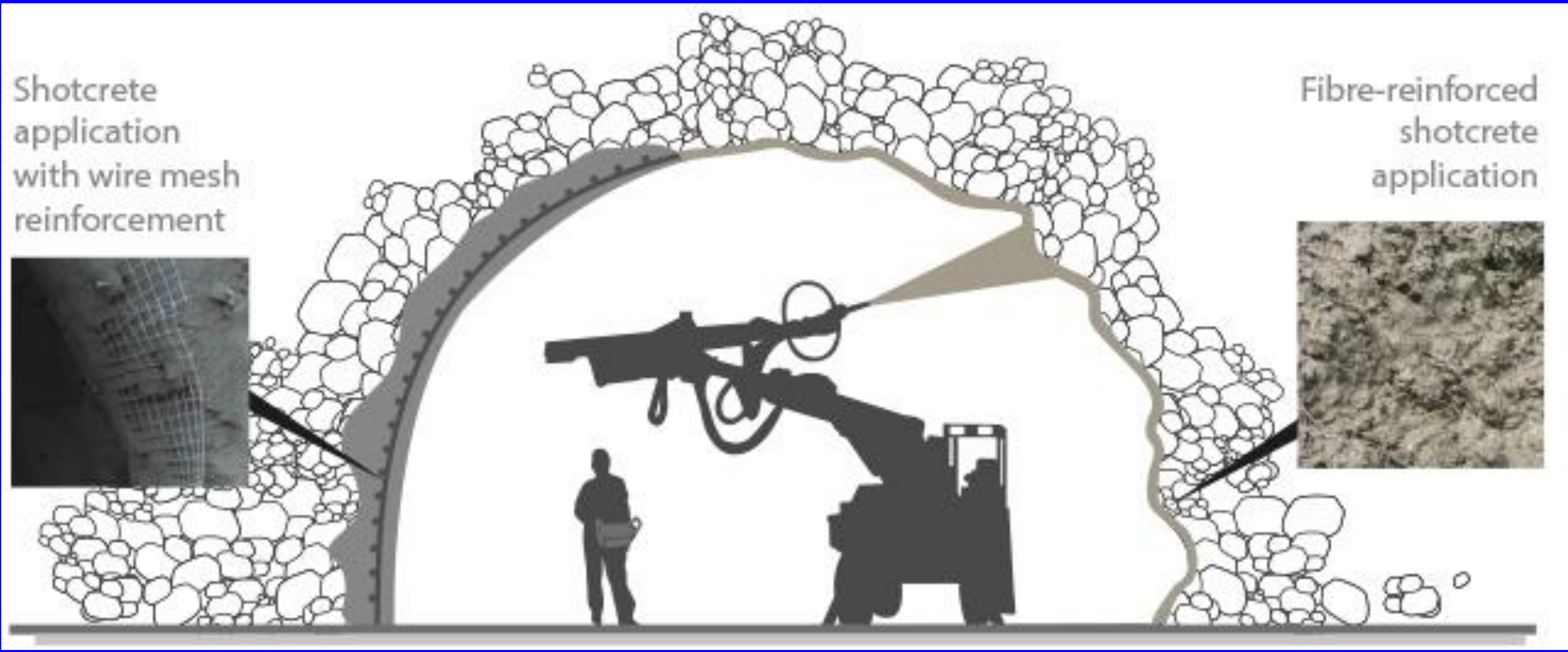
Shotcrete (sprayed concrete) – Dry mix

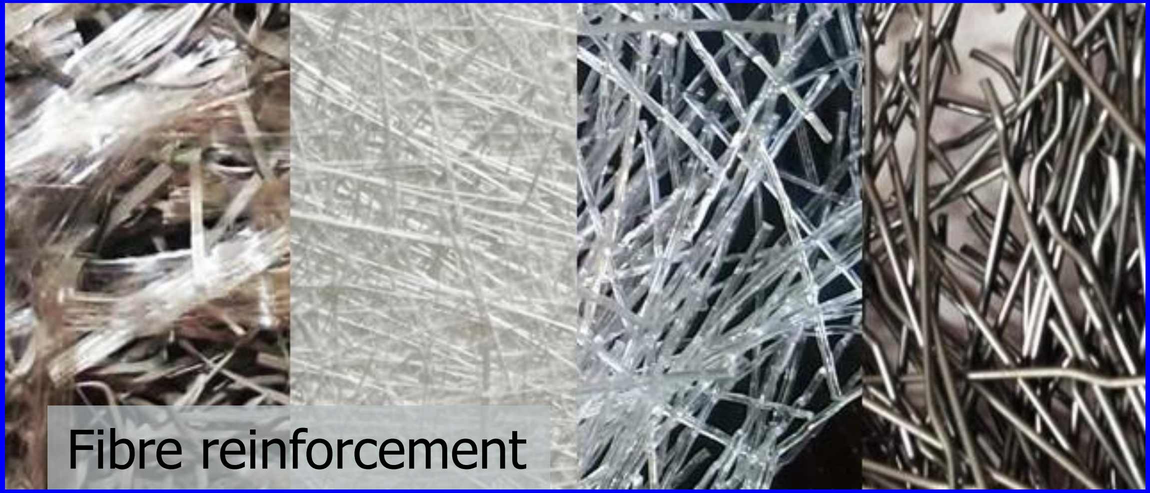


Shotcrete (sprayed concrete) – Wet mix

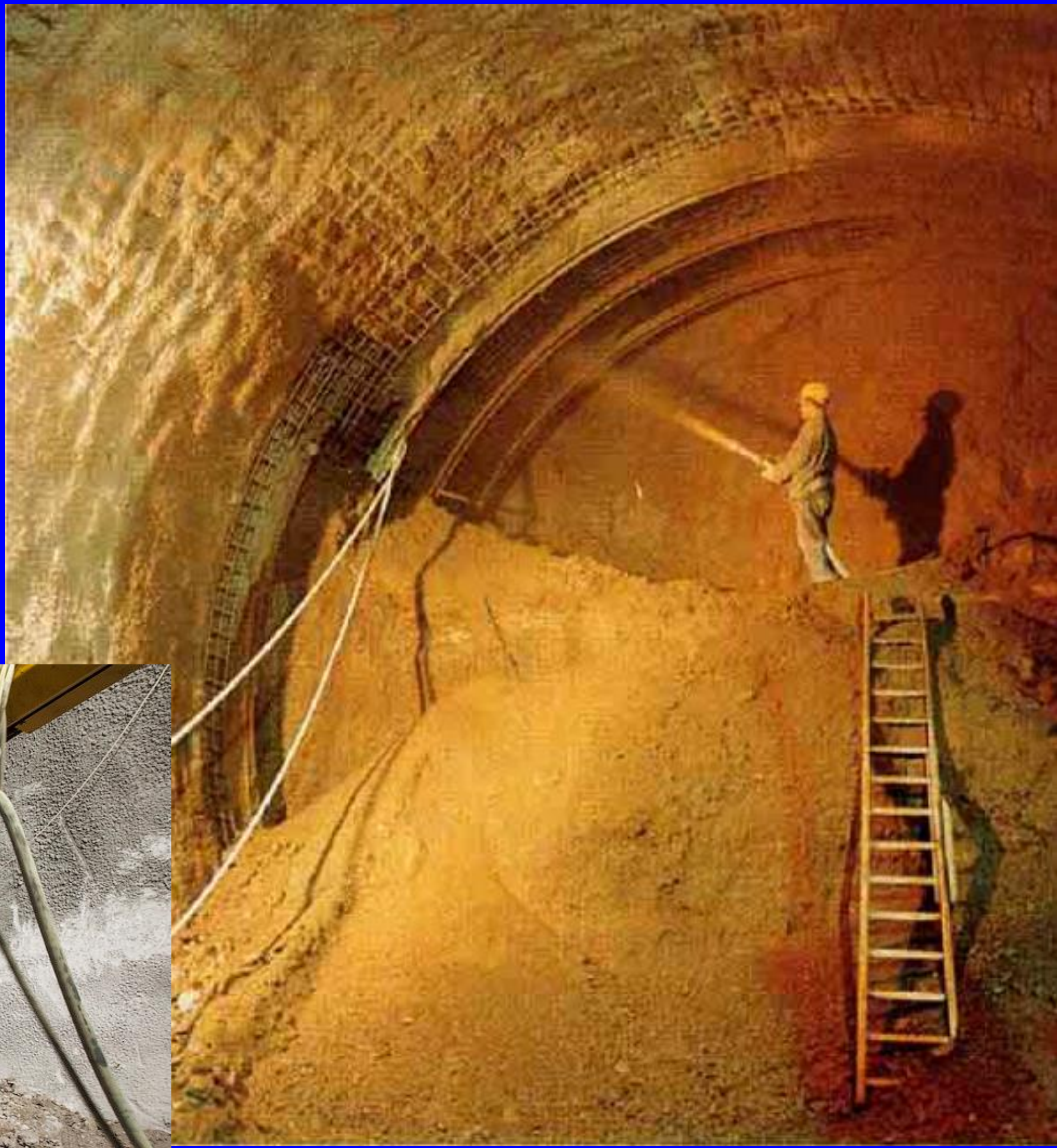


Shotcrete (sprayed concrete) – Steel reinforcement





Shotcrete (sprayed concrete)

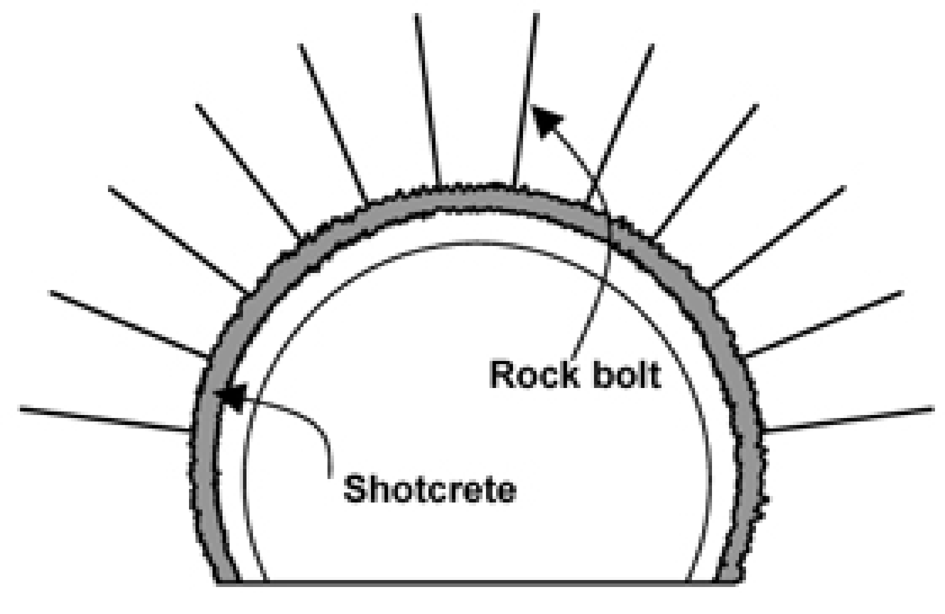


Shotcrete (sprayed concrete) – Wet mix

Rockbolts (passive anchors)

