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A P P U N T I

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MATERIA: Tunnelling 2 parte - Prof. Peila

4 EPB shield

Nowadays, EPB shields are the most used machines, since they represent the 85 ÷ 90% of the machines working around the world.

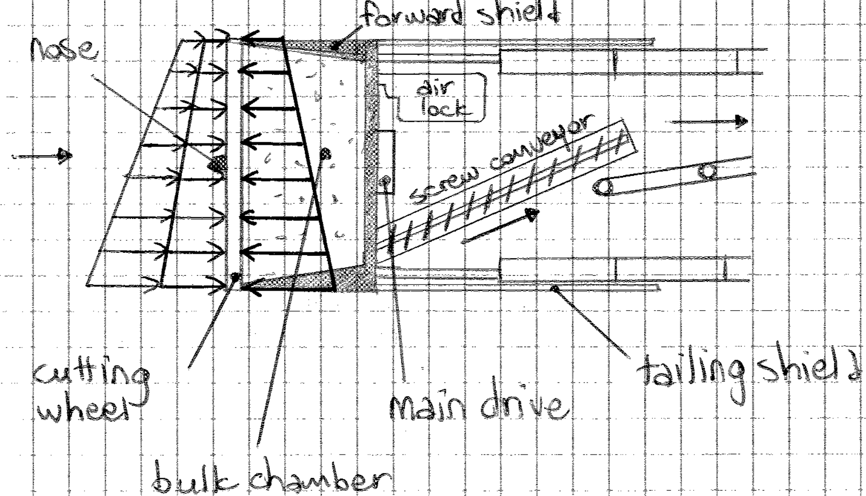
EPB shields were created in Japan in the end of 70s:

they had to make a big project in good clay and, since the slurry is a clay, in order to avoid the realization of the separation plant, they tried to use the ~~same~~ excavated soil itself to create the pressure. As first attempt, they mixed water with the excavated material and they created a mud. Yet, the mud was too much dense and not enough fluid to be pumped, so there was difficulty in the circuit. By consequence, they began to extract the material through a screw conveyor ("coclea"). The solution is cheaper with respect to slurry shield TBM, as it does not require the separation plant.

Then, they tried to apply this technique also in sands, but they discovered that sands are not able to apply a correct pressure and they are not impervious, so they do not create a filter cake able to control water pressure.
In order to apply this technology also to other materials, they changed the properties of the soil, through CONDITIONING, i.e. addition of some chemical products to the material in order to give the new material completely different properties, which are good for excavation (e.g. good to apply pressure, good for extraction, etc.).

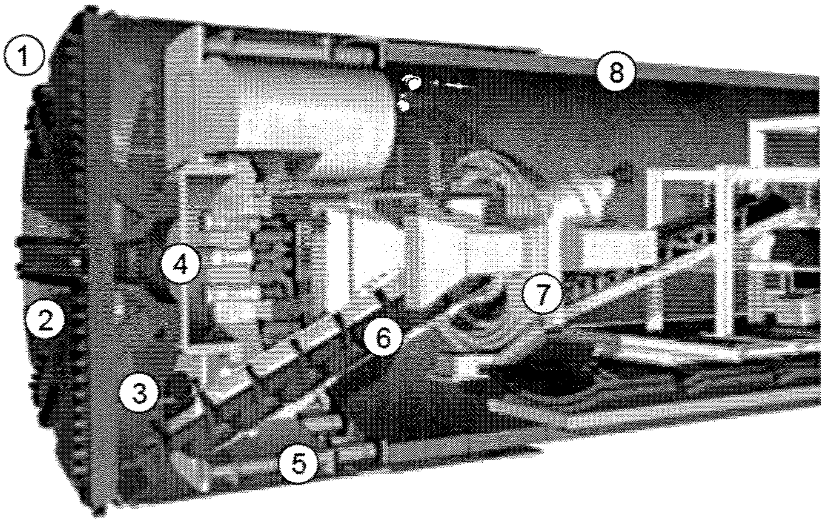
The machine is able to change its behaviour, thanks to the conditioning, and can work in all the possible grain size curves along the tunnel. Then, the machine is light because it requires a simple technology, with just the screw conveyor and not the separation plant.

