Tunnelling and Underground Construction Technology

Course Lectures

Part 2.2 – Ground Improvement

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Ground Treatment and Improvement

In order to improve the construction process when tunnelling through poor ground, a double philosophy exists:

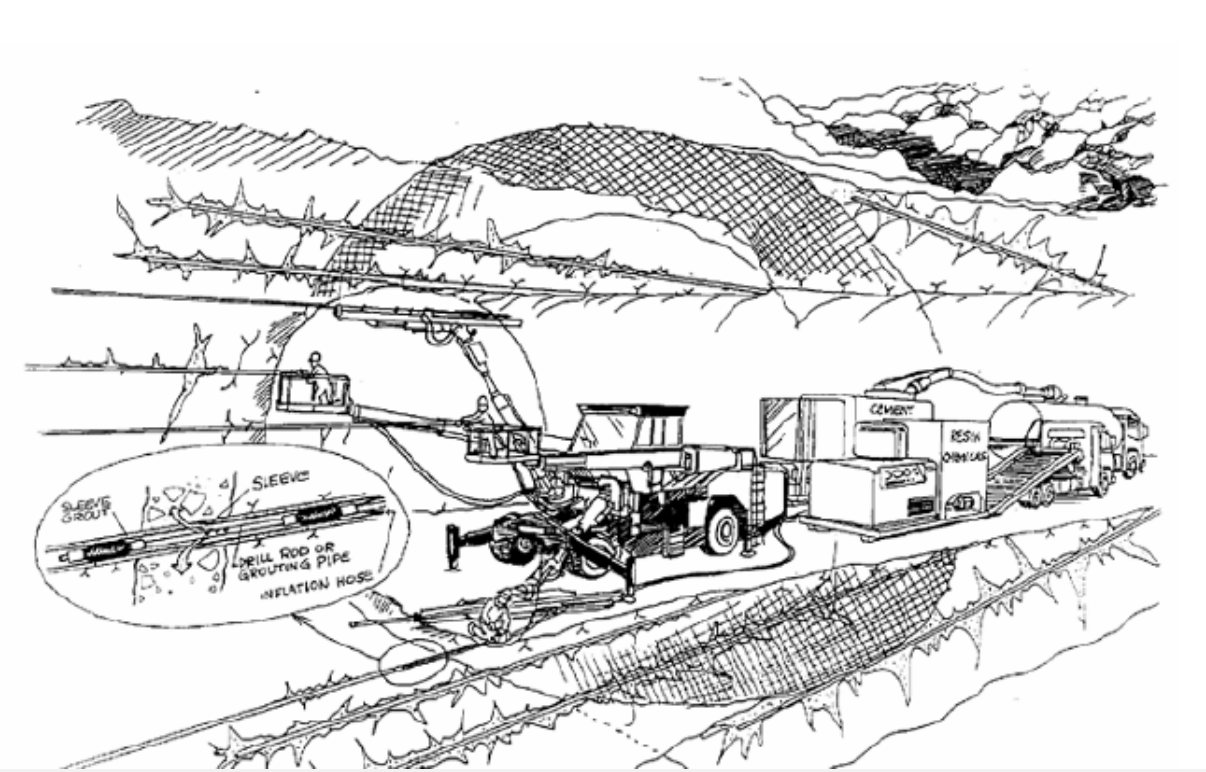
1. Improvement and adaption of the technology used for excavation and support to the conditions of the ground

or

2. Improvement of the ground to be excavated with the main goal of waterproofing and consolidating voids, cracks and porosity, by means of different techniques: Grouting, Freezing, Dewatering, Forepoling, etc.

Grouting

Grouting is the introduction of a hardening fluid or mortar into the ground to improve its stiffness, strength and/or impermeability



Grouting

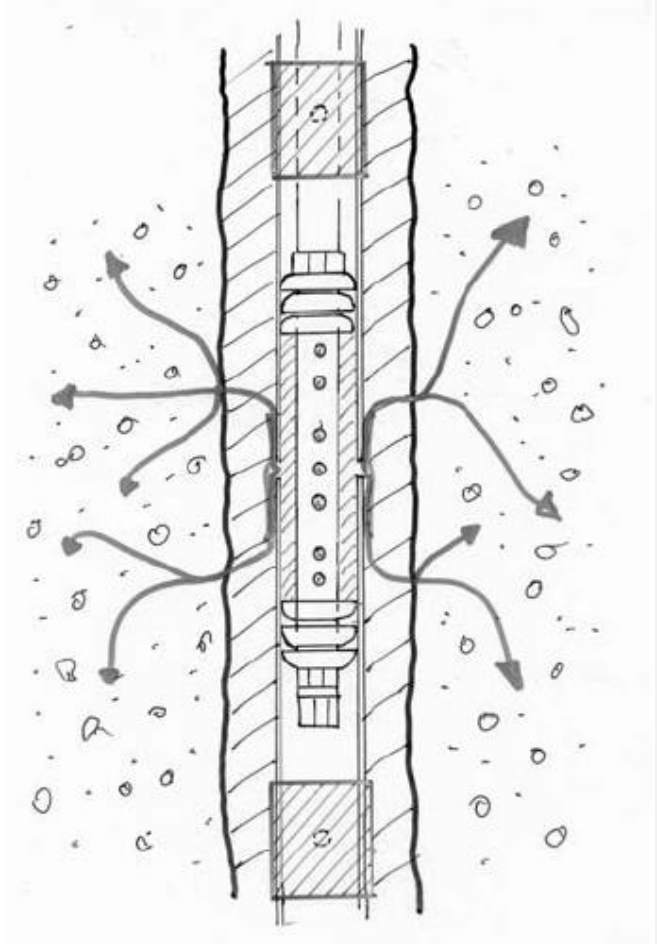
There are different patterns of the propagation of the grout within the ground:

- Low pressure grouting
- Compensation grouting
- Jet grouting

Grouting

Low pressure grouting

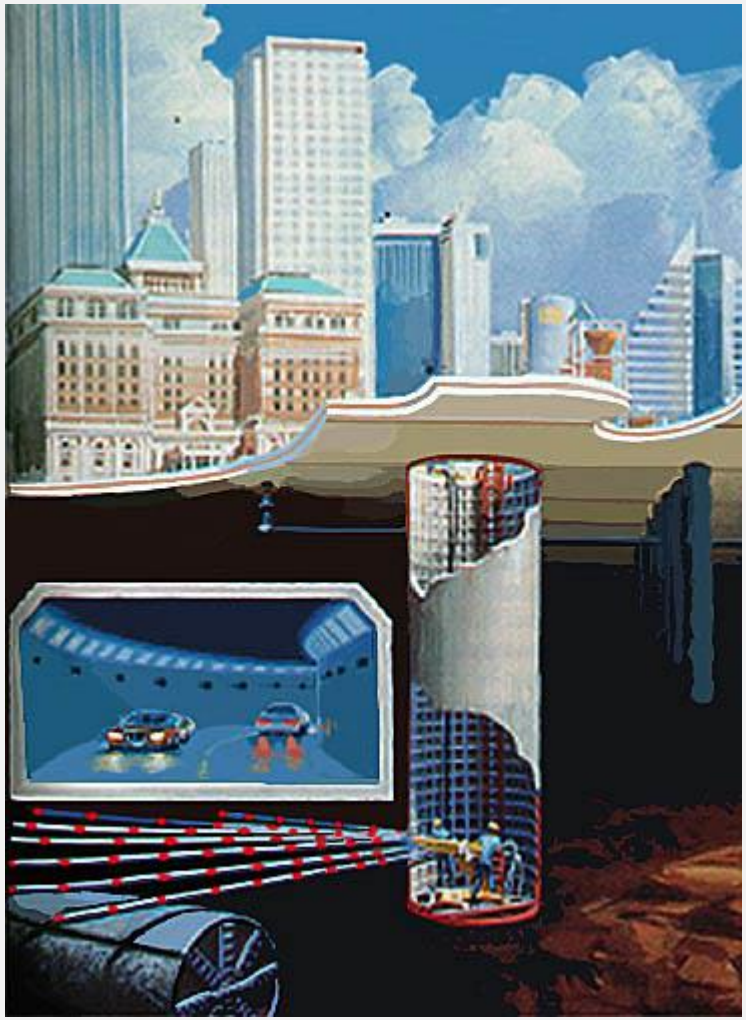
The grout is introduced into the ground with a movable double packer, by means of a pressure high enough to push the ground into the pores but low enough not to crack the ground



Grouting

Compensation grouting

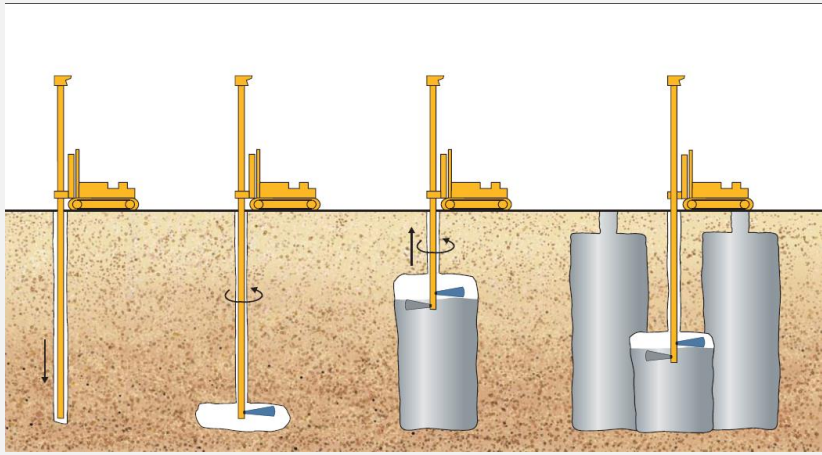
- The objective is to fracture the ground, with increased grouting pressure, in order to « swell » the ground.
- Used for compensation of surface settlements, by « heaving » the surface.
- Also called « grout-jacking »
- Caution must be taken as new loads might be exerted on the lining



Grouting

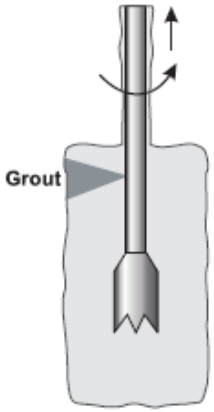
Jet grouting

- A high pressure (300 to 600 bar) is applied to a cement suspension which is pumped through a pipe with a lateral nozzle at its bottom end
- The jet erodes the surrounding soil. When the pipe is pulled out and rotated simultaneously, a cylindrical body of soil and cement is formed
- Different techniques of jet grouting exist: Single fluid, double fluid, triple fluid, etc



Grouting

Jet grouting: Single Grout



Single Fluid Jet Grouting (Soilcrete S)

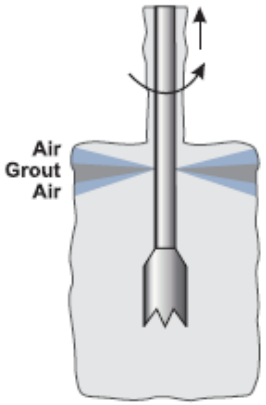
Grout slurry is pumped through the rod and exits the horizontal nozzle(s) in the monitor with a high velocity [approximately 650 ft/sec (200m/sec)]. This energy causes the erosion of the ground and the placement and mixing of grout slurry in the soil. In gravelly soils, soilcrete column diameters of 2 to 4 ft (0.6-1.2m) can be achieved. In loose, silty and sandy soils, larger diameters are possible. Single fluid jet grouting is generally less effective in cohesive soils.

Soilcrete S Applications

- *Cutoff walls in porous soil*
- *Soil consolidation for tunnel roof*
- *Bottom bracing for deep trenches in soft soil*
- *Anchorages*
- *Sealing applications*

Grouting

Jet grouting: Double Grout



Double Fluid Jet Grouting (Soilcrete D)

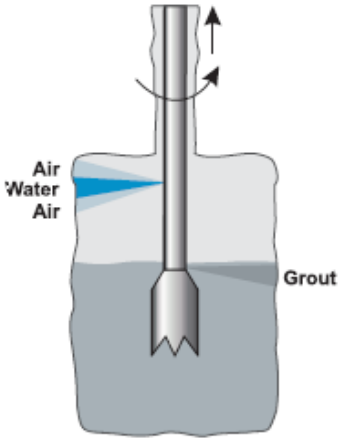
A two-phase internal rod system is employed for the separate supply of grout slurry and air down to different, concentric nozzles. Grout slurry is used for eroding and mixing with the soil. The air shrouds the grout slurry jet and increases erosion efficiency. Soilcrete column diameters of more than 3 ft (1.0m), in medium to dense soils, and more than 6 ft (1.8m) in loose soils, may be achieved. The double fluid system is more effective in cohesive soils than the single fluid system.

Soilcrete D Applications

- *Soil stabilization*
- *Some underpinning applications*
- *Panel cutoff walls*
- *Bottom bracing for deep trenches in soft soil*

Grouting

Jet grouting: Triple Grout



Triple Fluid Jet Grouting (Soilcrete T)

Grout slurry, air and water are pumped through different lines to the monitor. High velocity coaxial air and water form the erosion medium. Grout slurry emerges at a lower velocity from separate nozzle(s) below the erosion jet. This somewhat separates the erosion process from the grouting process and yields a higher quality soilcrete. Soilcrete columns with diameters ranging from 3 ft (0.9m) to more than 5 ft (1.5m) can be achieved. Triple fluid jet grouting is the most effective system for cohesive soils.