In combination with shotcrete, rockbolts increase the strength of the rockmass, by applying a compressive stress on the rockmass (corresponding to the tensile force of the bolts).

Rock bolts are also used to anchor rock blocks (and avoid rock falls) in rockmasses with widely spaced fissures.



Rockbolts (passive anchors)

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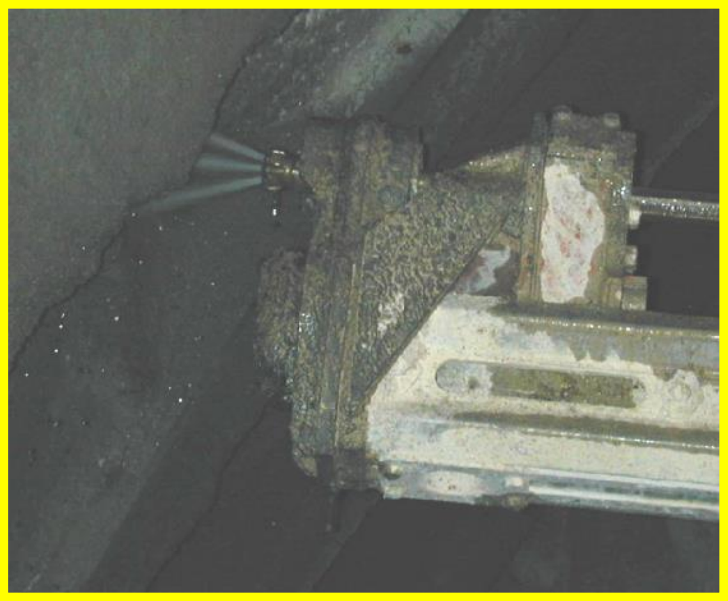