EPB TBM COMPONENTS



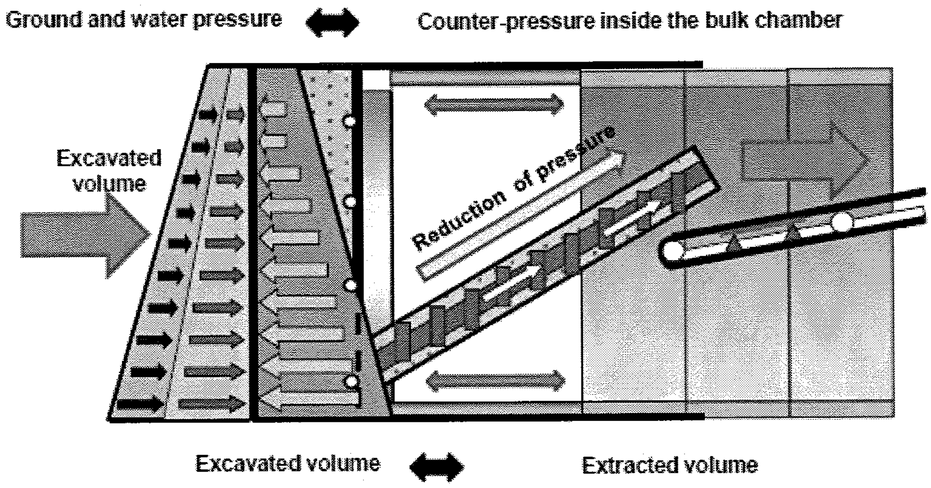
EPB TBM

Scheme of the main components

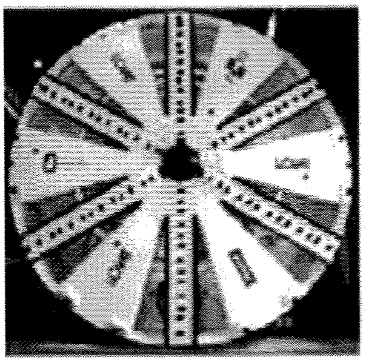


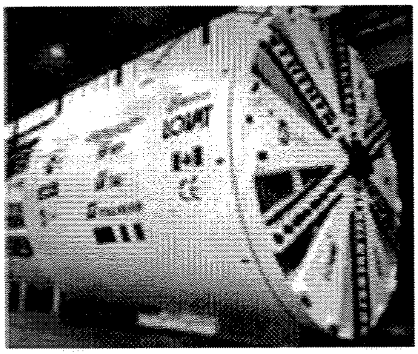
- 1. Tunnel face
- 2. Cutting wheel
- 3. Excavation chamber
- 4. Pressure bulkhead
- 5. Thrust cylinders
- 6. Screw conveyor
- 7. Segment erector
- 8. Segmental Lining

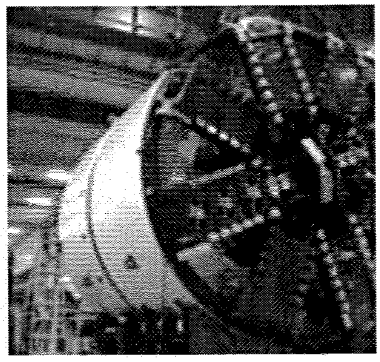
Conceptual scheme of face pressure control

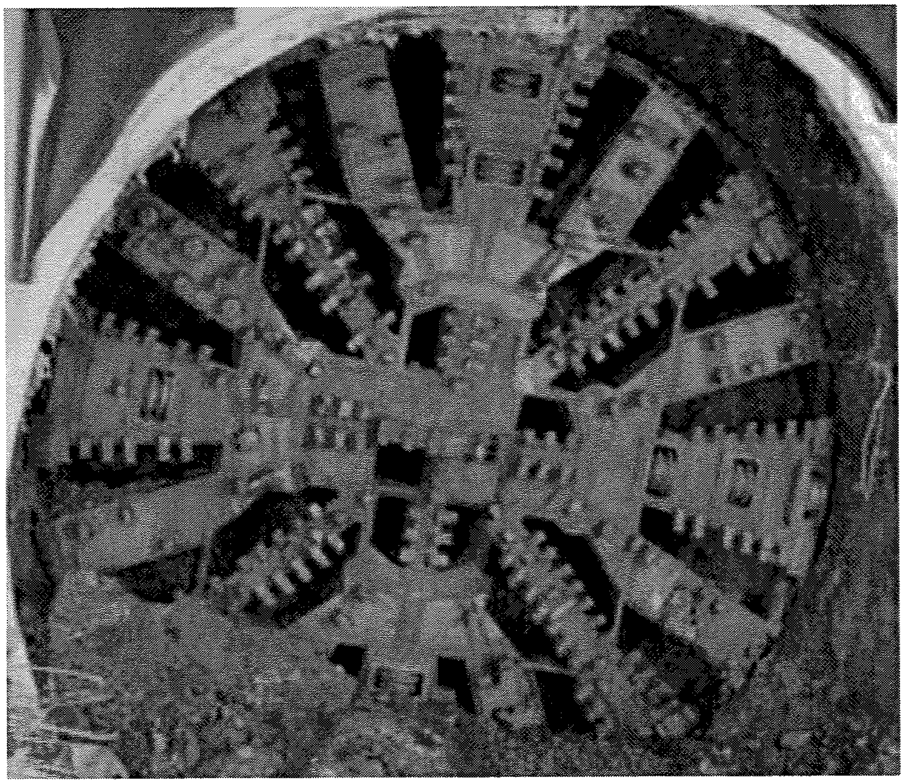


Cutting wheels: typical aspect









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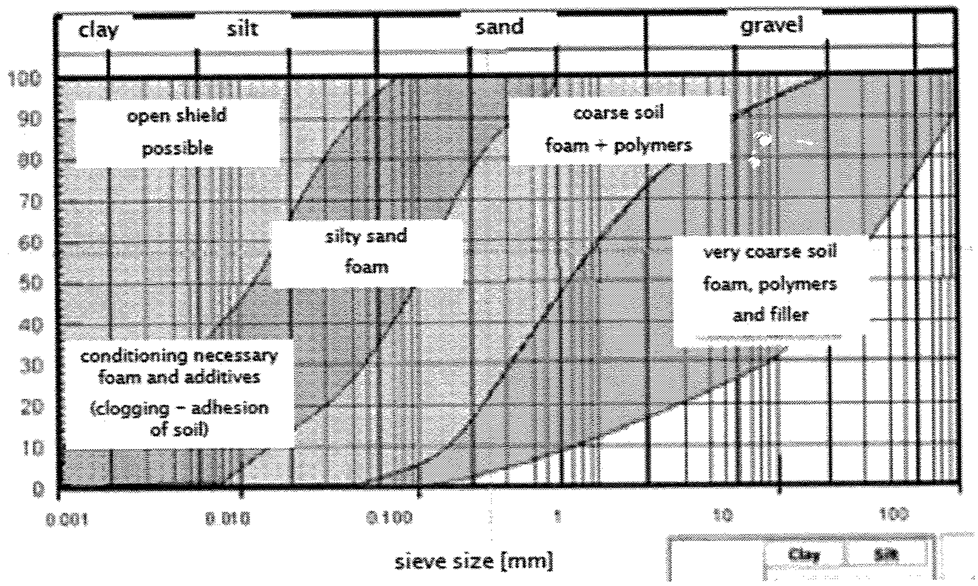
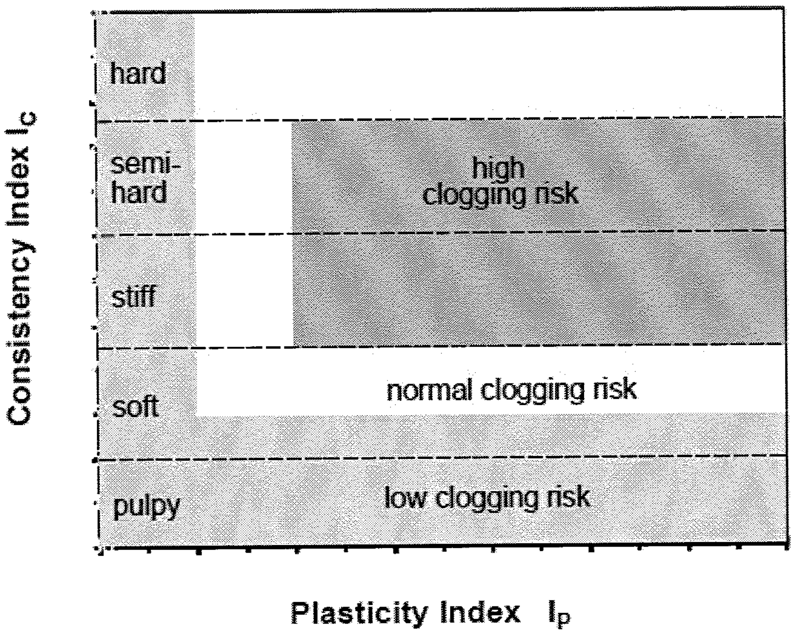
Field of application