Soilcrete T Applications

- *Underpinning and excavation support*
- *Horizontal slab/ ground water control*
- *Panel cutoff walls*
- *Sealing applications*
- *Most fine grained soil stabilization*

Grouting

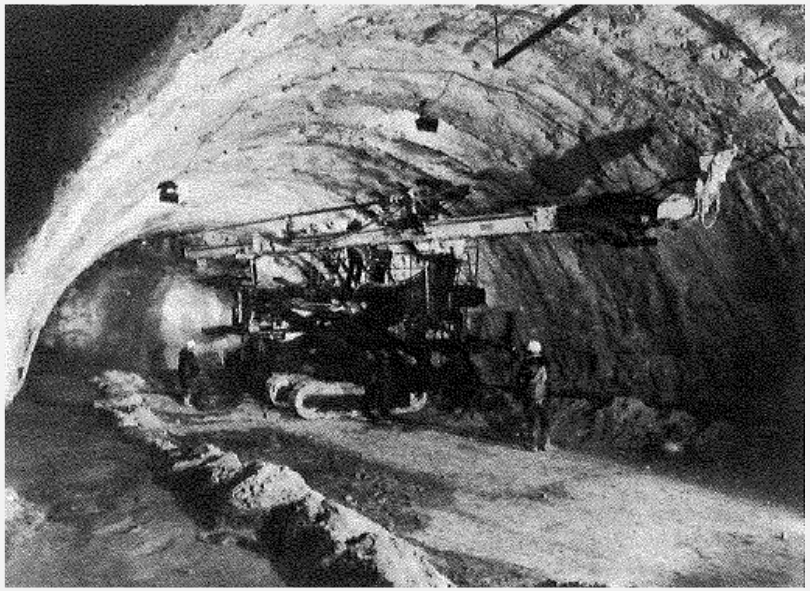
Tunnelling Application

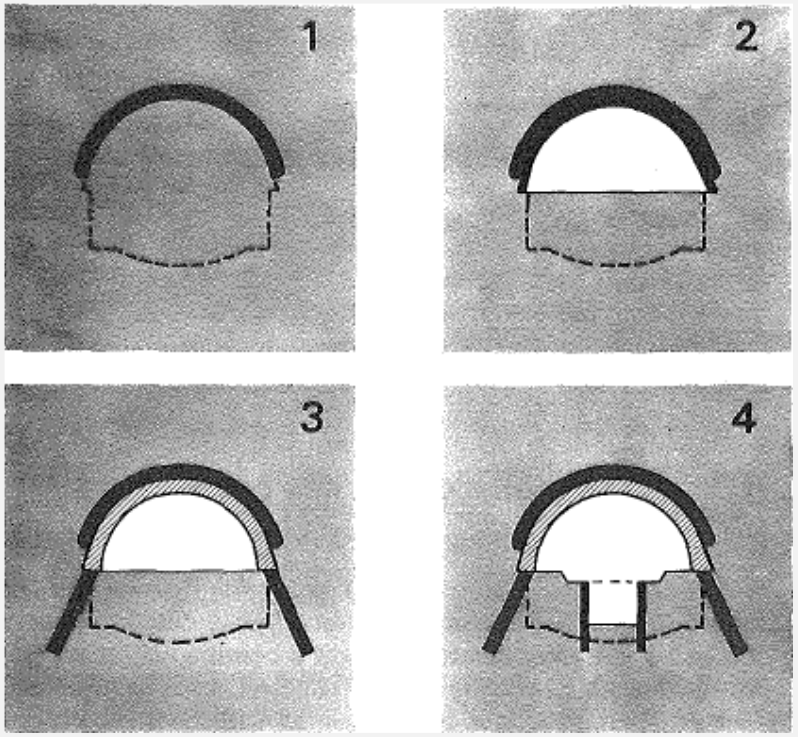
- Grouting is used in tunnelling to improve the quality of the ground around the future tunnel and to seal the tunnel against groundwater and thus prevent heading inrushes

- Staggered boreholes with lengths of around 20 m are driven from the face and grouted with a good overlapping, obtaining a kind of protective umbrella on the tunnel.