Rockbolts (passive anchors)

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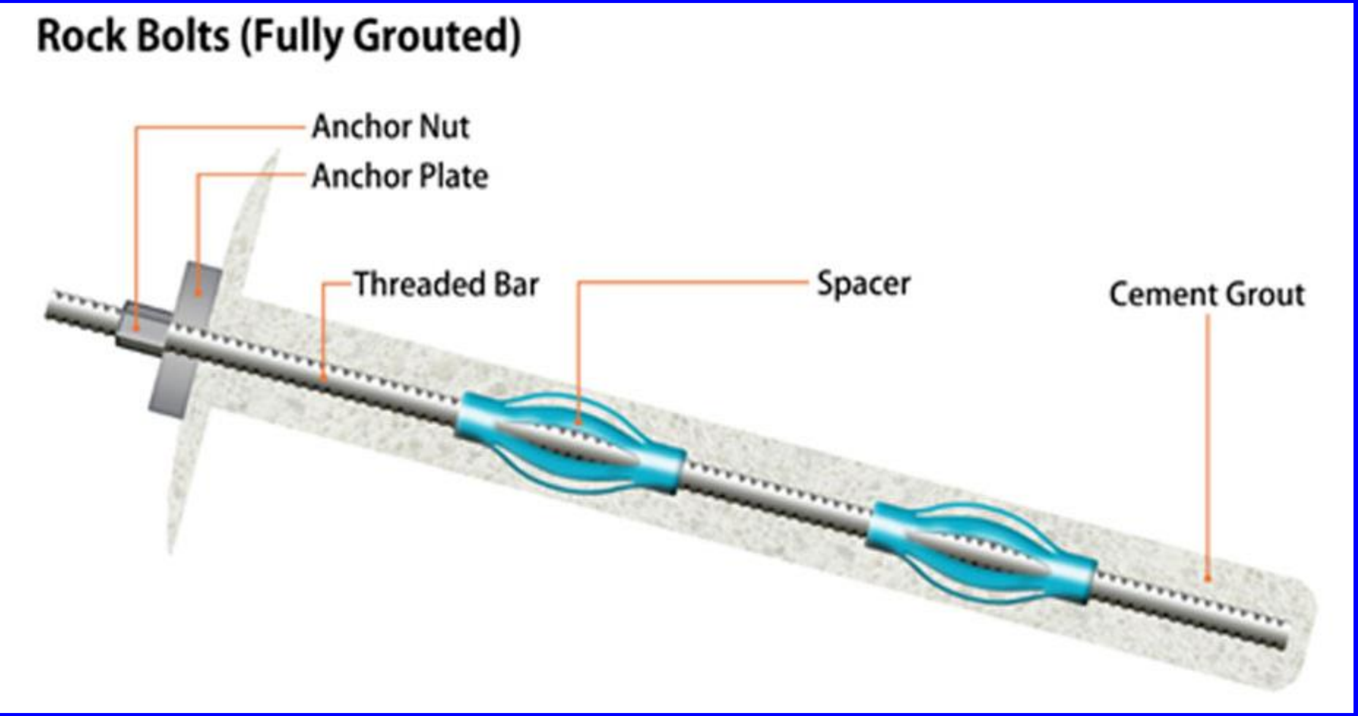