Clogging risk



Immediately behind the cutting wheel, there is the main drive ("cuscinetto principale"):

the main drive allows the thrust and the rotation of the cutterhead.
There is a continuous movement of grease from the main drive towards the chamber, in order to avoid the income of soil.
If some soil entered, the drive might get stuck.

Then, there is the bulk chamber - or "plenum" -, which keeps the excavated ground under pressure, in order to provide the face support.
The plenum presents inside some STATORS, i.e. bars used to guarantee a better mixing of the soil, as the material is kept in movement.

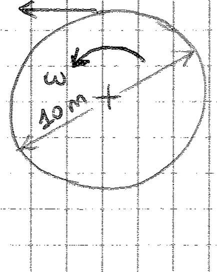
The bulk chamber ("camera in pressione") is completely full of the excavated and conditioned material.
Then, the material is extracted by using a screw conveyor ("coclea"), which presents some welded anti-wear elements to protect the device.
At the beginning, there is a device which can be closed in case of sudden and unforeseen entrance of material inside the bulk chamber, in order to avoid problems.

The screw conveyor should be always completely full because, in close mode, it is not only an extracting medium, but it grants the CONTROL OF PRESSURE and MINIMIZES THE FILTRATION FORCES.
In other words, it acts like a plug ("tappo").
Thus, the control of pressure is not made by pumps and circuits, like in slurry shield TBMs, but through the control of the extraction:

the pressure is controlled by extracting the same volume of the volume excavated by the machine.

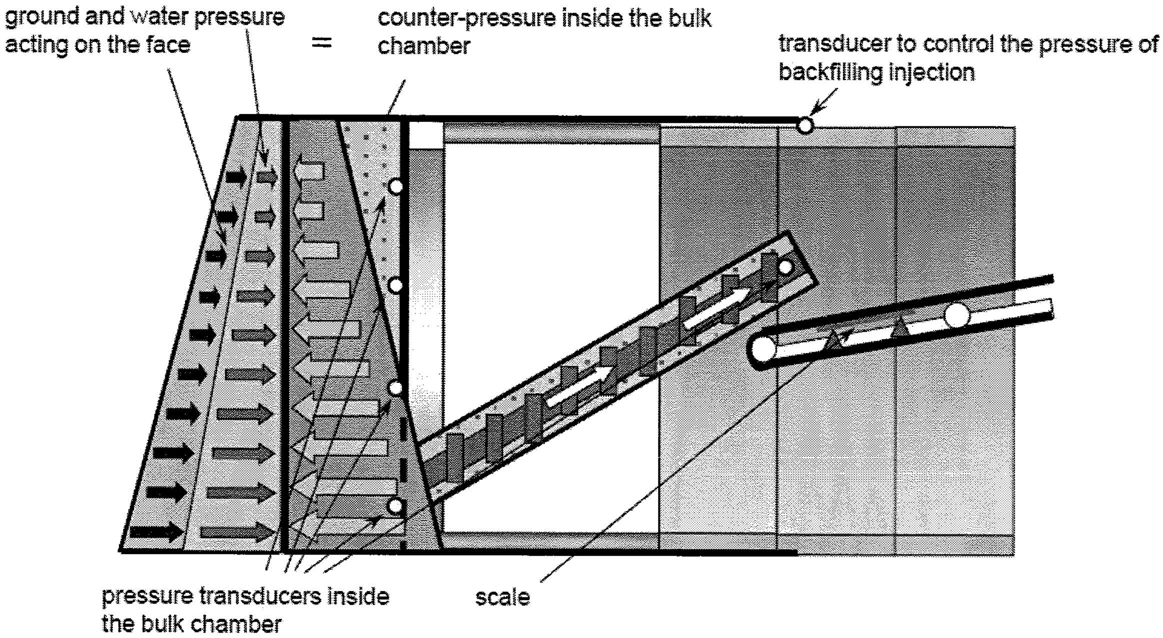
For instance, we may adopt an advancement speed in sand or gravel equal to

$$pen = 1\ cm/round \qquad \omega_{c.h.} = 2 \div 6\ rpm$$



The rotation speed of 6 rpm is used in homogeneous soil without big boulders.
In presence of blocks, if rotation speed is high, the periphƩric tools will be fast and hit against blocks.
This means damages and high tool consumption.
Indeed, rotation speed is linked to the necessity of limiting peripheric speed, especially in big machines.