Grouting

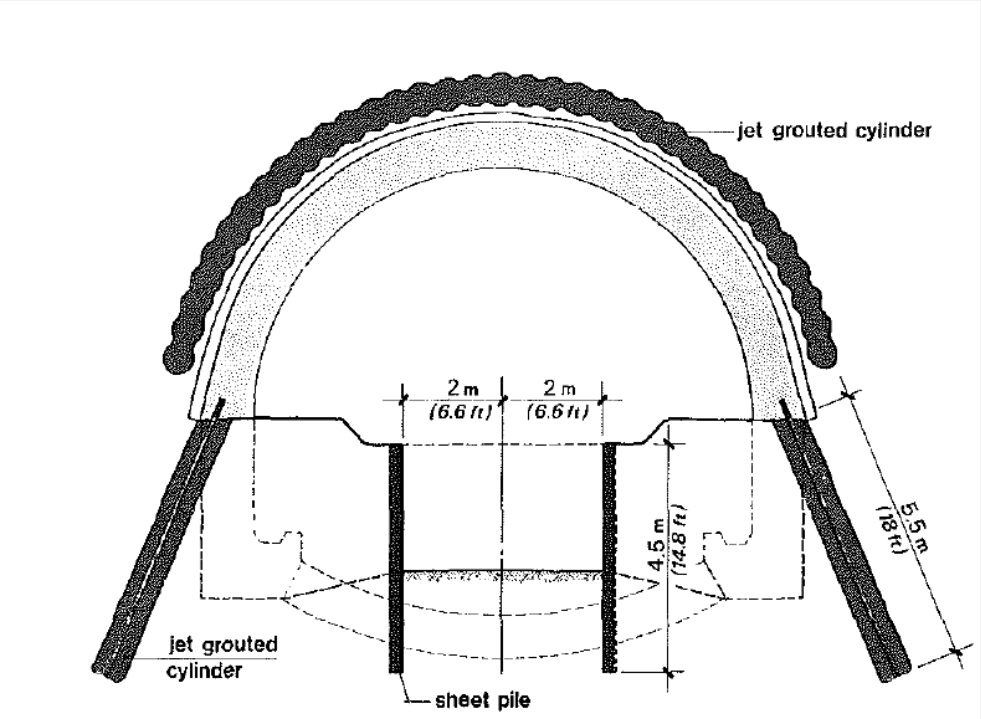
Tunnelling Application Example

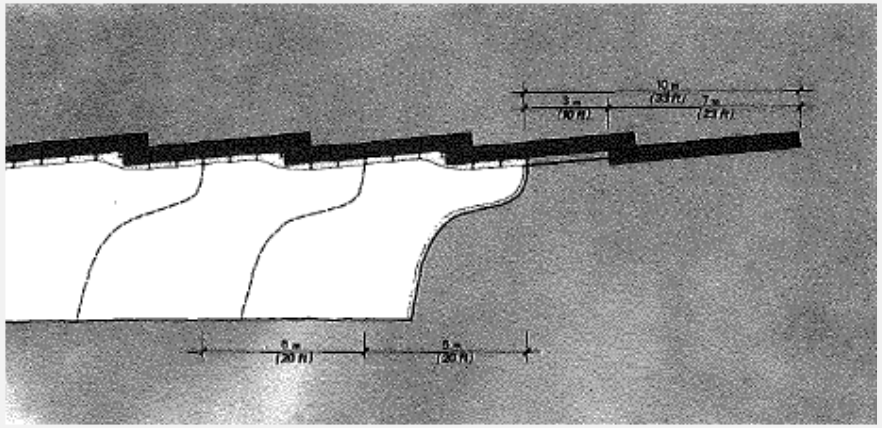




Grouting

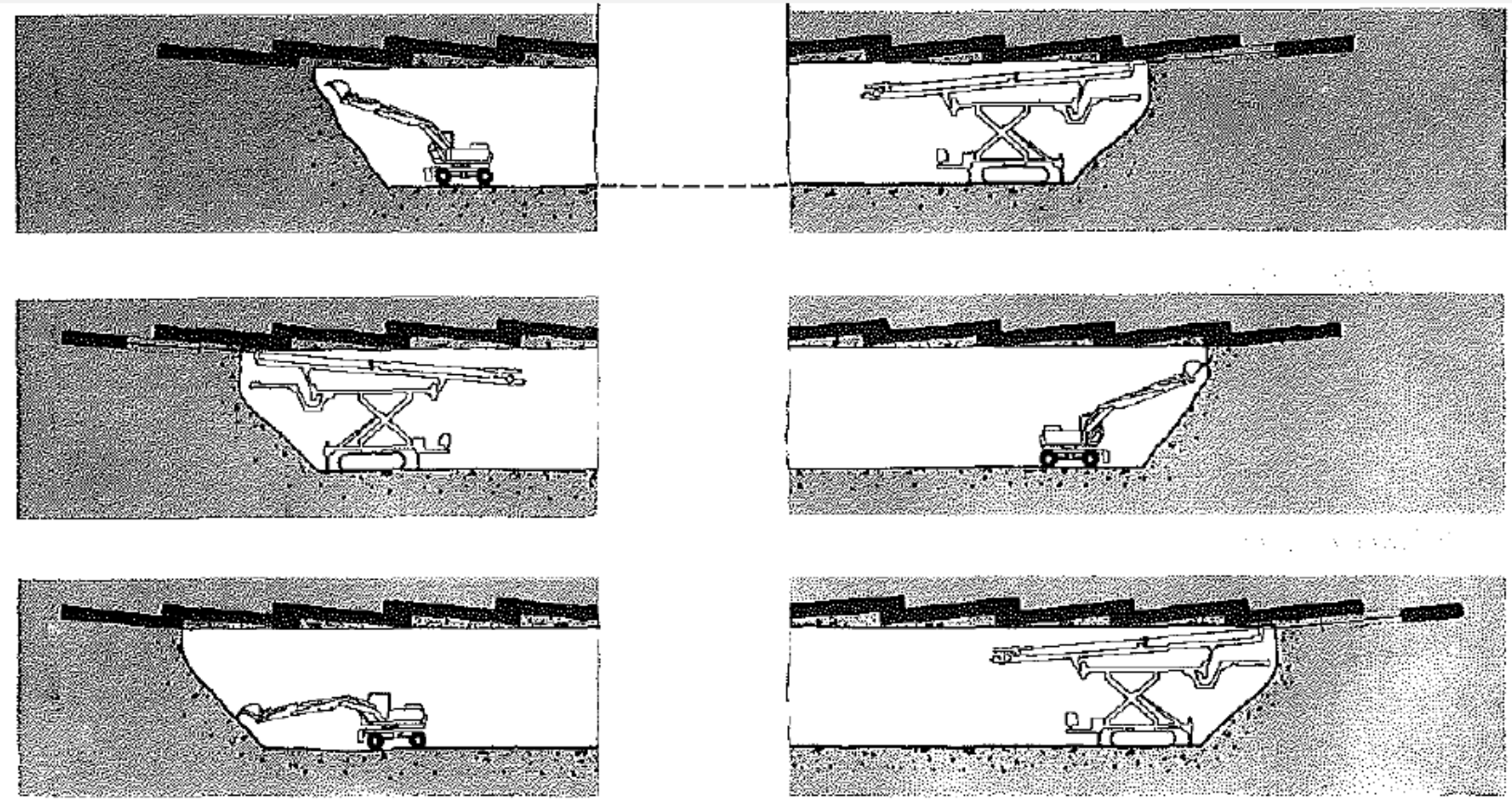
Tunnelling Application Example





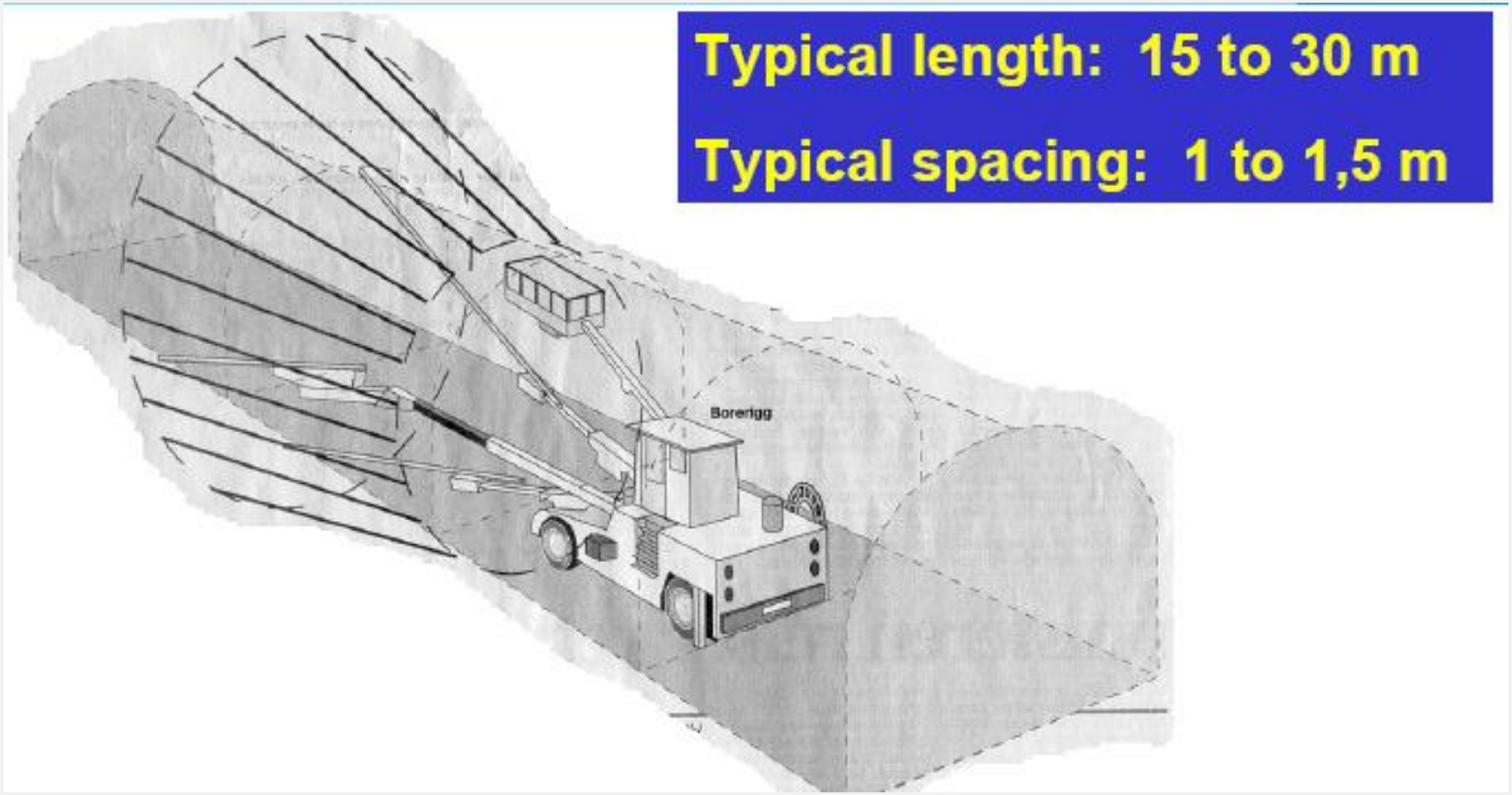
Grouting

Tunnelling Application Scheme



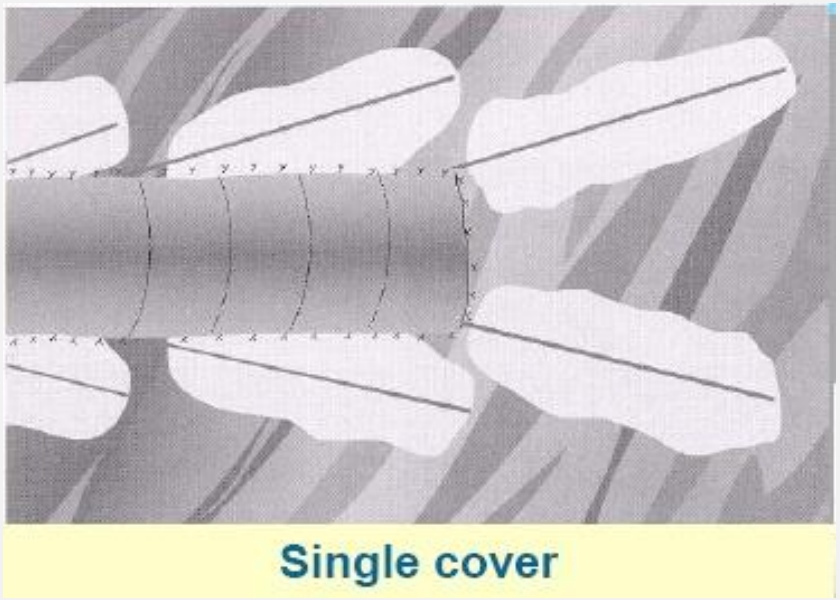
Grouting

Tunnelling Application Scheme

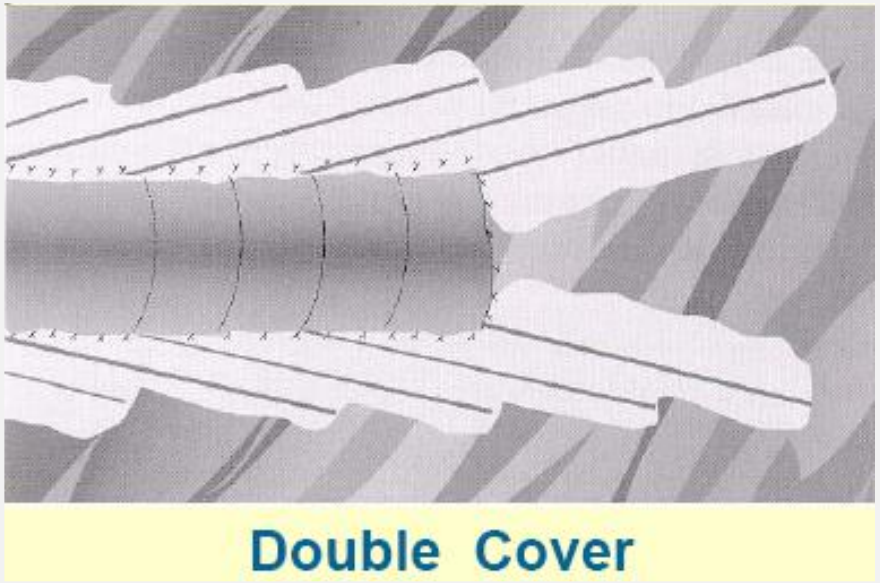


Grouting

Tunnelling Application Scheme



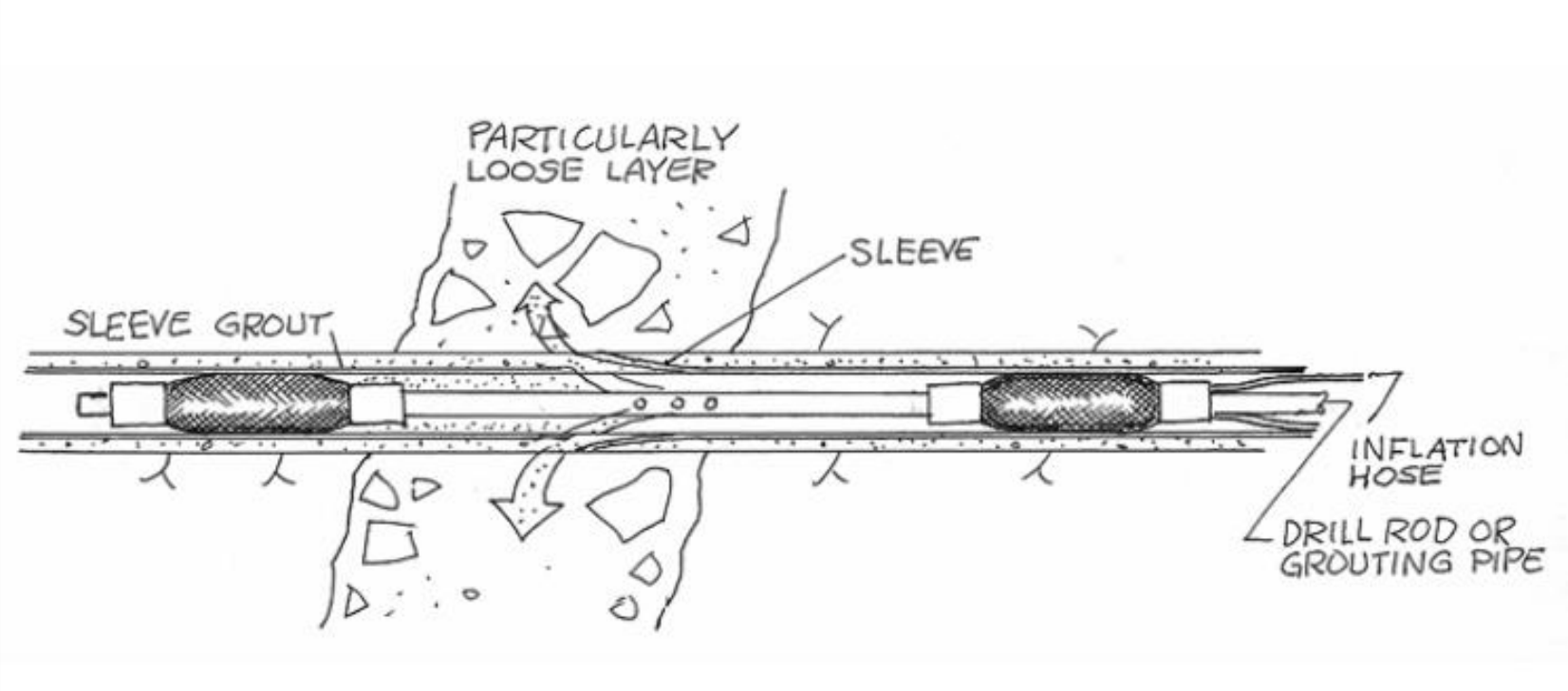
Single cover



Double Cover

Grouting

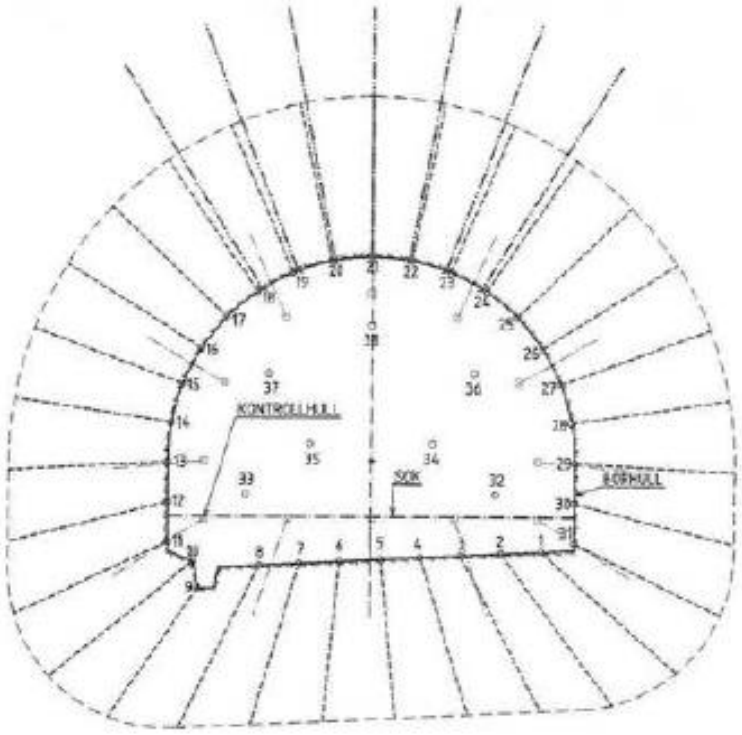
Tunnelling Application Scheme



Grouting

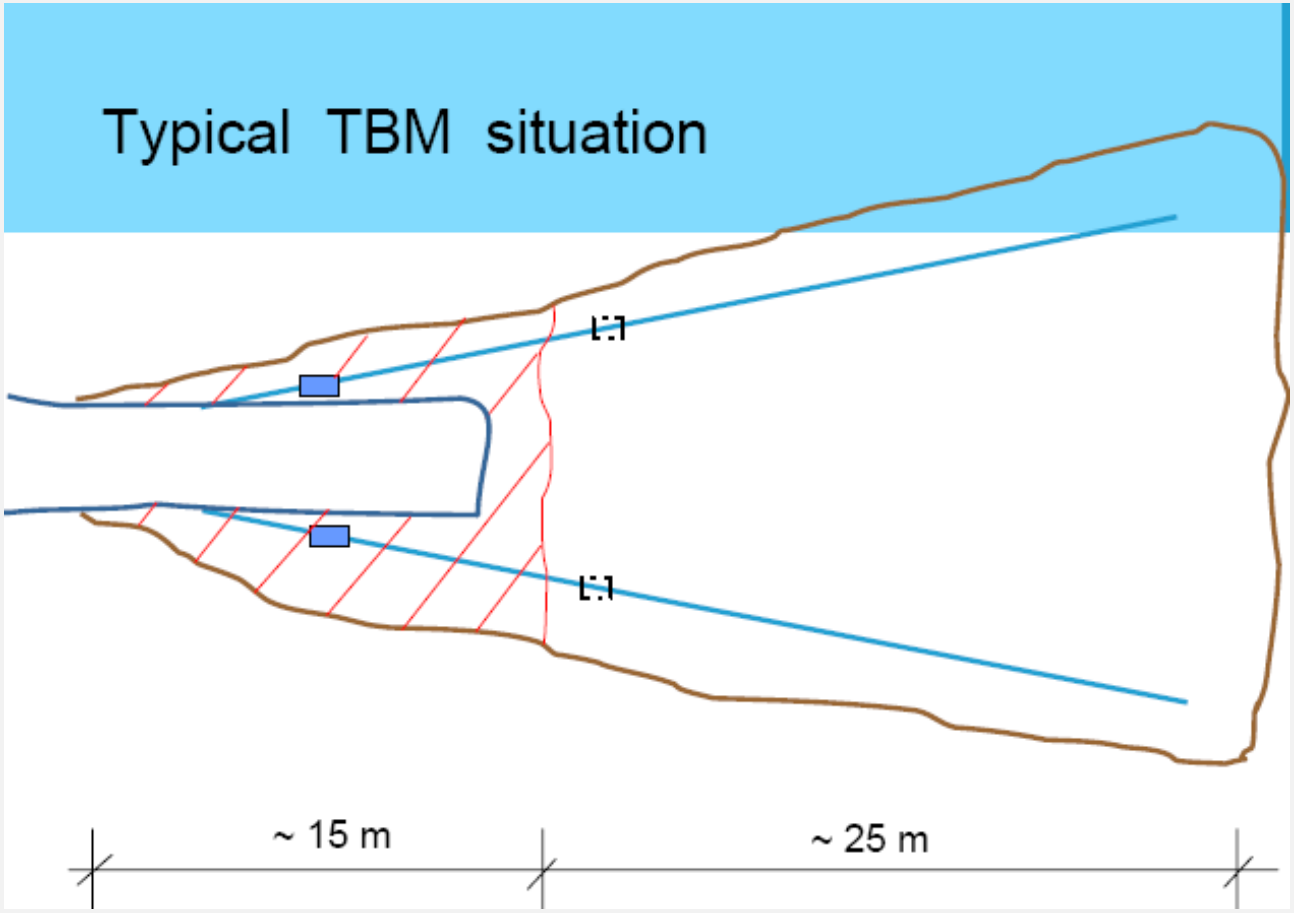
Tunnelling Application Scheme

- Typical injection fan layout.
- Length of holes: 21 m
- Angle: 7°
- Distance between holes: 1,2 m