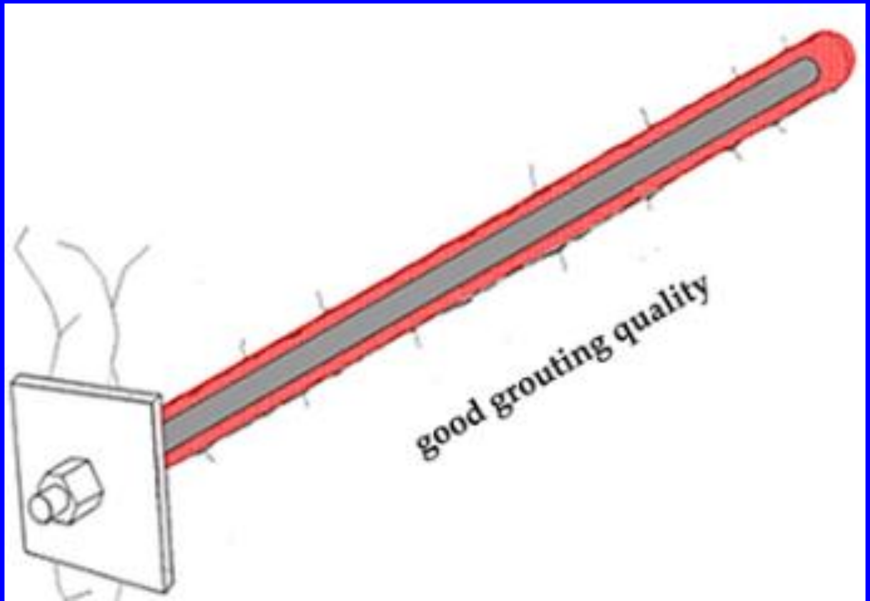
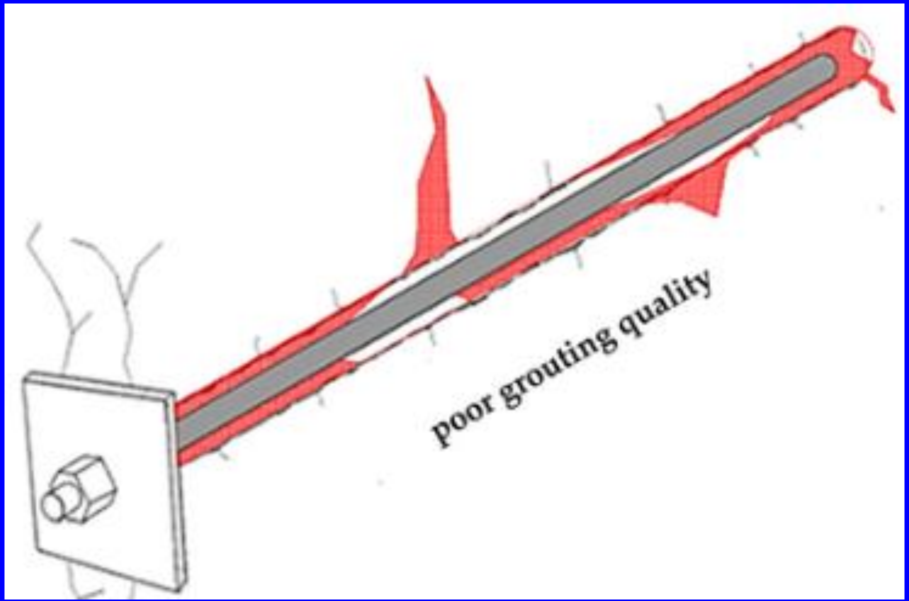
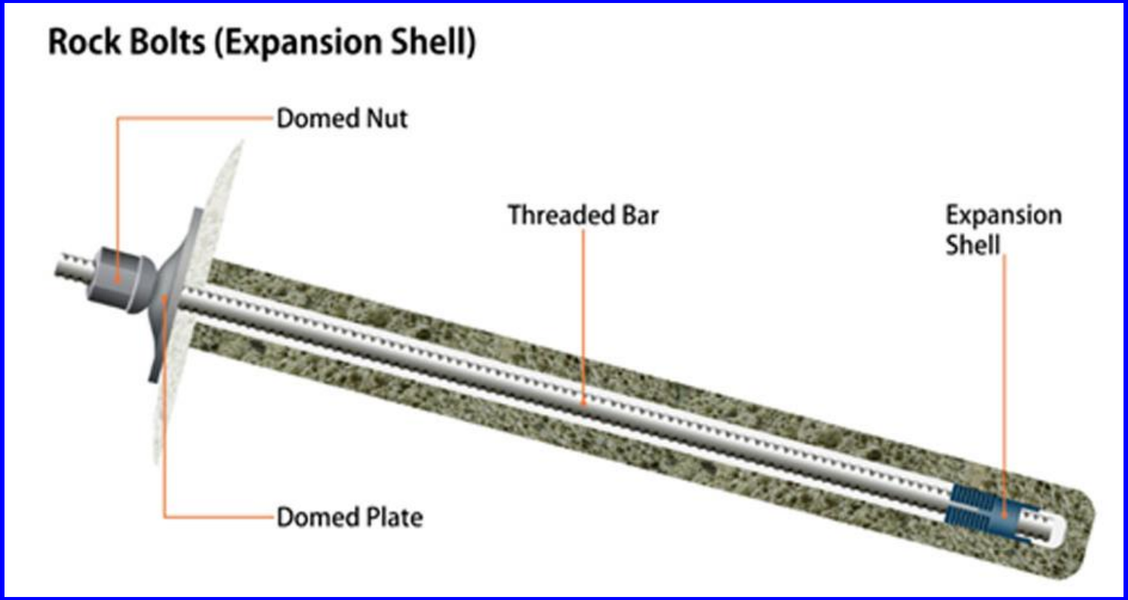