Sensors


ground and water pressure acting on the face
=
counter-pressure inside the bulk chamber
transducer to control the pressure of backfilling injection
pressure transducers inside the bulk chamber
scale

The bulk chamber is protected by a wall, called forward shield - it is the first part of the shield -, and it is linked to an air lock ("camera iperbarica").

The air lock is a necessary device when we have to change tools in the cutterhead.
Indeed, to perform this operation, we have to lower down the level of material inside the plenum and send workers there.
A lowering of the level corresponds to a lowering of pressure but the face stability is guaranteed by the cutterhead - that's why we tend to closed cutting wheels.
If we are below the water table, in order to avoid water income, we will create an air bubble in pression.

↓ the air bubble is just to prevent water from coming in, not to stabilize soil

Yet, in this way, we force workers to work in hyperbaric conditions and it is a very complex and delicate operation because we need special measures to make the body to accept the variation of pressure.

Behind the chamber, the erector performs the segments installation.
The erector is a vacuum system, typically, which grabs the segments, rotates around an axis and install them.
This is a delicate operation because here we are movimentating a heavy element, i.e. the segment - about 7 tons.

Then the machine is pushed forward by a propulsion thrust, made of jacks pushing against the already installed lining.

The control of the pressure and the volume injected in the backfill injection is fundamental to understand if the machine is working well.
For instance, if we discover that we are injecting a bigger volume than the predicted, it may be due to some over-excavation linked to a bad control of face pressure. If injection is performed at high pressure, it may be due to infiltration.

⇒ if we find a bigger volume, something is wrong.

Of course, we need to check all the data and, for the purpouse, we need sensors.
Sensors are used for monitoring different parameters

→ counter-pressure in the bulk chamber

→ pressure of backfilling injection

In this way, we make clear understanding of the situation.

DESIGN OF AN EPB TBM

In the design, we have to know the soil properties, in terms of

→ geology: grain size distribution, unit weight, resistance parameters, clay mineralogy, Atterberg's limits, quartz content, elastic modulus, etc.

→ hydrogeology: permeability and ground water condition

From these properties, we design several elements

→ shield structure, i.e. shield thickness:

it is modelled as an anular ring embedded in soil, with water load.
Shields assume a standard thickness between 3 cm and 7 cm and are directly computed only in big machines.

→ support pressure at face

→ torque moment:

it depends on the type of the machine and it is proportional to the cube of the diameter.
In this way, the biggest is the machine, the biggest will be

Soil conditioning

1 Soil conditioning:

it is an important operation in order to fulfill all the requirements for a good EPB tunnelling process and to extend the applicability of this technology to a wide range of soils.

The principle of soil conditioning is that the material inside the bulk chamber will change its properties and it should have

→ good plasticity

→ low permeability

→ pulpy consistency

AIMS → reduction of the wear for all the mechanical parts in contact with the soil

→ guarantee better uniformity of the pressure distribution inside the bulk chamber

→ control of the flow of the excavated material, that should go through the cutterhead, enter inside the bulk chamber and be collected by the screw conveyor

→ reduction of the friction forces in the bulk chamber

→ reduction of the permeability, in order to control the water inflow

→ smooth the flow of material along the screw conveyor

→ create the plug in the screw

→ easier spoil handling

→ prevent the stickness of the clay on the mechanical parts

→ avoid that the excavated clay will reconstruct as a mass in the bulk chamber.

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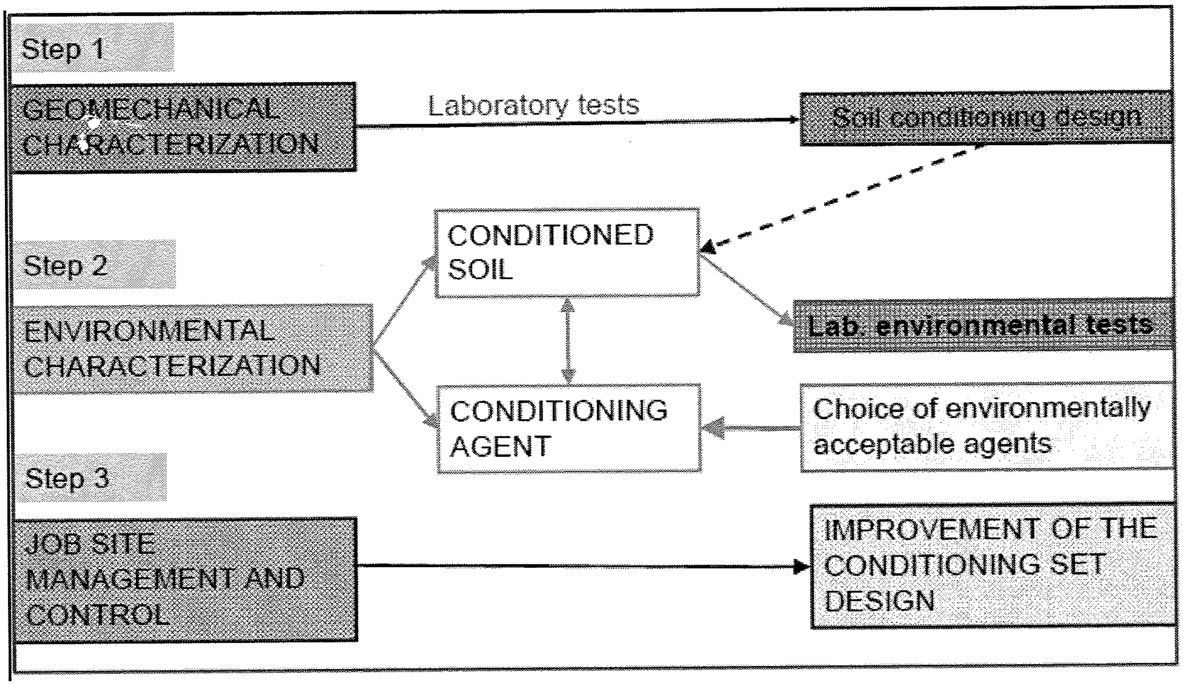
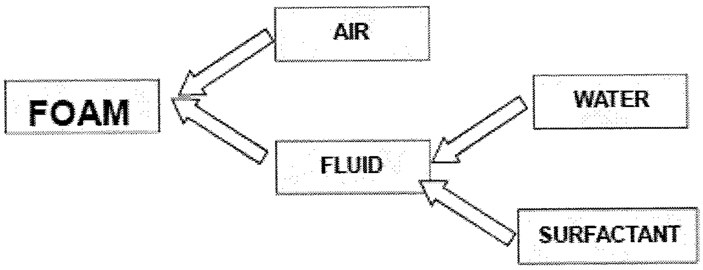
DESIGN PROCEDURE OF SOIL CONDITIONING