Grouting

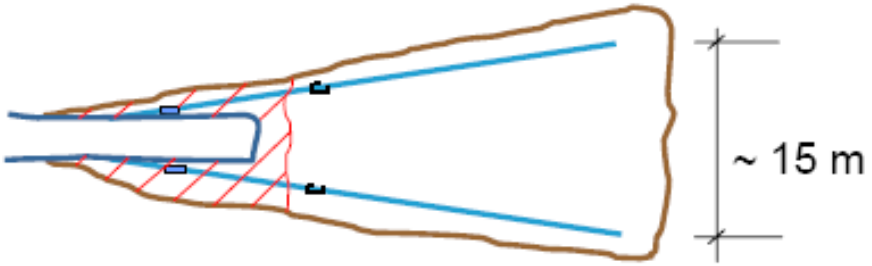
Tunnelling Application Scheme TBM



Grouting

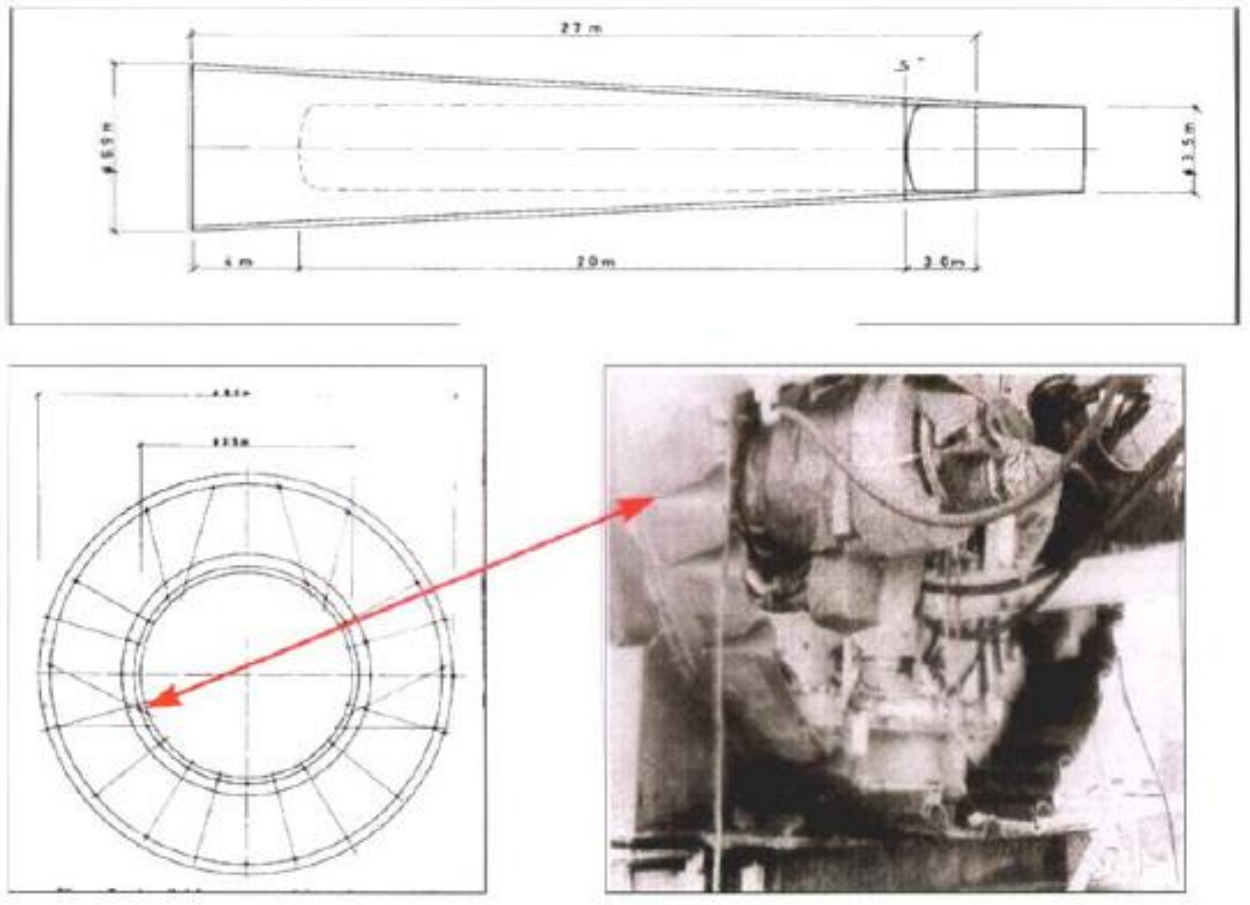
Tunnelling Application Scheme TBM

- The biggest problem: Most TBM's are not made for pre-injection!!
- Before injection can take place, you need to be able to drill injection holes, and to guide the drill rod.
- Length of holes: about 20 – 30 meters in front of the face.
- Remember, this means some extra meters in many cases



Grouting

Tunnelling Application Scheme TBM



Grouting

Commonly used grouts

- **Cement Grouts**: cement content between 100 and 500 kg per m^3, and bentonite (to reduce sedimentation, permeability and strength); several hours must be awaited for setting before any blasting and drilling into the grouted area
- **Micro Cements**
- **Colloidal silica suspensions**
- **Chemical Grouts**: the majority is sodium silicate; setting time is reduced (30 to 60 minutes); mechanical properties can be tailored
- **Polyurethanes**: they react with water and produce foam which remains ductile after hardening
- **Acrylic Grouts**: liquids of low viscosity until the polymerisation sets on (around an hour)
- **Epoxy Resins**: less used, difficult handling
- **Thermoplastic materials**: asphalt or melt polyamides pumped with fast flowing water

Grouting

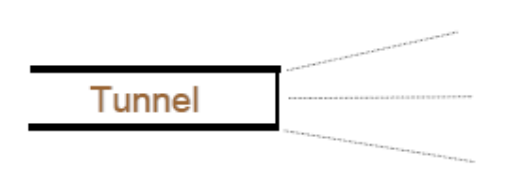
Particularities of Rock Grouting

- Rock has a much smaller pore volume than soil, so that it is difficult to uniformly grout all voids of rock
- In order to avoid grout escaping through large joints:
  - Thicker grouts must be used
  - A limit for the grout volume V must be imposed (to avoid filling of too large and not needed areas)
  - A limit for the grouting pressure P must be imposed (to avoid hydro-fracturing of the rock and fracture opening)

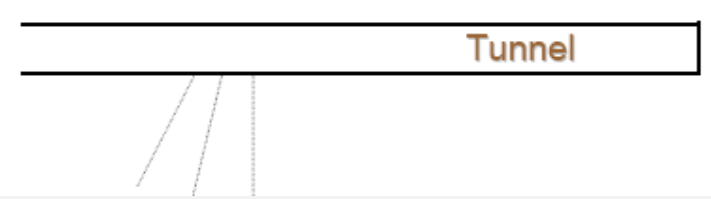
Grouting

Moment of intervention

- According to when the grouting is executed, we can talk about:
  - Pre-injections



  - Post-injections



Grouting

Moment of intervention

- Pre-injections
  - They can be performed from the face of the advancing tunnel (what normally affects the excavation process) or from the surface (what gives extra-flexibility).
  - They are preferable to post-injections, as they are easier to perform, cheaper, more effective and treat the ground before water starts moving and leaking into the tunnel.
  - The present a marginal risk of uncontrolled water in-rush
  - They provide dry working conditions in the tunnel
  - There is marginal influence on the surroundings

Grouting

Moment of intervention

- Post-injections:
  These injections are not preferable to pre-injections, as:
  - Not ideal, as it « chases » the water from place to place
  - Normally relatively expensive chemical resins are used
  - Specialized teams are necessary
  - Time consuming and difficult to achieve success
  - They work better when applied on pre-injected ground

Ground Freezing

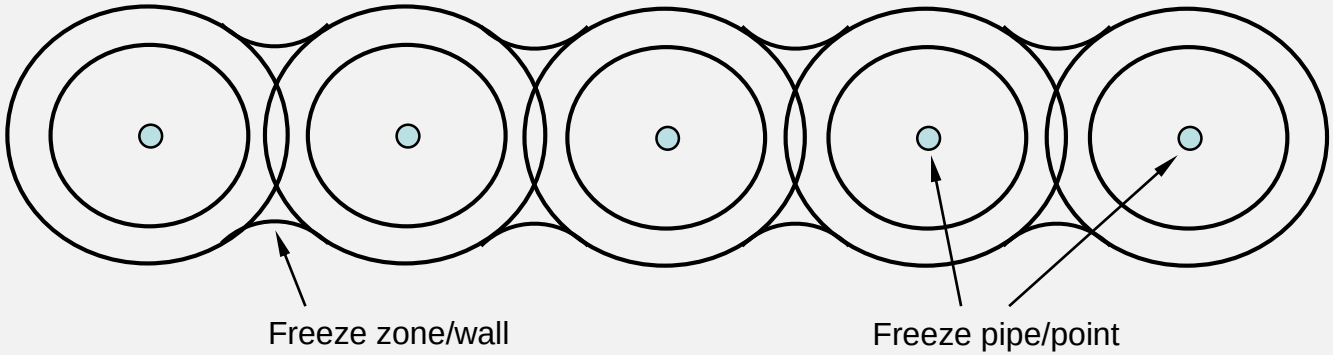
Principle of Ground Freezing

Ground freezing is a technique used extensively for groundwater control and ground control in the underground construction.

The process involves the circulation of a refrigerated coolant through a series of subsurface pipes to convert soil water to ice, creating a strong and watertight material.