Standard, fully grouted rockbolts - Steel reinforcement bar (usually Φ25mm S500, ultimate capacity 220 kN)

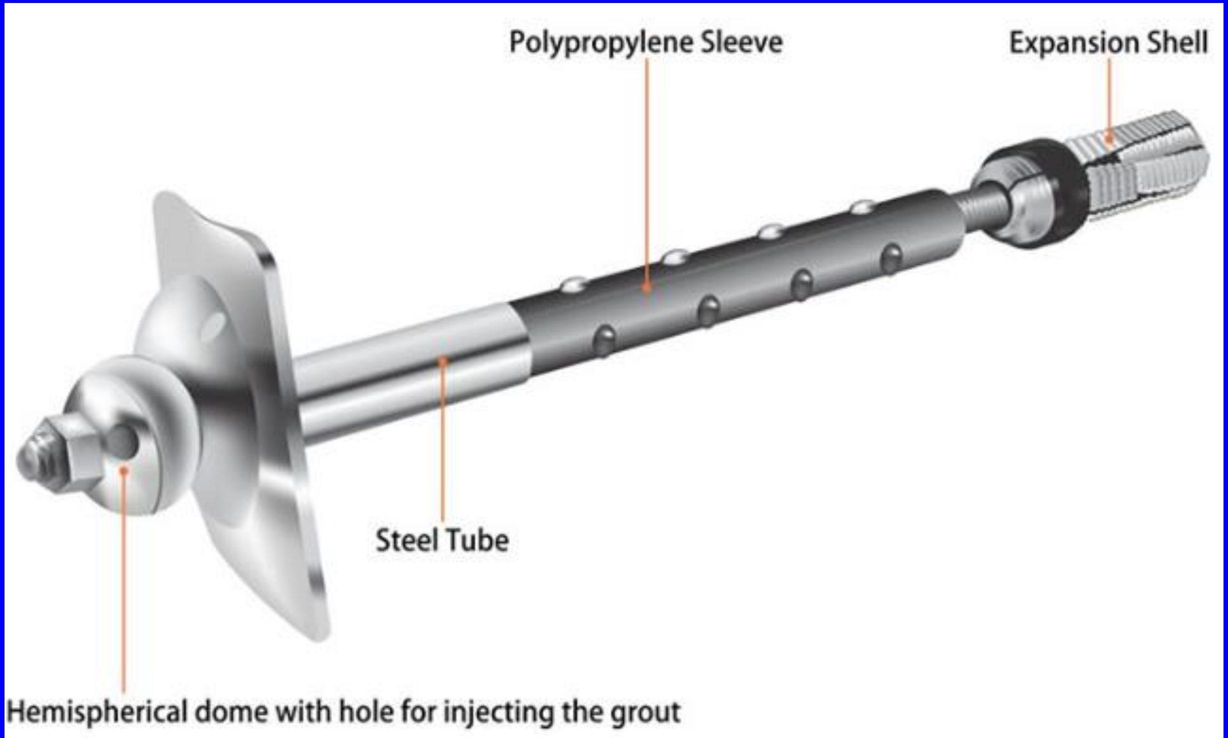


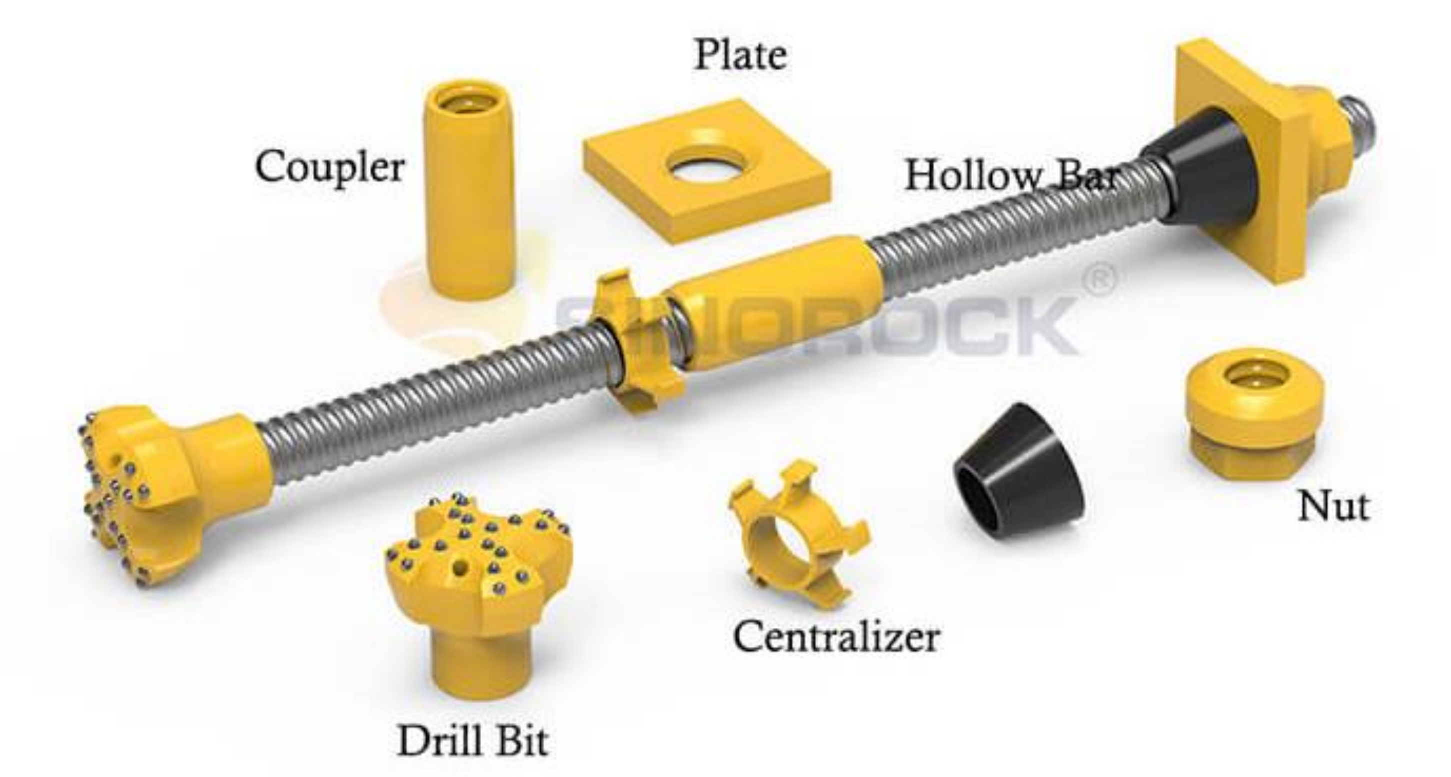


Rockbolts (passive anchors)



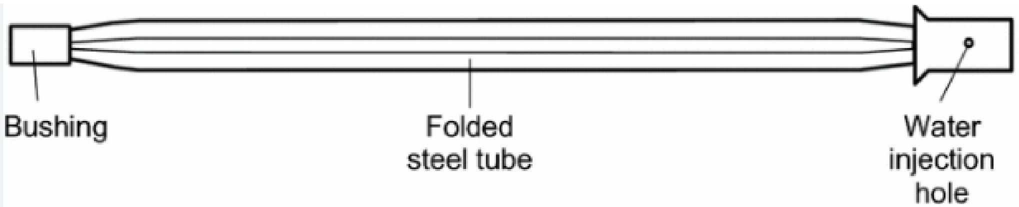
End-anchored rockbolts with expansive end (locks on good rock when nut is tightened