FOAM PRODUCTION



There are some design parameters to describe the quality of the foam.

→ Foam Expansion Ratio (FER):

it is the ratio between the volume of foam and the volume of generation fluid (water + surfactant)

$$FER = \frac{V_{foam}}{V_{gen.fluid}}$$

If FER is bigger, the foam will be more dry because there is less water.
The normal range is

$$FER = 8 \div 20$$

and we use $16 \div 20$ (dry foam) in sands, whereas in clay we need more water and we use wet foam.

FER is an index of quality of the foam and should be chosen correctly in function of the type of soil.

→ Foam Injection Ratio (FIR):

it is the ratio between the volume of foam and the volume of excavated material.

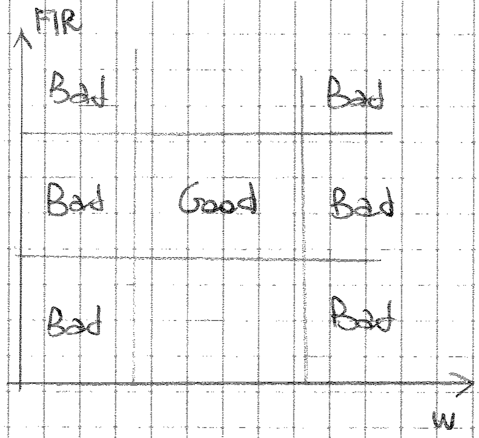
$$FIR = \frac{V_{foam}}{V_{excav.soil}} \cdot 100$$

In easy sands, FIR is about 50% but it is quite a variable parameter, depending on the type of soil.
Due to variability, there are no rule and we have to carry out laboratory test.

→ Foam density

→ Foam half time life (t_{50}):

it is an index measuring the durability of the bubbles at atmospheric pressure and corresponds to the time taken by a given amount of bubbles to release half of its generation fluid.

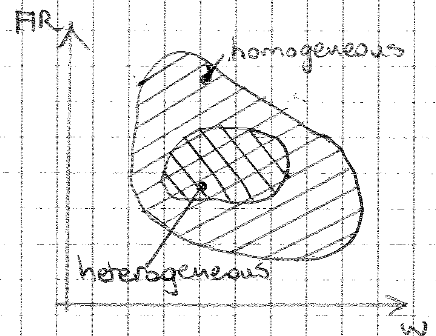


From several laboratory tests, we get a relationship between the FIR and the water content w.
The best situation is in the middle, with an intermediate foam content and an intermediate water content.

The plot is useful to determine how much foam to add to soil.

If water content is too high, we have to add also long chain polymers with the foam.
Normally, a lot of soil gets separated from water; with the polymers, the polymers grab the water and avoid the separation. Polymers give also some CONSISTENCY to the mass, which is good when we work in rock mass.
Yet, even if environment-friendly, polymers have a very slow decay from the environmental point of view. This is a problem because Italian law for material disposal requires some constraints to the material to be considered no more as waste, related to decay speed. Of course, if the material is waste, we will have to consider the cost for the disposal; if not, we can re-use it.

Furthermore, tests on different types of GRAIN SIZE have been carried in order to define the area in the plot FIR-w with reasonable slump.



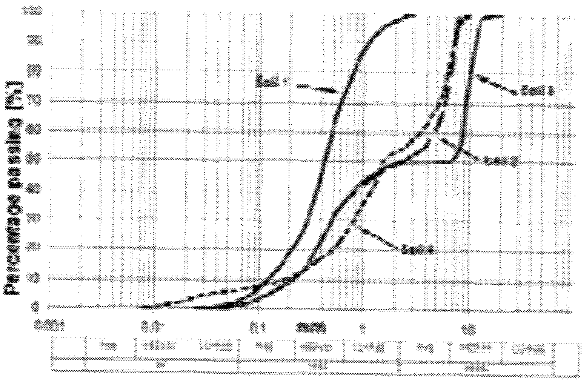
In homogeneous soil, the area where we can get good slump is wider.

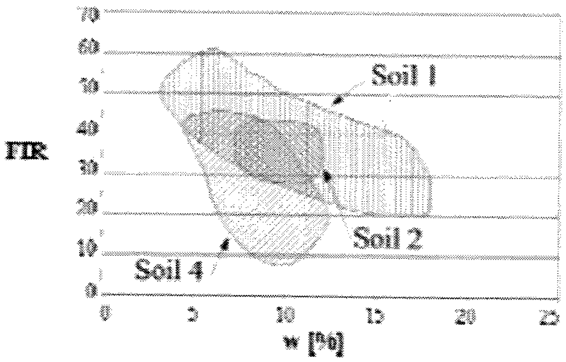
In heterogeneous soil, the area is smaller.