Ground Freezing

Formation of freeze wall

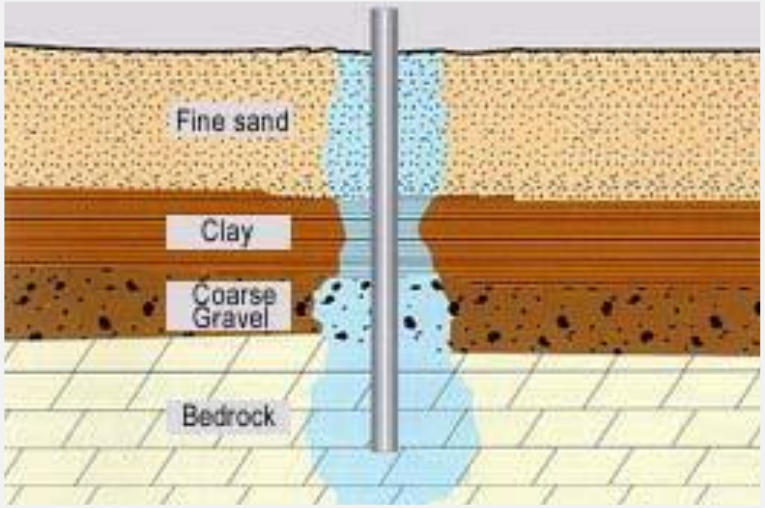


In tunnelling, freeze zone or wall around tunnel can be formed for excavation

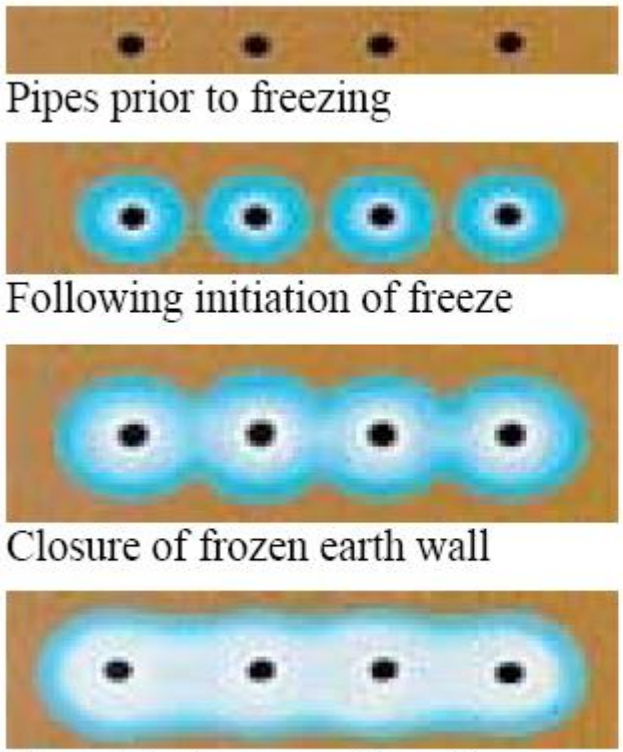
Ground Freezing

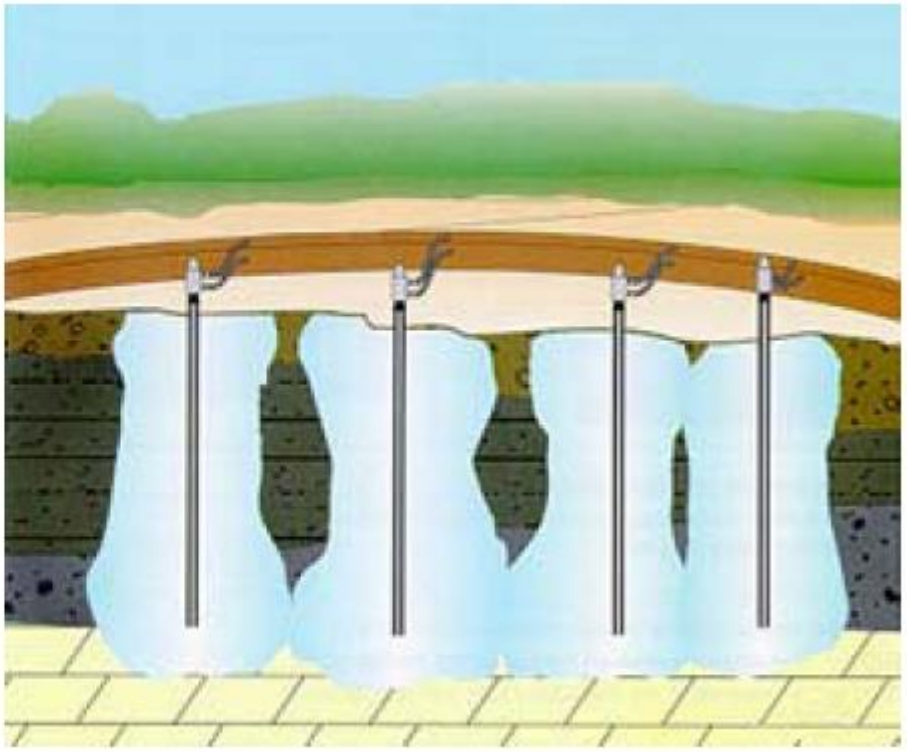
The design of a frozen earth barrier is governed by the thermal properties of the underlying soils and related response to the freezing system. Formation of frozen earth barrier develops at different rates depending on the thermal and hydraulic properties of each stratum

Typically, rock and coarse-grained soils freeze faster than clays and silts



Ground Freezing





Ground Freezing

Ground Freezing in Tunnelling

Provides stable shoring to allow tunnelling in wet, loose soils or highly fractured rock.

Effective for cutting off ground water into tunnel excavation.

Frozen soil/rock can be used as shoring around unfrozen soil or the entire soil/rock mass can be frozen (similar to hard-rock tunnelling).

Frozen soil shoring can also be used to stabilize ground entrance and exit access shafts

Ground Freezing

Properties of Frozen Ground

Frozen material	Compressive strength at -10°C, MPa
Pure ice	1.5
Sand	10
Silt	4
Clay	2
Crushed rock and gravel	2

Ground Freezing

Ground Freezing System

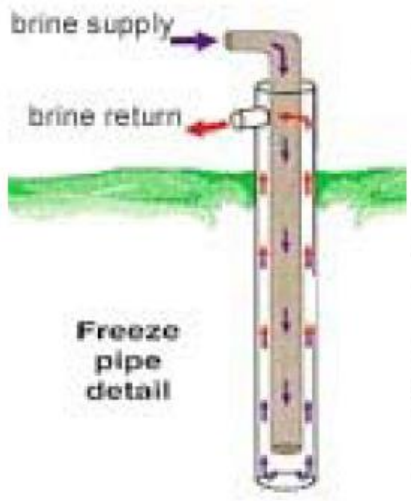
- Subsurface refrigeration system, consisting of a series of refrigeration pipes installed with various drilling techniques.
- The coolant can be brought to temperatures well below freezing, by using either a large portable refrigeration plant or liquid nitrogen.
- After the initial freezing and the frozen barrier is in place, the required refrigeration capacity is significantly reduced to maintain the frozen barrier.

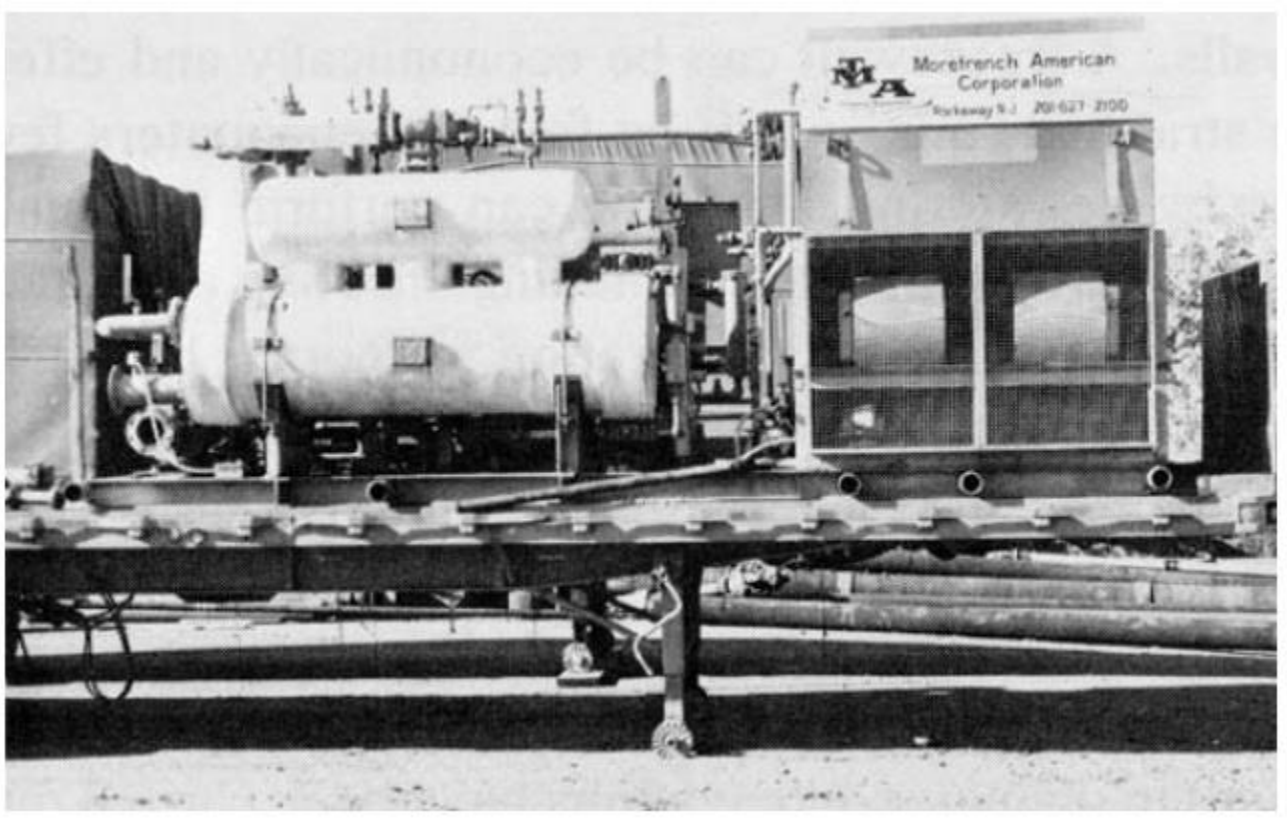
Ground Freezing

Ground Freezing System – Conventional System

- Primary refrigerate gas, usually ammonia, being compressed and conducting its cold energy on evaporation to a secondary coolant, usually calcium chloride **brine** which **is circulated through the freeze tube system to cool the strata.**
- The refrigeration plants are usually self contained. The conventional system can operate at as low as **-40°C and are suitable for the larger projects where freezing will be carried on for several weeks.**

Ground Freezing





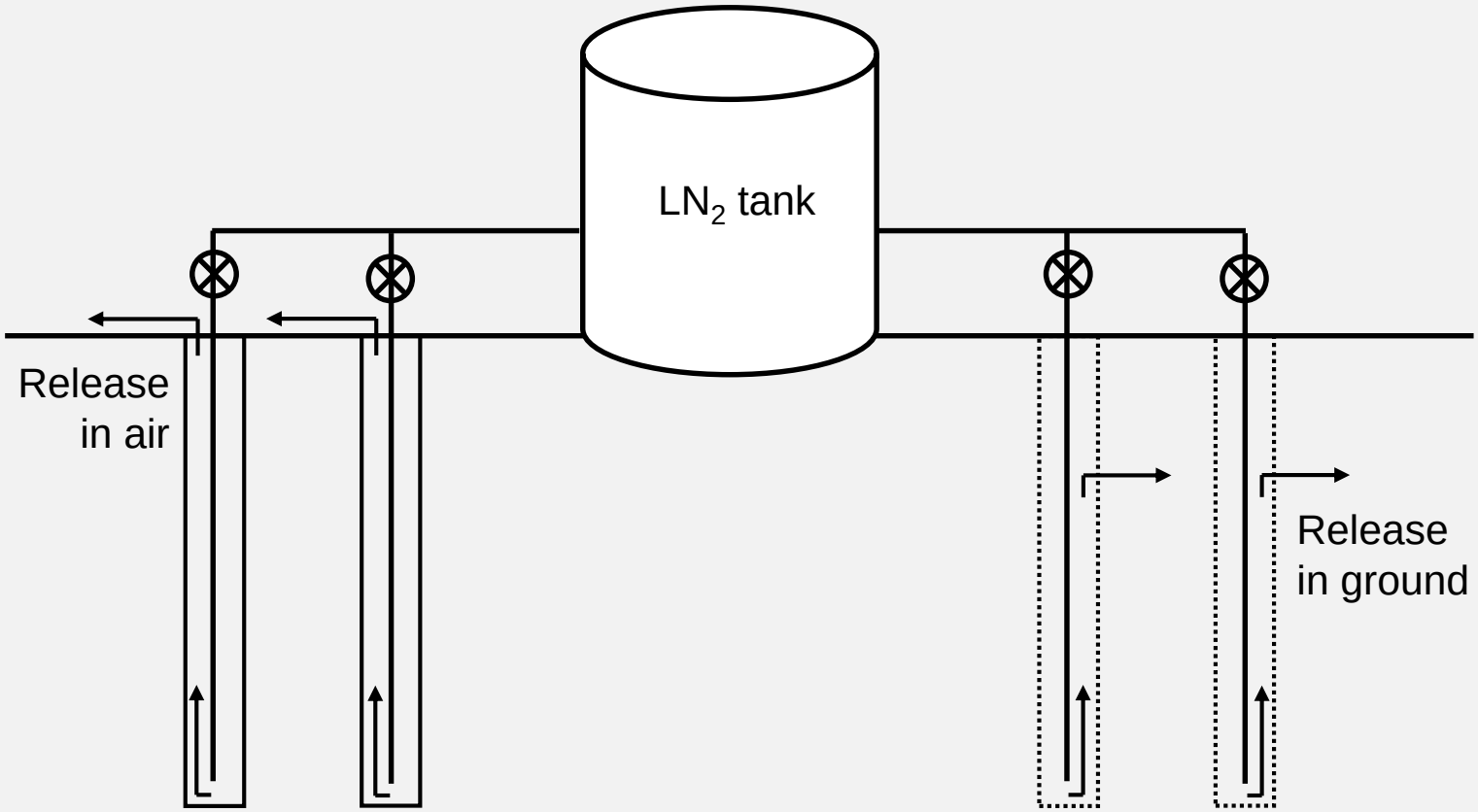
A portable twin 60-ton brine refrigeration unit

Ground Freezing

Ground Freezing System – Cryogenic System

- It uses liquid nitrogen that is applied directly to the freeze tubes where it evaporates at -196°C and the resultant gas is exhausted to atmosphere.
- It is used in cases where remedial action is urgent and for small compact projects where time is of paramount importance.
- The freeze wall formation can be completed in typically 3-7 days. It may also be used where water movement or saline condition (e.g., up to 1000 m below river).