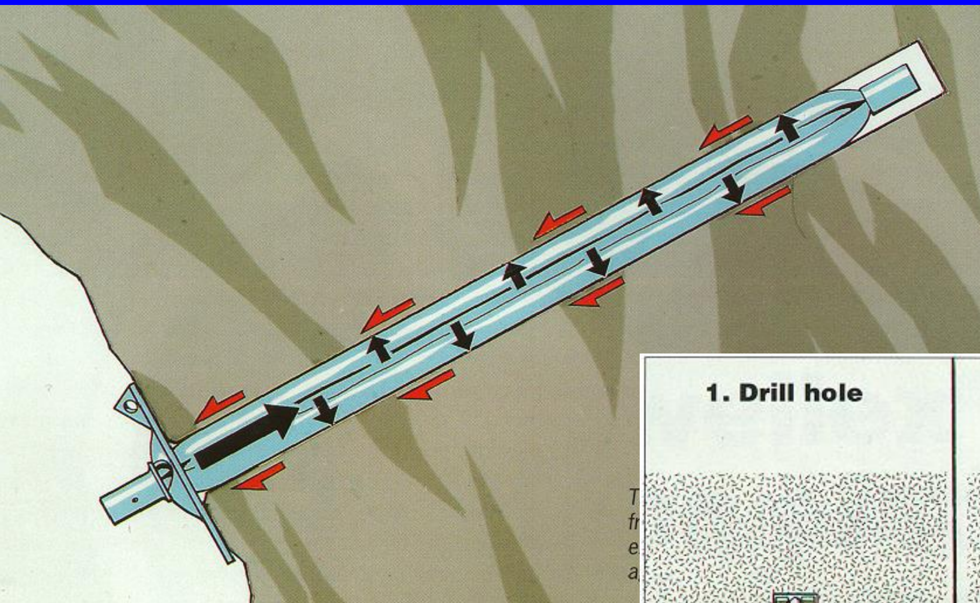


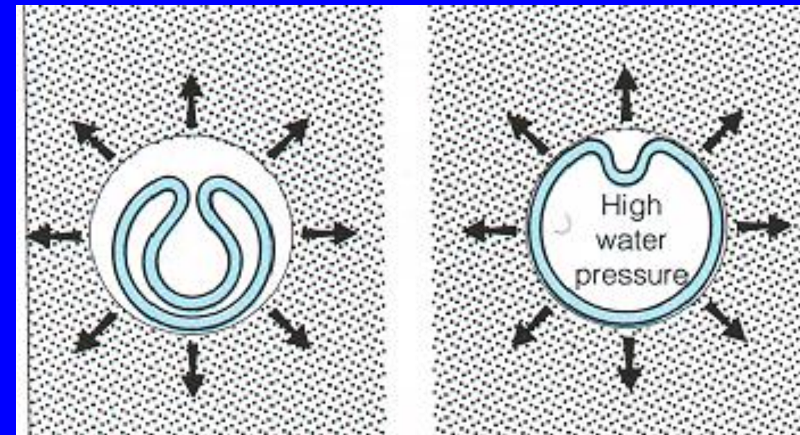


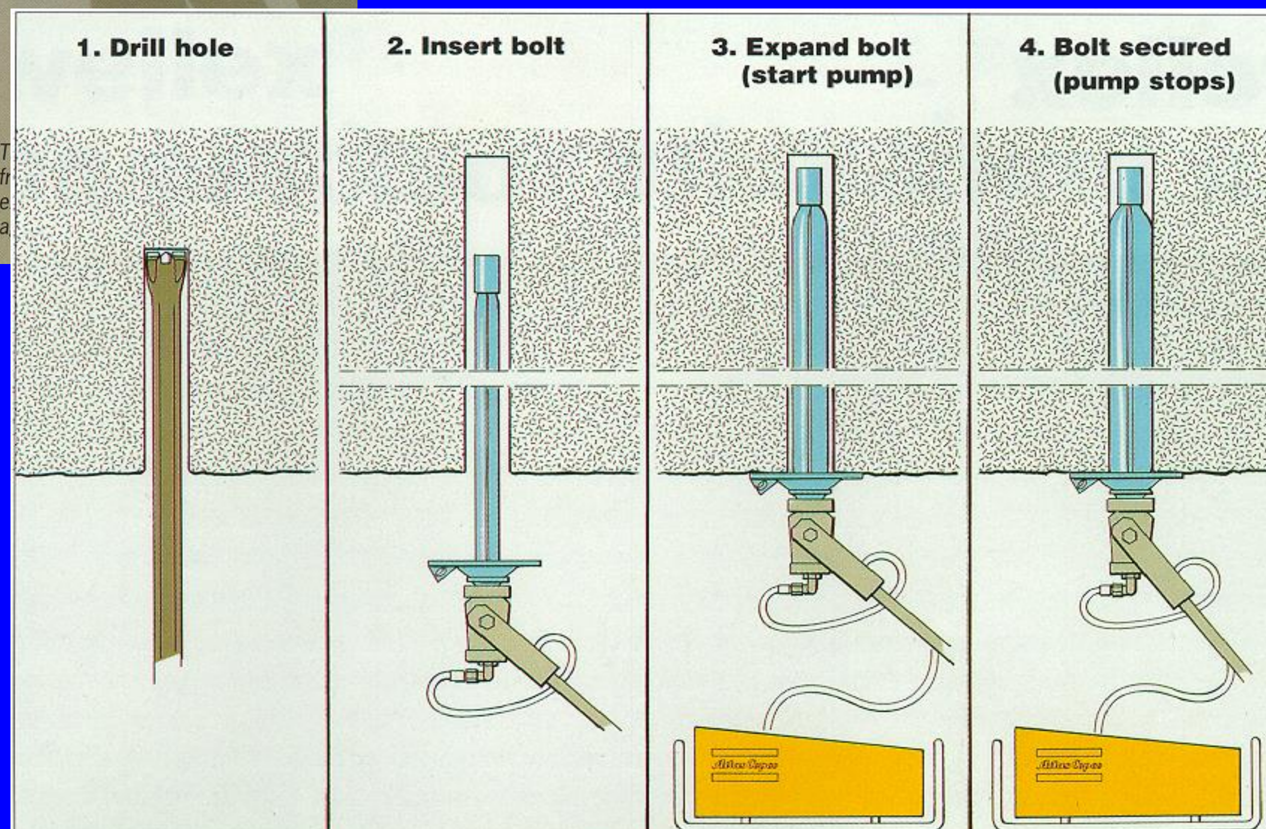
Self-drilling rockbolts. Grouting of the borehole is performed through the hollow stem and holes of the drill bit

Rockbolts (passive anchors)









Atlas Copco
Swellex rockbolts
(100 kN capacity)