If there is a lot of gravel, conditioning is not possible and we need to add some FILLER (i.e. fines) to change the grain size distribution and make the conditioner to work better.

As a rule of the thumb, we need at least 15% of grains smaller than silt to obtain good conditioning.

Soil assessment: role of grain size



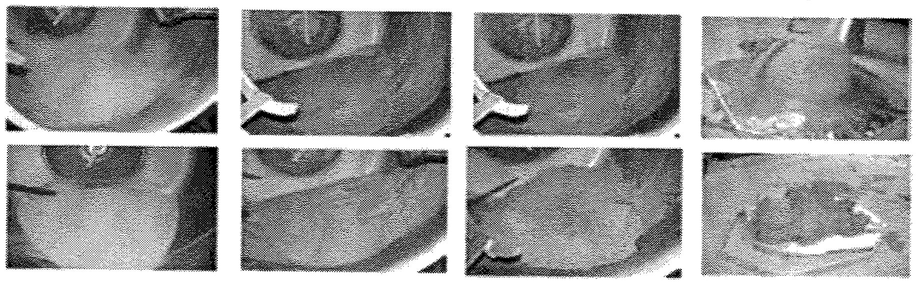


Soil assessment: effect of long chain polymers

10kg dry Material	Saturated Material	Treated Material	Slump

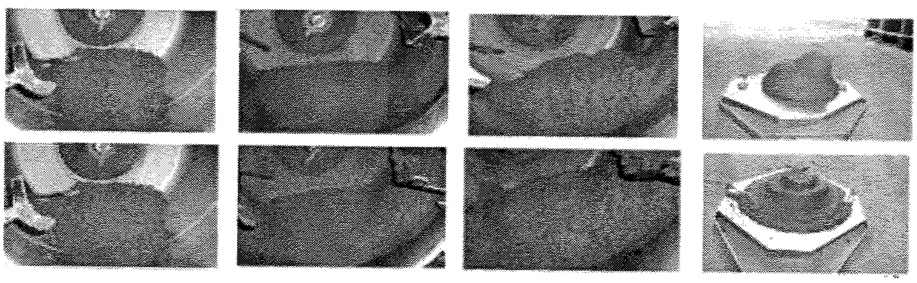
Natural monogranual sand
3 Litres Water
No Polymer Added

Natural monogranual sand
3 Litres Water
60ml Polymer Added



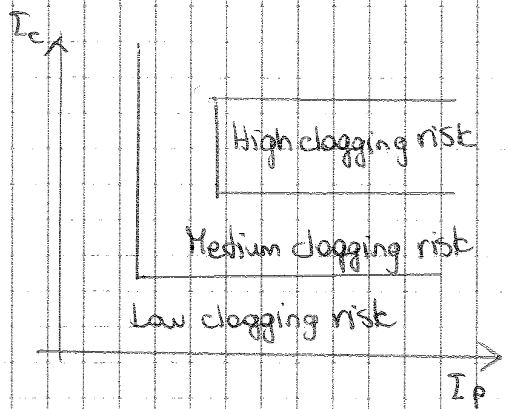
Natural Rome Metro soil
2 Litres Water
120ml Polymer Added

Natural Rome Metro soil
2 Litres Water
100ml Polymer Added



5 Conditioning of clays

The tests are practically the same but we have to take care of a critical aspect, which is stickness ("collosità").
Indeed, the adhesion can lead to the clogging of the screw conveyor or of the bulk chamber, slowering the advance rate of the machine.



Stickness properties can be assessed in the Thewes' plot, which compares

→ plasticity index I_p

$$I_p = LL - PL$$

→ consistency index I_c

$$I_c = \frac{LL - w}{I_p}$$

The plot - now upgraded to a newer version - shows an area where the soil has a high risk of stickness.

Clay conditioning usually requires a lot of water - up to 0,5 m^3 per m^3 excavated -, with foam and anti-adhesion polymer, which reduces stickness properties.
The polymer creates a coating of the clay grains with a lubricating film, thus facilitating the reciprocal sliding of the clay grains between each other and preventing the ri-aggregation of the clay.

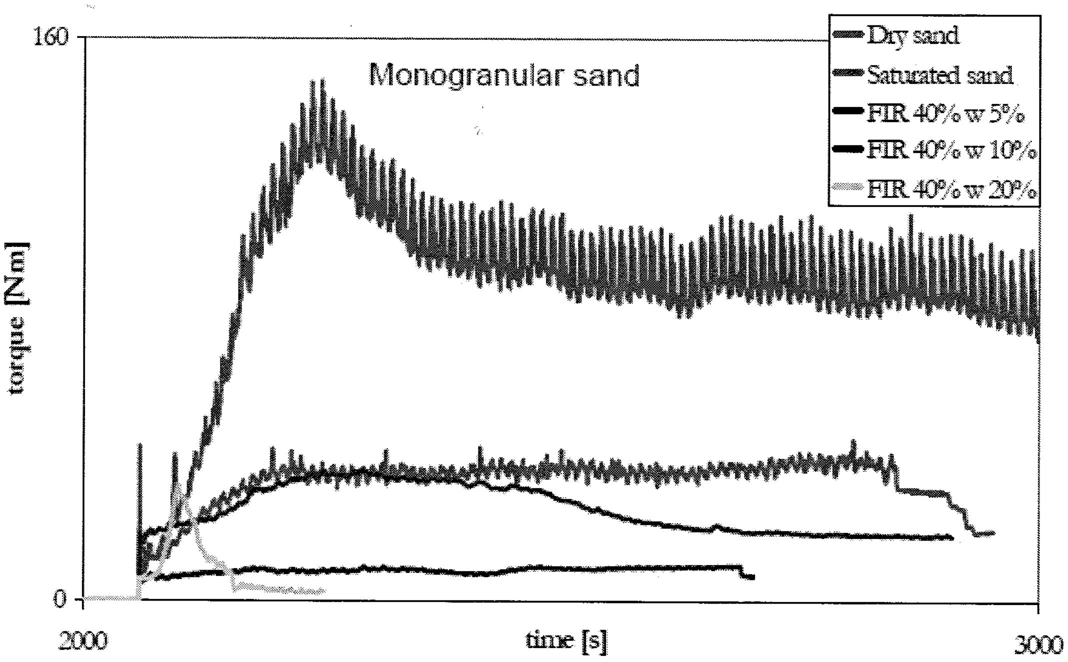
6 Conclusions

Dry granular soil ⇒ Foam

Granular soil with high water content ⇒ Foam + ev. Polymer (dry)