Ground Freezing



Liquid nitrogen freezing system

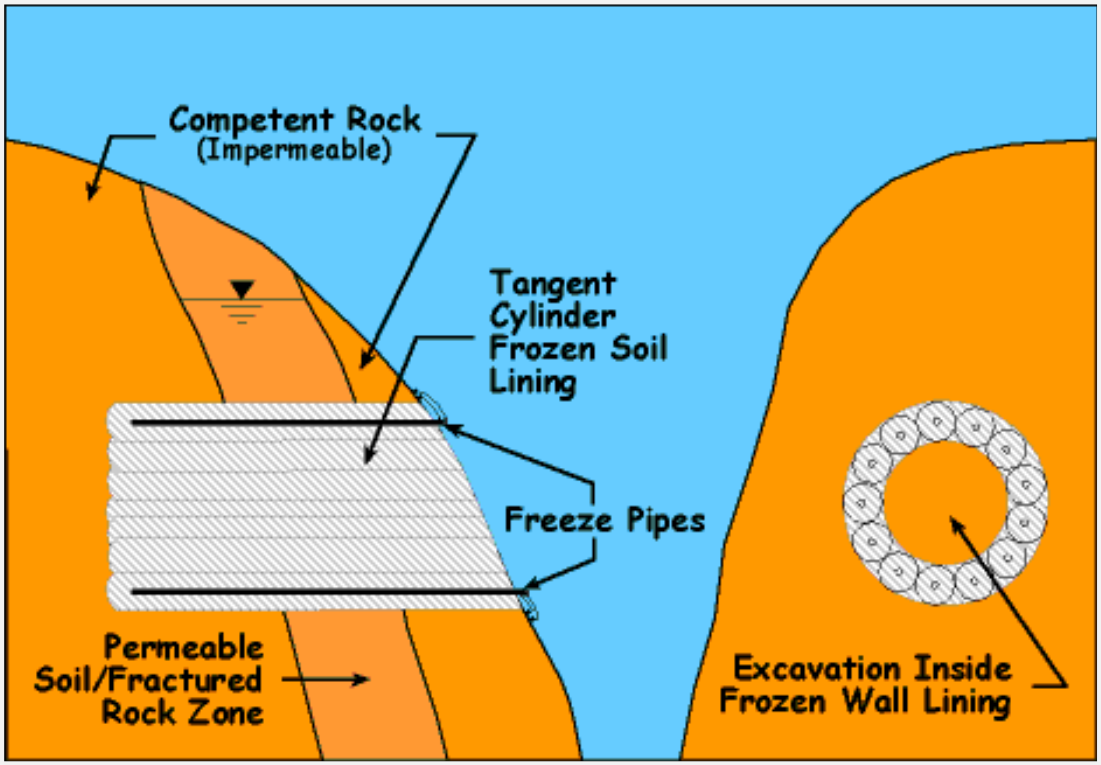
Ground Freezing

Advantages of Ground Freezing (i)

a) **Strength** – is increased many times and frequently excavations are rendered stable without any further temporary support. Frozen soil is similar to a weak concrete or rock therefore complete stability can be assured.

b) **Waterproofing** – is common to all frozen soil types thus the requirement for dewatering or pumping is eliminated.

Ground Freezing



Ground Freezing

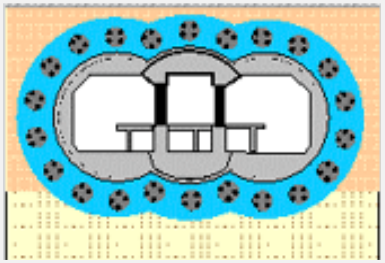
Advantages of Ground Freezing (ii)

c) **Stability** – Settlement associated with vibration during piling and removal of fines due to pumping are eliminated.

d) **Non-pollution** – Freezing does not pollute the ground water or affect its level in any way.

e) **Versatility** – Freezing satisfactorily stabilises and excludes ground water in all types of ground from fine micro-grain to fissured rock structures.

Ground Freezing



Metro tunnel in Berlin

Ground Freezing

Advantages of Ground Freezing (iii)

f) **Safety** – A safe working environment is provided eliminating hazards associated with toxic chemicals compressed air working excessive noise and the possibility of pumping contaminated groundwater.

g) **Cost effectiveness** – Ground freezing is a very cost effective and time saving process. In all too many cases the client has only realised this when he has committed to another stabilisation technique that has failed to give the performance expected.

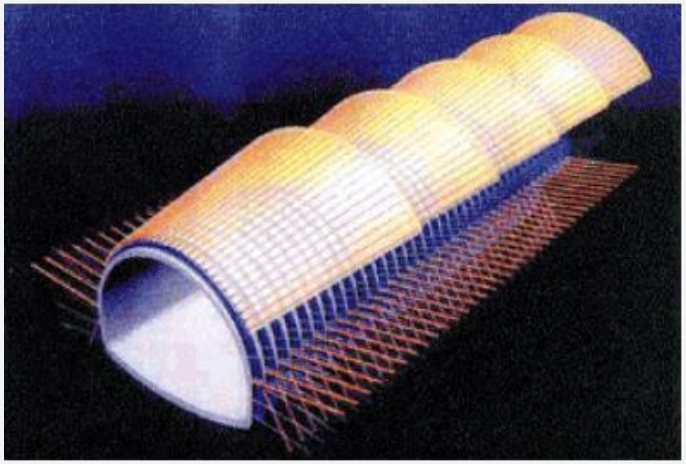
Forepoling

- If the **strength of the ground is so low** that the excavated space is unstable for a short time, a pre-driven support is applied
- In this way, the excavation increments occur under the protection of a previously driven canopy
- It can be used when **tunnelling with low overburden** and wanting to prevent large surface settlements, or when **tunnelling through poor ground**
- Forepoling is achieved by **spiling, pipe roof**

Forepoling

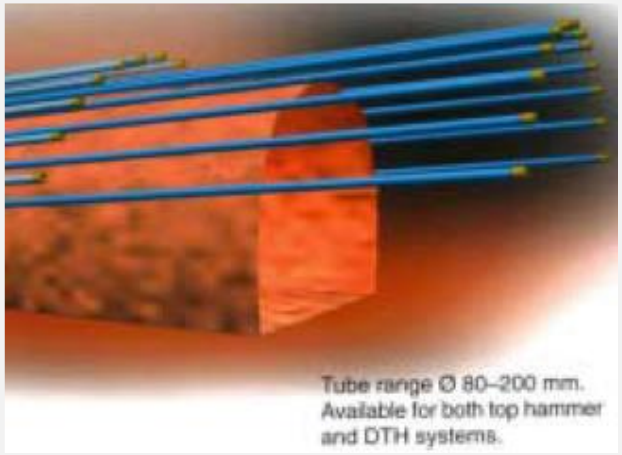
Spiling

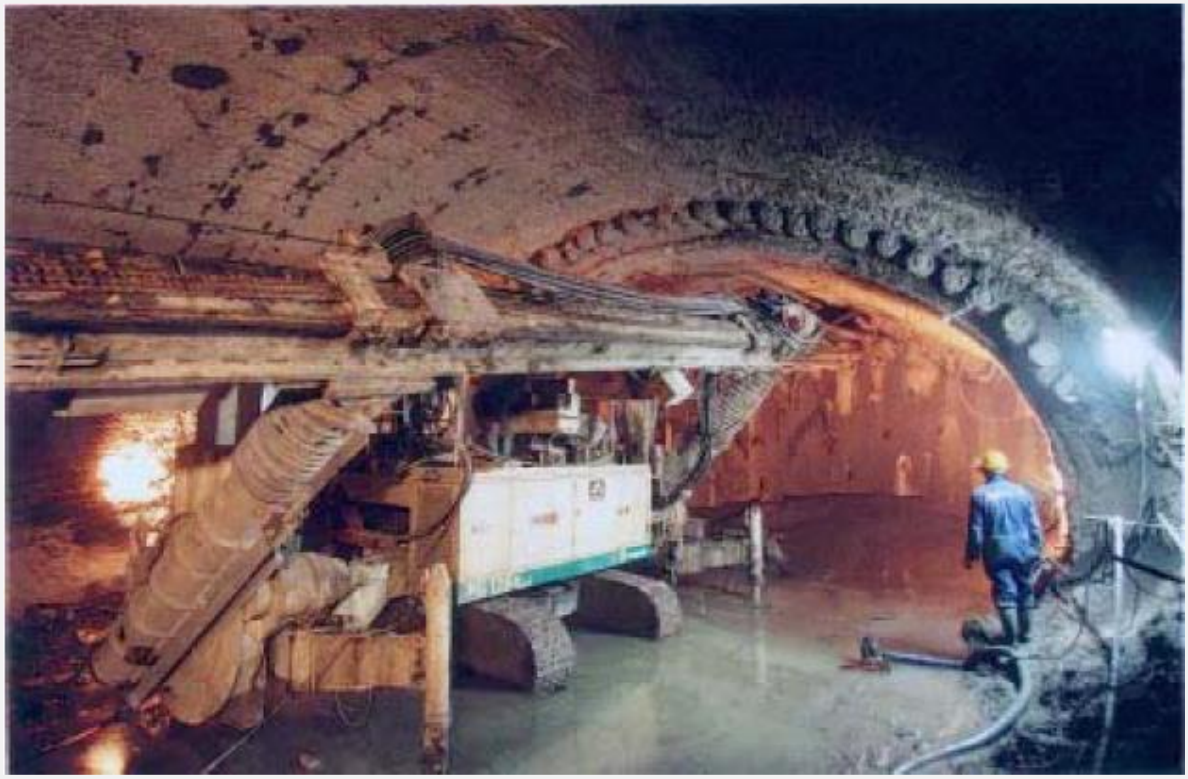
- This method consists of drilling a canopy of steel rods or pipes of 80-200 mm diameter into the face
- The typical length is 4 m
- The surrounding soil is grouted through the steel pipes or sealed with shotcrete, in order to form a protective arch over the excavated space



Forepoling

Spiling

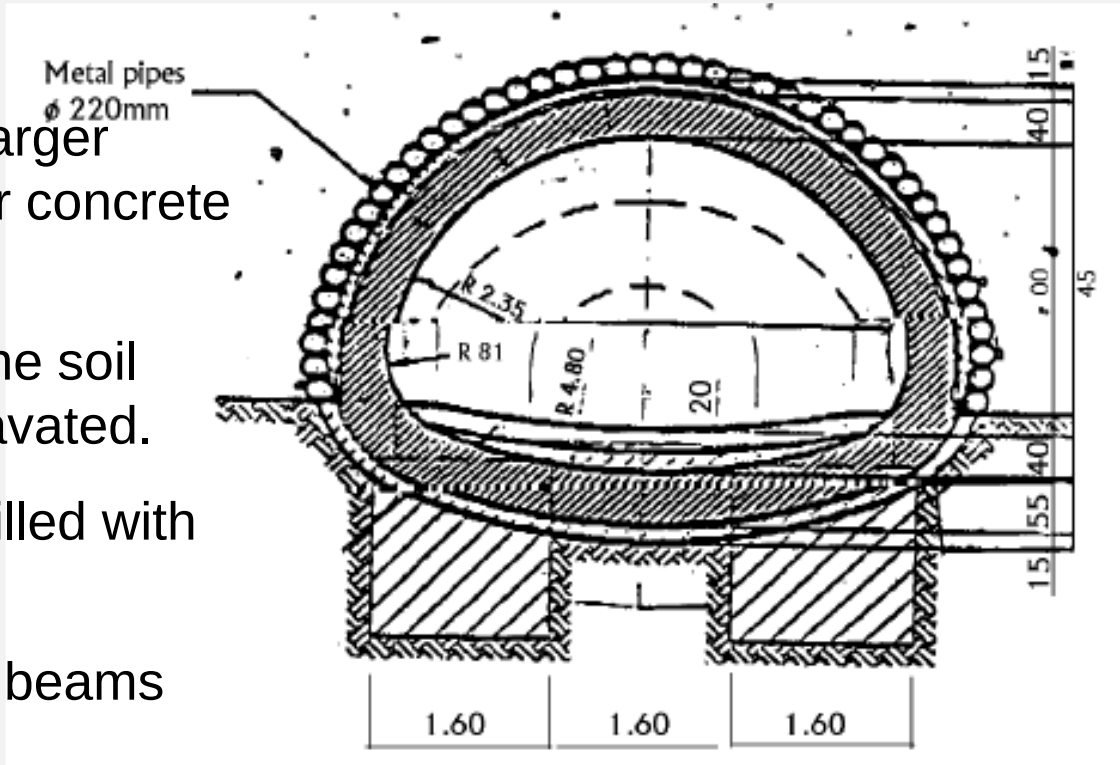




Forepoling

Pipe Roof

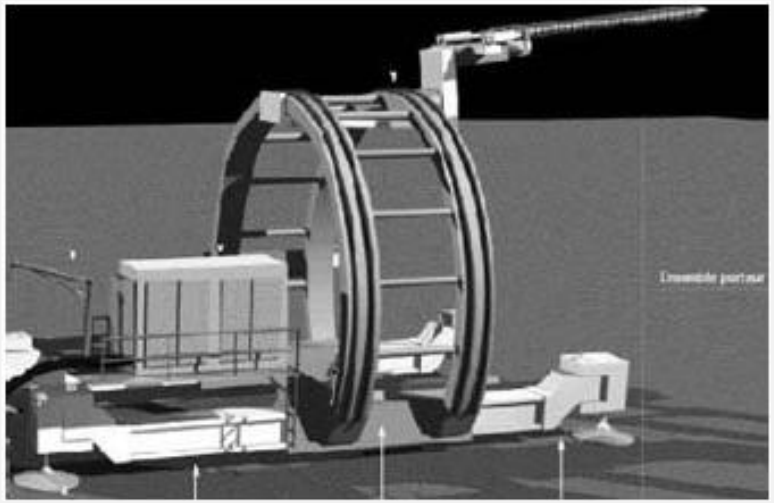
- Similar to spiling, but with larger diameter (>200mm) steel or concrete tubes.
- The tubes are jacked into the soil above the space to be excavated.
- Sometimes, the tubes are filled with concrete
- The steel tubes only act as beams and do not form an arch
- Pipe roofs do not protect the overburden soil from considerable settlements