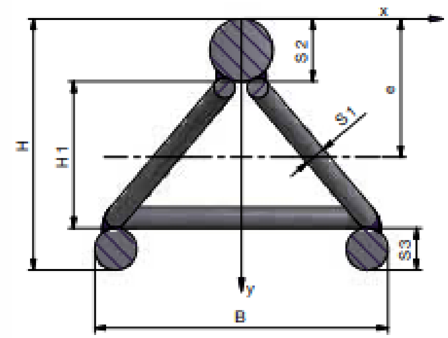
Steel ribs

Steel ribs

Lattice girders

Lattice girders

Lattice girders



Specifications

3-bar girder

No.	Designation [1]	H1	S1	S2	S3	Weight [2]	H	B	A	W_x [3]	I_x	Article No. [4]
[#]	[PS1-S3-S2]	[mm]	[mm]	[mm]	[mm]	[kg/m]	[mm]	[mm]	[cm²]	[cm³]	[cm⁴]	[---]
1	P50-20-25	50	10	25	20	10.2	95	100	11.19	28	148	14102025XXXX
2	P50-20-30			30	20	11.9	100		13.35	38	193	14102030XXXX
3	P50-20-36			36	20	14.3	106		16.46	42	246	14102036XXXX
4	P50-25-30			30	25	14.7	105		16.89	42	255	14102530XXXX
5	P50-25-36			36	25	17.1	111		20.00	58	336	14102536XXXX
6	P50-30-36			36	30	20.5	116		24.32	64	424	14103036XXXX
7	P70-20-25	70	10	25	20	10.4	115	140	11.19	37	239	14122025XXXX
8	P70-20-30			30	20	12.1	120		13.35	51	306	14122030XXXX
9	P70-20-36			36	20	14.5	126		16.46	54	383	14122036XXXX
10	P70-25-30			30	25	14.9	125		16.89	56	398	14122530XXXX
11	P70-25-36			36	25	17.3	131		20.00	77	517	14122536XXXX
12	P70-30-36			36	30	20.7	136		24.32	83	644	14123036XXXX
13	P95-20-25	95	10	25	20	10.8	140	180	11.19	49	384	14142025XXXX
14	P95-20-30			30	20	12.5	145		13.35	66	485	14142030XXXX
15	P95-20-36			36	20	14.9	151		16.46	69	598	14142036XXXX
16	P95-25-30			30	25	15.3	150		16.89	72	625	14142530XXXX
17	P95-25-36			36	25	17.7	156		20.00	100	799	14142536XXXX
18	P95-30-36			36	30	21.1	161		24.32	107	986	14143036XXXX
19	P115-20-25	115	12	25	20	11.0	160	220	11.19	58	525	14162025XXXX
20	P115-20-30			30	20	12.7	165		13.35	78	658	14162030XXXX
21	P115-20-36			36	20	15.1	171		16.46	82	804	14162036XXXX
22	P115-25-30			30	25	15.5	170		16.89	86	842	14162530XXXX
23	P115-25-36			36	25	17.9	176		20.00	120	1,070	14162536XXXX
24	P115-30-36			36	30	21.3	181		24.32	126	1,312	14163036XXXX
25	P130-20-25	130	12	25	20	11.2	175	220	11.19	66	644	14182025XXXX
26	P130-20-30			30	20	12.9	180		13.35	87	805	14182030XXXX
27	P130-20-36			36	20	15.3	186		16.46	91	980	14182036XXXX
28	P130-25-30			30	25	15.7	185		16.89	96	1,027	14182530XXXX
29	P130-25-36			36	25	18.1	191		20.00	134	1,299	14182536XXXX
30	P130-30-36			36	30	21.5	196		24.32	141	1,589	14183036XXXX

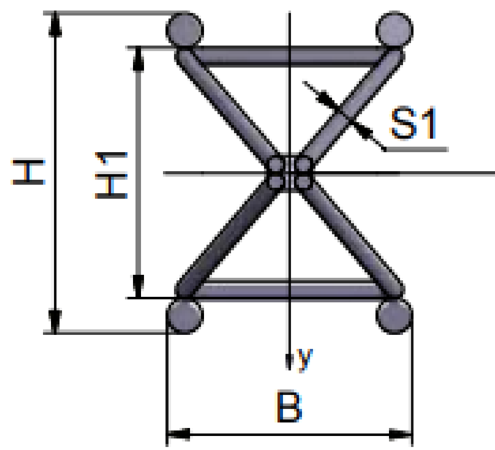
1) Designation: PH1-S3-S2, e.g. P130-20-30 ; 2) Weight including stiffeners (average values)
3) Quotient moment of inertia and maximum distance from the neutral axis to the outer fiber ; 4) „XXXX" … project-specific designation

Lattice girders

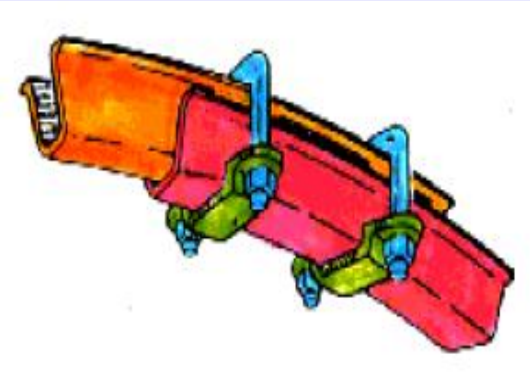
4-bar girder

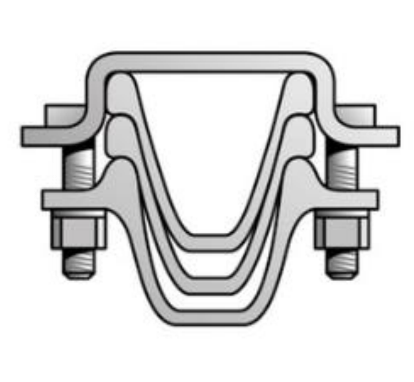
No.	Designation [1)]	H1	S1	S2	Weight [2)]	H	B	A	W_x	W_y	Article No. [3)]
[#]	[PH1-S2]	[mm]	[mm]	[mm]	[kg/m]	[mm]	[mm]	[cm^2]	[cm^3]	[cm^3]	[---]
1	P100-20	50	10	20	12.7	140	100	12.57	65	41	14200020XXXX
2	P100-25			25	14.3	150		19.63	103	56	14200025XXXX
3	P100-30			30	19.4	160		28.27	151	72	14200030XXXX
4	P100-36			36	26.7	172		40.72	222	88	14200036XXXX
5	P140-20	75	10	20	13.1	190	140	12.57	96	65	14220020XXXX
6	P140-25			25	18.5	200		19.63	151	94	14220025XXXX
7	P140-30			30	25.3	210		28.27	219	124	14220030XXXX
8	P140-36			36	35.1	222		40.72	319	161	14220036XXXX
9	P190-20	95	10	20	13.9	230	180	12.57	121	90	14240020XXXX
10	P190-25			25	19,3	240		19.63	190	132	14240025XXXX
11	P190-30			30	26.1	250		28.27	275	178	14240030XXXX
12	P190-36			36	35.9	262		40.72	399	237	14240036XXXX
13	P230-20	115	10	20	14.3	270	220	12.57	146	114	14260020XXXX
14	P230-25			25	19.7	280		19.63	228	170	14260025XXXX
15	P230-30			30	26.5	290		28.27	330	233	14260030XXXX
16	P230-36			36	36.3	302		40.72	479	316	14260036XXXX
17	P260-20	130	10	20	14.7	300	220	12.57	164	114	14280020XXXX
18	P260-25			25	20.1	310		19.63	258	170	14280025XXXX
19	P260-30			30	26.9	320		28.27	372	233	14280030XXXX
20	P260-36			36	36.7	332		40.72	539	316	14280036XXXX

1) Designation: PH1-S2, e.g. P140-30
2) Weight including stiffeners (average values)
3) „XXXX" … project-specific designation