Clays ⇒ Wet foam (FER = 6 ÷ 4) + anti-adhesion polymer

Differences conditioned soil-wet sand: torque



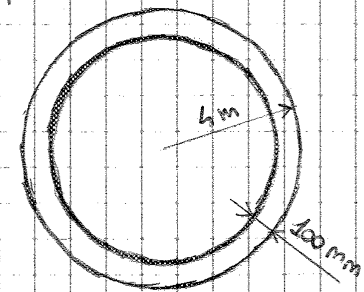
Backfilling

1 Backfilling

Backfilling is the material injected between the soil and the segments of the final lining.

We inject some grout in pressure by using directly the shield and the grout must completely fill the gap.
Originally, the grout was mortar, i.e. a mixture of water and cement, and it was injected with a pressure equal to the face pressure plus 0,5 bar.

The backfilling ~~has~~ is performed with a certain amount of grout, equal to 2,5 m³/m in case of a 8 m diameter tunnel with 100 mm of gap.



The backfilling has different goals.

→ guarantee the contact between the soil and the segments, in order to block them immediately in their position.

→ guarantee that segments will not move due to the back-up load and the waterproofing of the ring

→ minimize settlements

2 FUNDAMENTAL PARAMETERS

→ resistance: the required resistance is not high and is comparable with soil strength.

→ workability:

workability has to be good for long time - up to 72 h - because mortar is normally produced in a batching plant outside the tunnel, ~~and~~ pumped inside through a pipe and stored in tank. If advancement is stopped, durability will help to avoid throwing away the mortar.

→ two component mix:

it is very popular and is a mortar made with two elements.

WATER	CEMENT	BENTONITE	
800 L	300 ÷ 400 kg	30 ÷ 50 kg	in 1 m^3 of mix

+

retarder, added for lavorability and segregation

The mix is mixed in the tailshield with a **triggerer** e.g. silicate, which makes the mix to harden very quickly

→ in about 10 seconds, it gelifies

→ in few hours, the compressive strength is 0,5 MPa

The mix is able to remain good for more than 72 h but it is difficult to reach strength bigger than 4 MPa after 28 days. Actually, it is not necessary to reach high strength, but it is more important have some immediate strength and completely fill the gap.

As regards stability of the two component mix, it is not well known but it has no durability in dry environment, since the mix is mainly composed by water, which evaporate.
In case of 5% of umidity - like underground environment, the mix remains stable because water has not the possibility to escape from the mix and there is no decay.

4 DESIGN OF THE BACKFILLING

In design, we have to define several parameters, like

→ hardening time

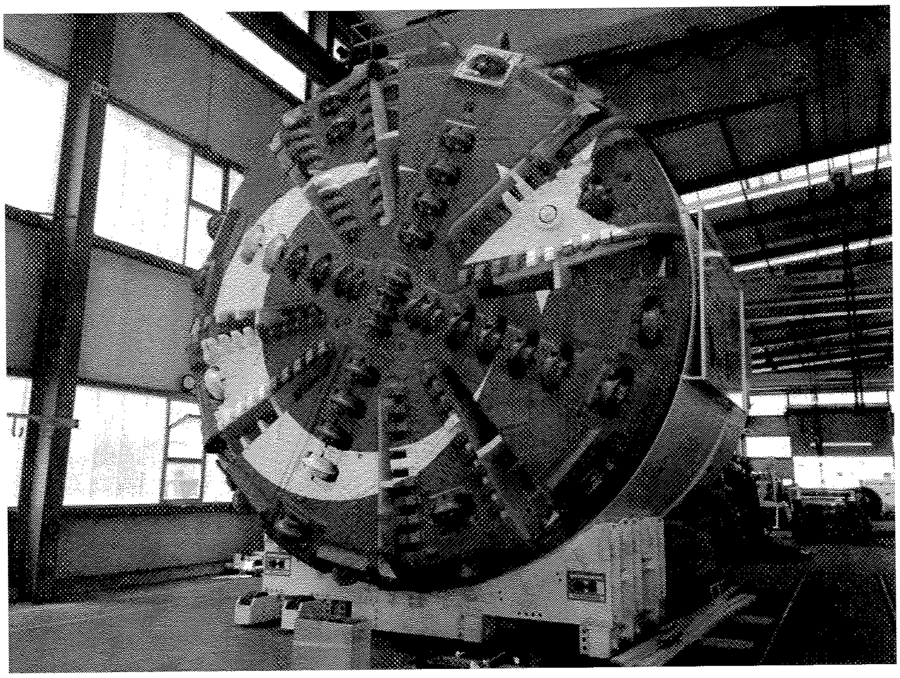
→ minimum hardness, to minimize settlements