Forepoling

Pre-sawing

- Also called Perforex-method or Peripheral slot pre-cutting method
- A peripheral slot is cut using a movable chainsaw mounted on a rig
- The individual slots have a depth up to 5 m and a thickness between 19 and 35 cm
- The slots are filled with shotcrete, forming a vault that protects the space to be excavated
- The slots are staggered with an overlapping



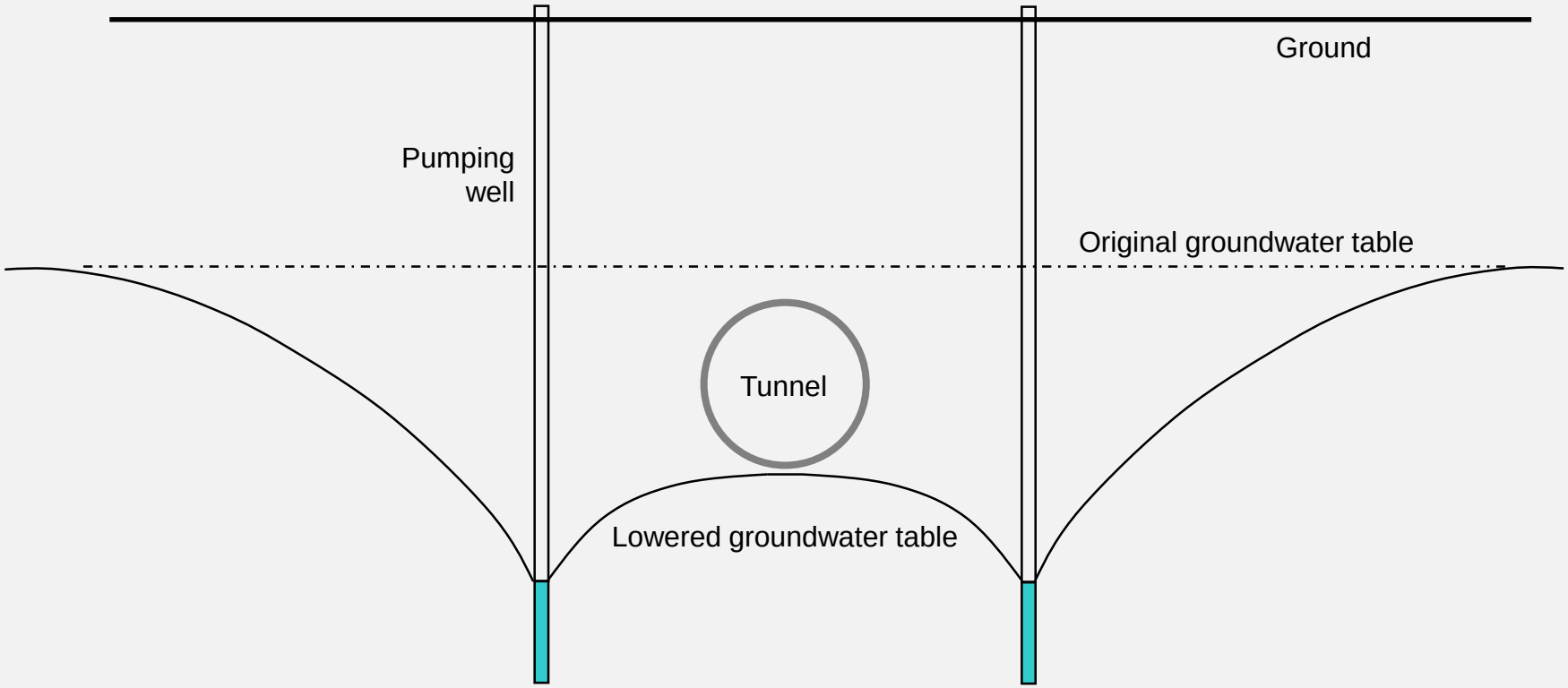
Dewatering

Groundwater in Tunnelling and Dewatering

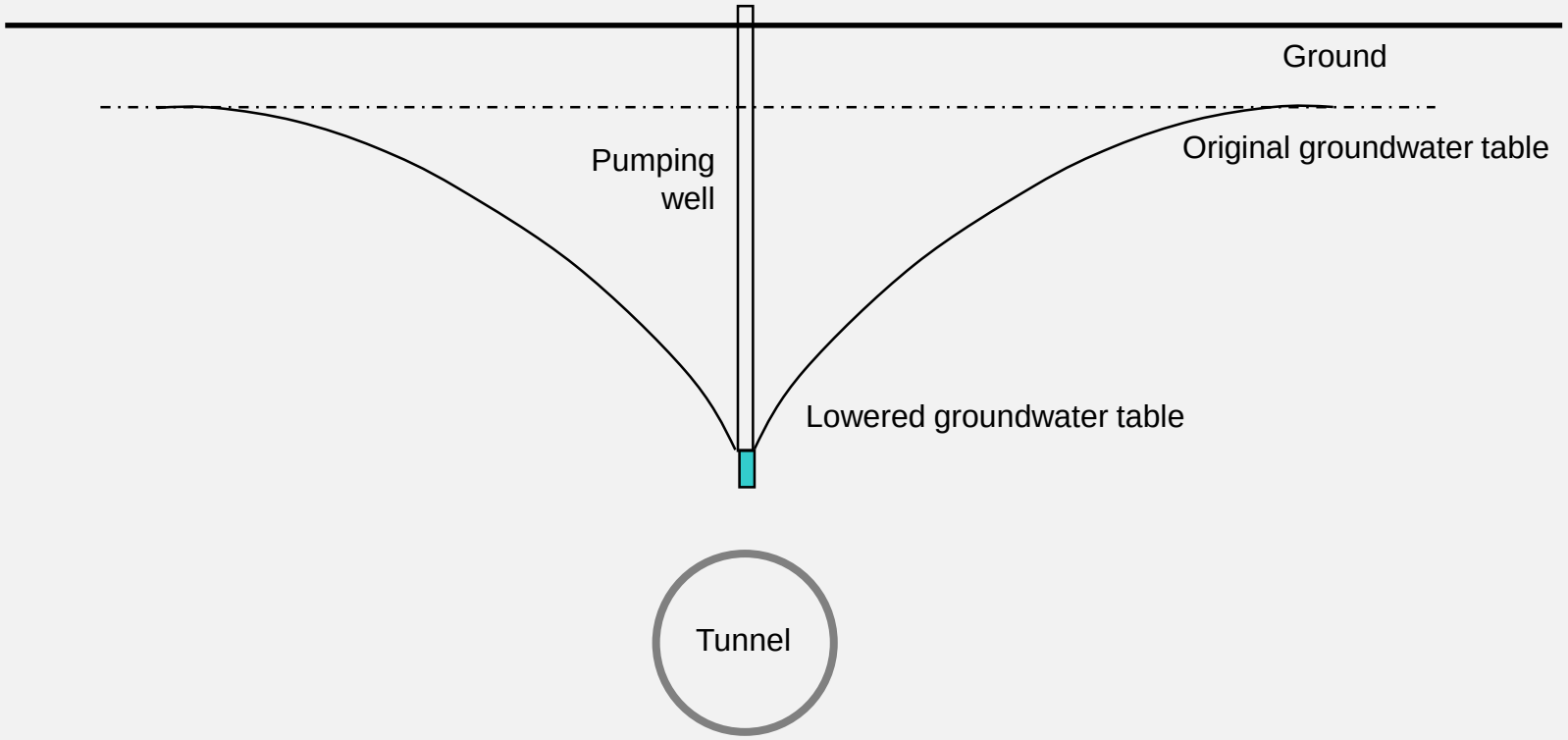
High groundwater pressure, often associated with high water flow usually makes excavation difficult. Dewatering is a technique that takes water away from the ground by:

- Set dry ground condition for excavation
- Lower groundwater pressure in the ground
- Reduce the quantity of water flow at excavation

Dewatering


Ground
Pumping well
Original groundwater table
Tunnel
Lowered groundwater table

Dewatering


Ground
Pumping well
Original groundwater table
Lowered groundwater table
Tunnel

Dewatering

Groundwater Flow to Well

When water is pumped out from a well, the groundwater level nearby in the aquifer is lowered (drawdown).

The greatest drawdown occurs immediately near the well. Drawdown is less at further distances away from the well. At some distance away, the groundwater level remains unchanged.

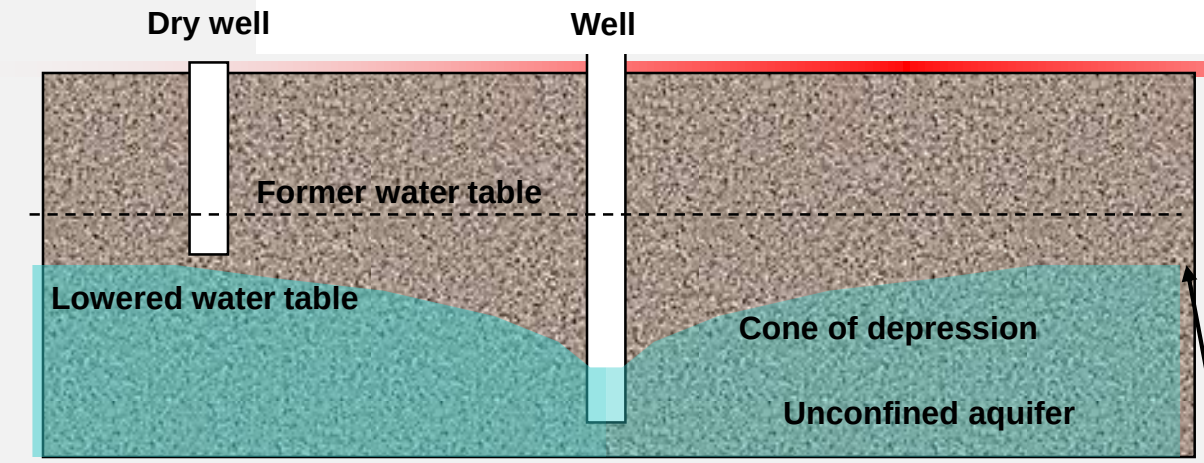
Dewatering

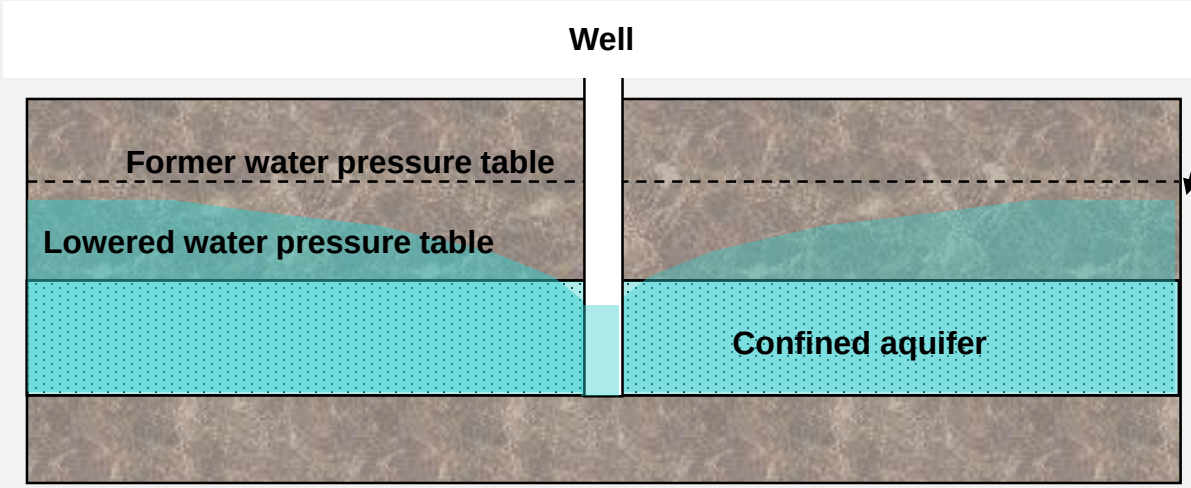
Groundwater Flow to Well

The lower groundwater table forms a cone of depression around the well. Cones of depressions can occur for both unconfined and confined aquifers.

The depth and horizontal extension of the cone of depression depends on the pumping rate and the permeability of the aquifer.

Dewatering





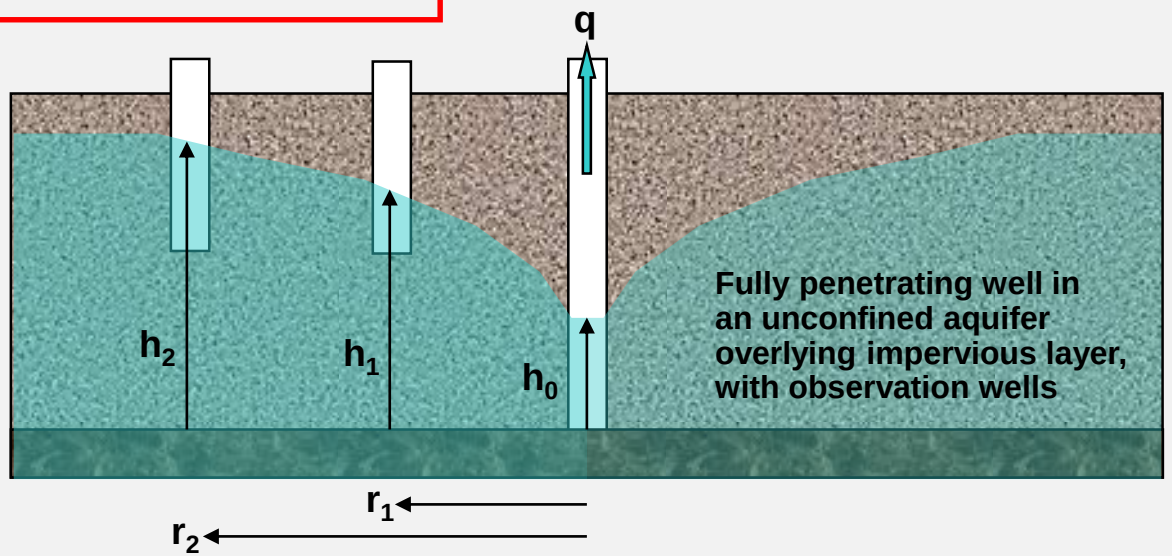
At some distance away, the groundwater level will be at the original level.