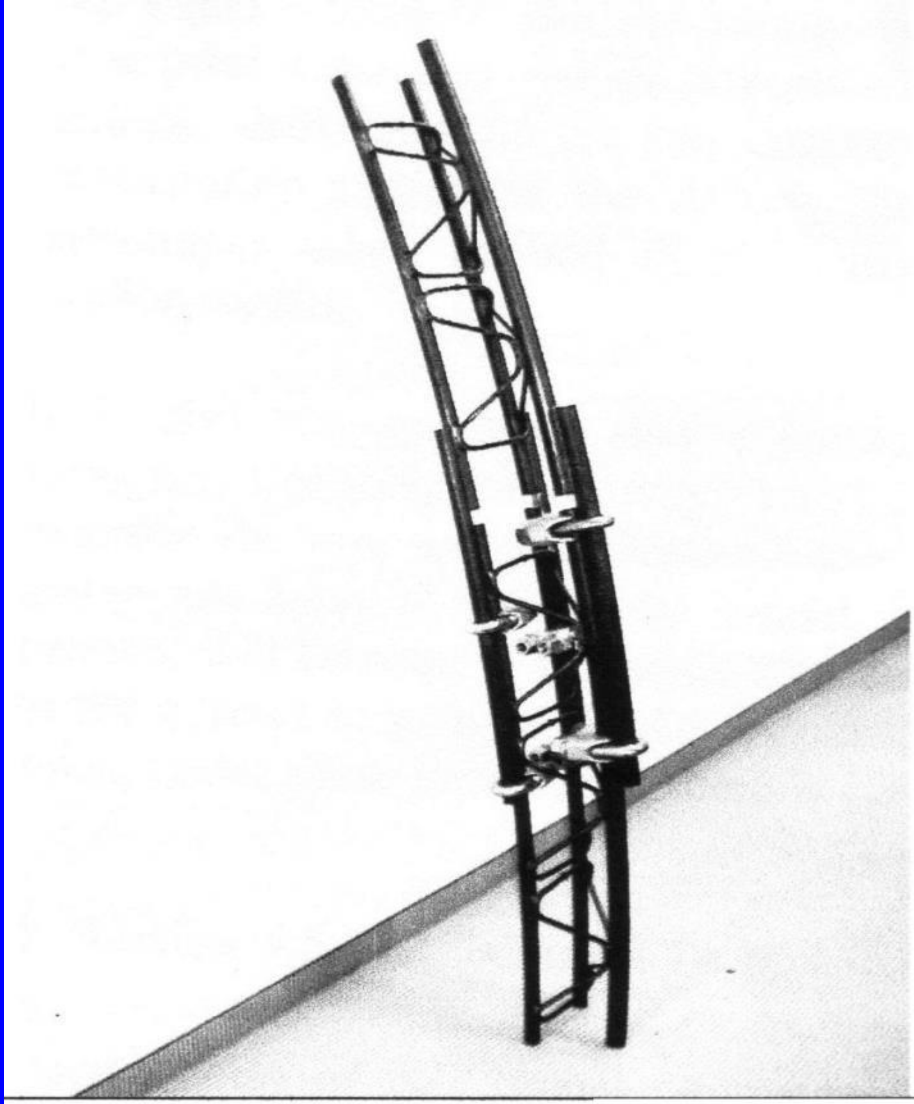
Sliding steel ribs
(TH steel sets)



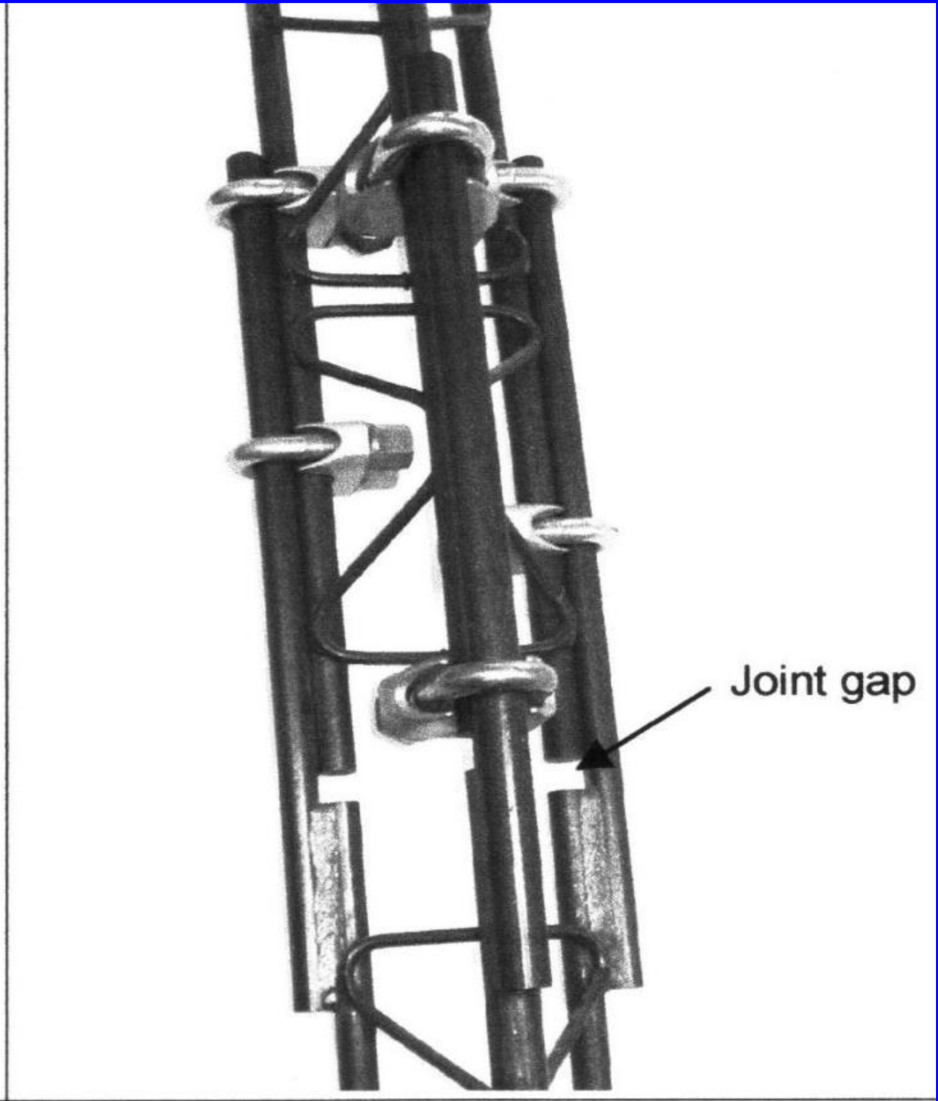


Sliding steel ribs

Sliding steel ribs



Lattice girder with sliding joint element.



Detail of the sliding joint showing the gap to be closed.