Dewatering

Drawdown in Unconfined Aquifer

General equation relating pumping rate (q), permeability (k), drawdown and distance.

$$q = [\pi k (h_2^2 - h_1^2)] / [\ln(r_2/r_1)]$$

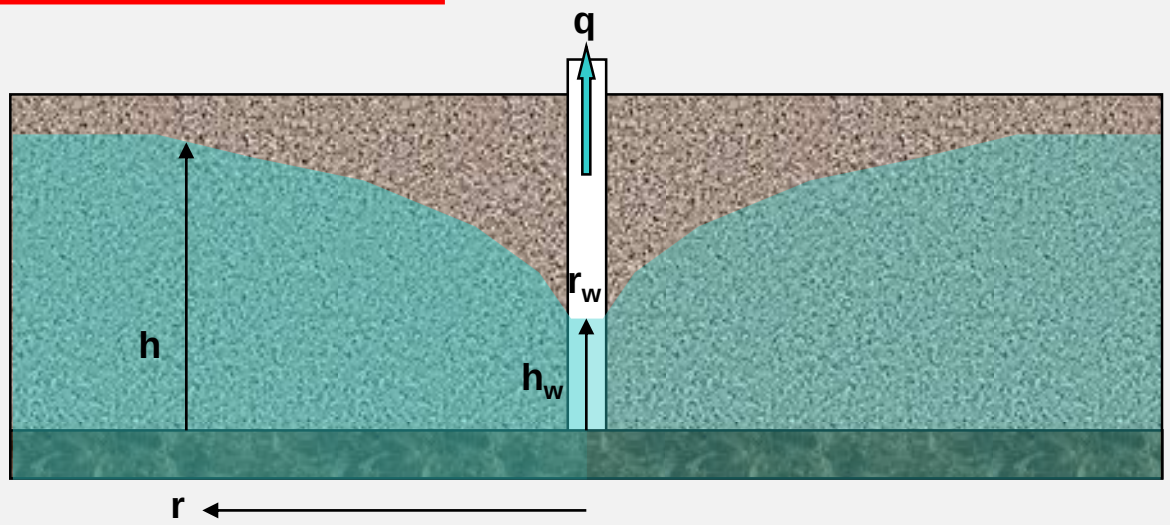


Dewatering

Drawdown in Unconfined Aquifer

Equation to calculate drawdown from q, k, distance (r), and radius of pumping well (r_w).

$$q = [\pi k (h^2 - h_w^2)] / [\ln(r/r_w)]$$

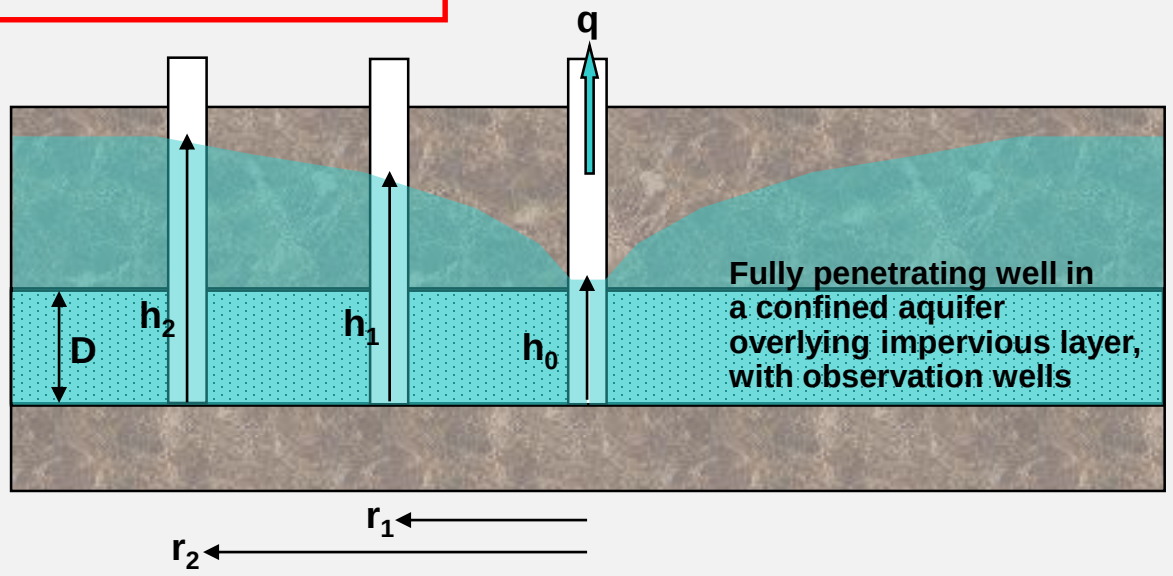


Dewatering

Drawdown in Confined Aquifer

Equation relating pumping rate (q), permeability (k), drawdown, aquifer thickness (D) and distance.

$$q = [2\pi Dk\,(h_2-h_1)]/\,[\ln(r_2/r_1)]$$



Dewatering

Drawdown in Confined Aquifer

Equation to calculate drawdown from q, k, thickness of the confined aquifer (D), distance (r), and radius of pumping well (r_w).

$$q = [2\pi Dk(h-h_w)]/ [\ln(r/r_w)]$$

Dewatering

Example – Tunnel in Weathered Granite

A tunnel of 4.9 m diameter by EPB TBM with roller cutters, at depth up to 50 m, in granite interfacing with residual soil. High groundwater pressure (5 bars) and high permeability.

Recommendation is to operate in 3 bars allowing frequent cutter changes.

Dewatering

Suggestions

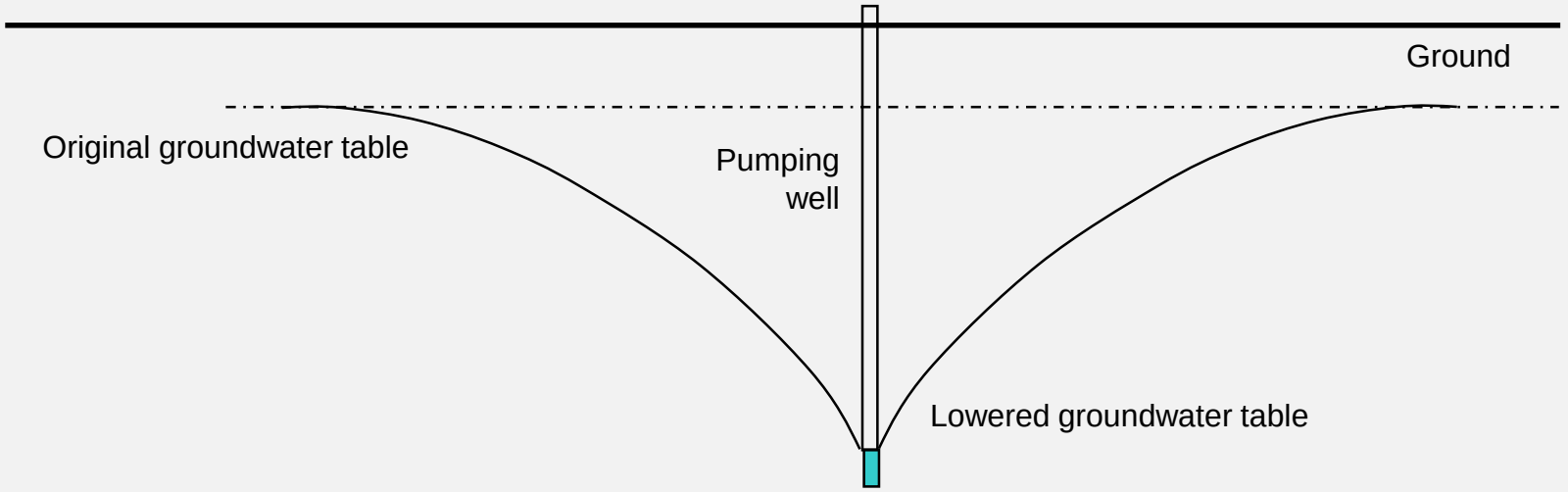
Temporarily lowering down groundwater table to reduce water pressure and water inflow.

Jet grouting in completely weathered granite.

Adopted Solutions

Temporarily lower down of groundwater table at face by dewatering from surface boreholes.

Dewatering


Ground
Original groundwater table
Pumping well
Lowered groundwater table

Tunnel
Groundwater pressure

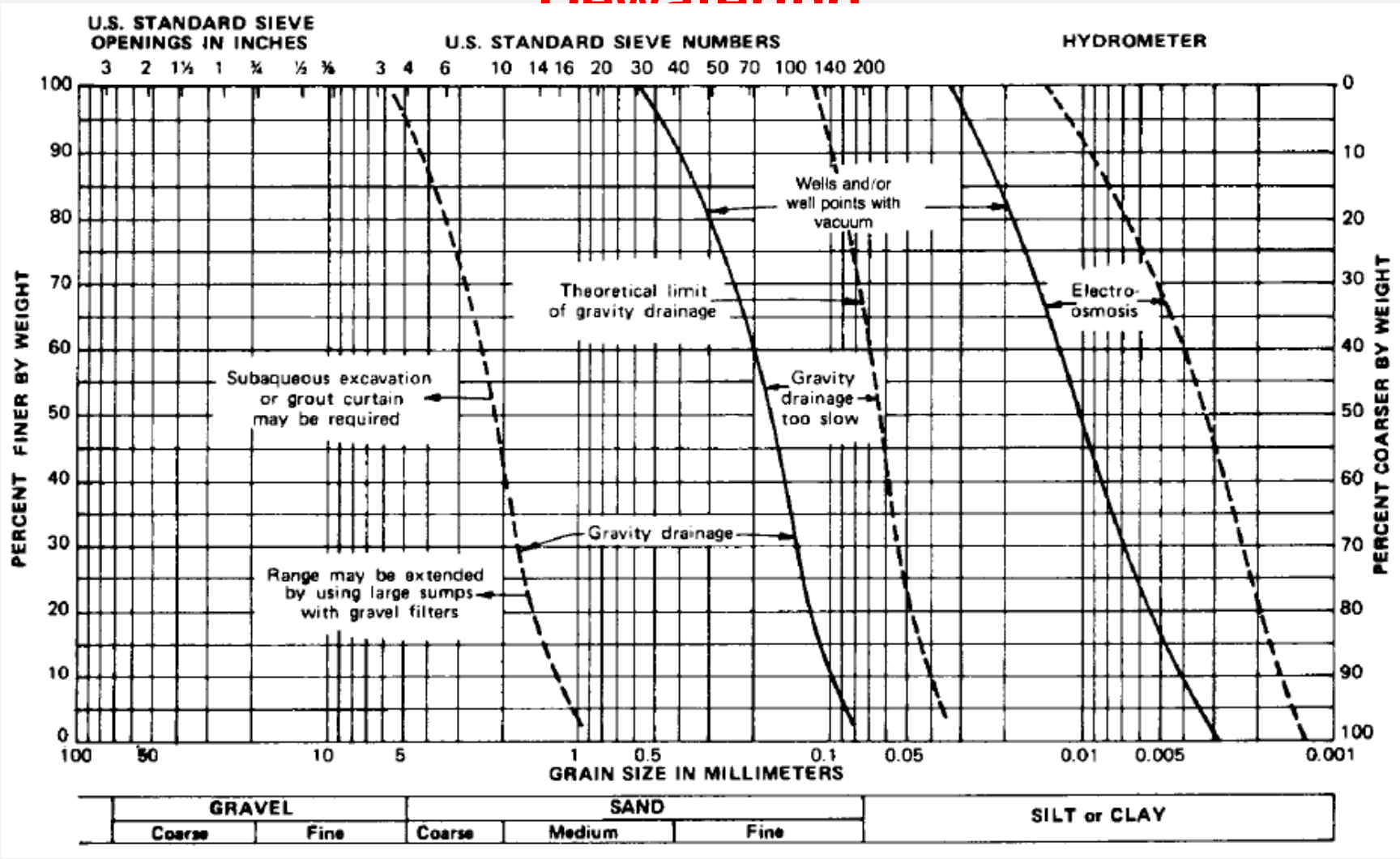
Dewatering

Hydrogeological Consideration

Lowering groundwater pressure in the ground is a function of:

- Permeability of the ground material, more effective in sandy ground with high permeability.
- Well size and depth, govern the area of water inflow.
- Pumping rate and duration, govern total water pumped out.

Dewatering



Applicability of dewatering in various grounds

Dewatering

Geo-environmental Consideration

Lowering of groundwater may have many environmental implications:

- Ground settlement (due to change of effective stress).
- Effects on local hydrogeology setting.
- Effects on vegetations.

Dewatering

Geo-environmental Consideration