→ minimum mechanical resistance

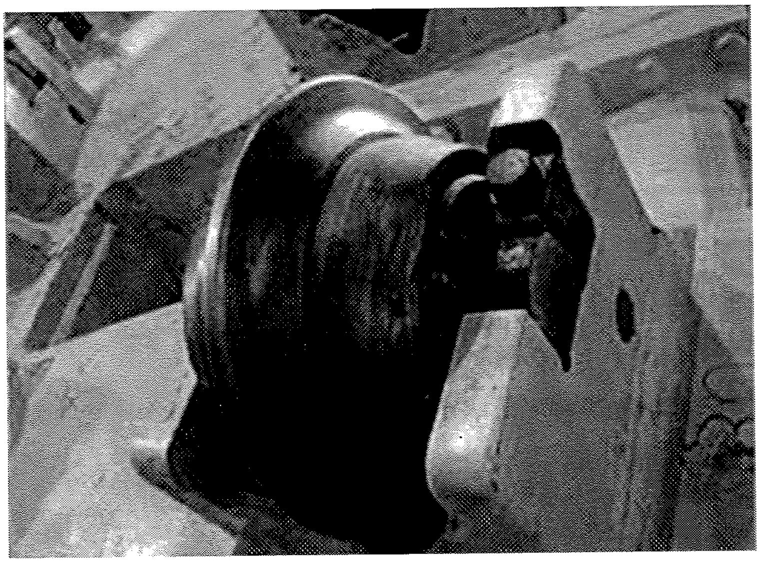
→ type of cement, influenced by the chemistry of water - the mix is in contact with underground water, which is sulphatic, and sulphur attacks cement.

ROCK TOOLS

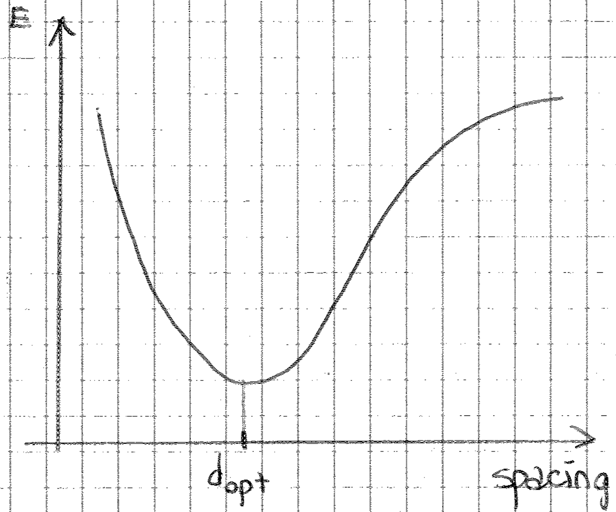
Typical cutter head (rock tools + scrapers)



Rock tool and housing



A Fundamental parameter is the spacing between the tools.



If spacing is small and tools are too close to each other, we are still able to excavate but we use more energy than needed i.e. we have overcrush and lost of energy.

If spacing is too large, we should employ more energy, otherwise we would not have chip formation.

There is an optimum distance, which requires small energy and gives good results.

The optimum spacing is function of many parameters and depends on

→ NATURAL FRAGMENTATION of the rock mass:

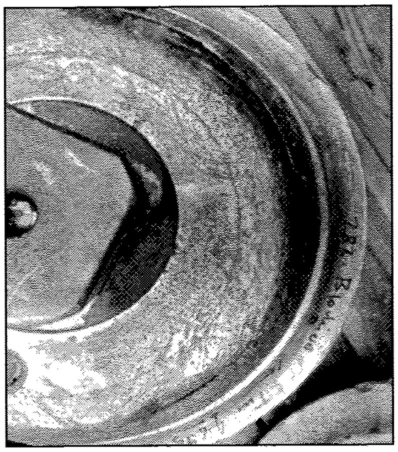
For instance, if foliation is parallel to the excavation front, we will always get chips easily.
If foliation is orthogonal to the face, bigger energy will be required.

→ BRITTLE / DUCTILE BEHAVIOUR:

in brittle material, we can create cracks more easily but we need bigger energy and pressure, due to the bigger strength. On the other side, when we reach the peak, the material explodes.
In ductile material, the pressure applied is smaller and we obtain a crushing area, but cracks are more difficult to propagate.

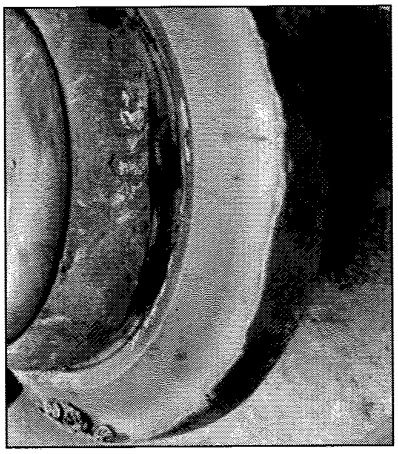
WEAR PATTERNS

Crack, brittle fracture

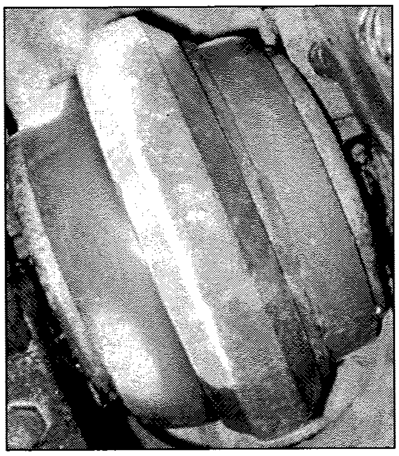


Wear at housing

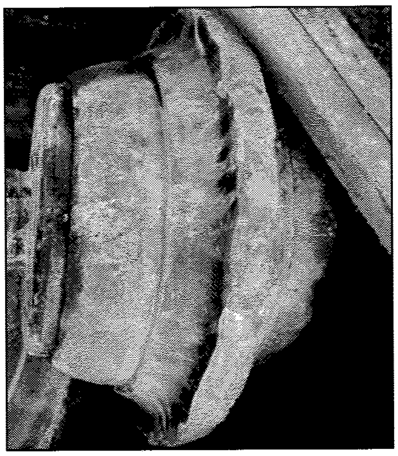
Blocked disc



Mushrooming



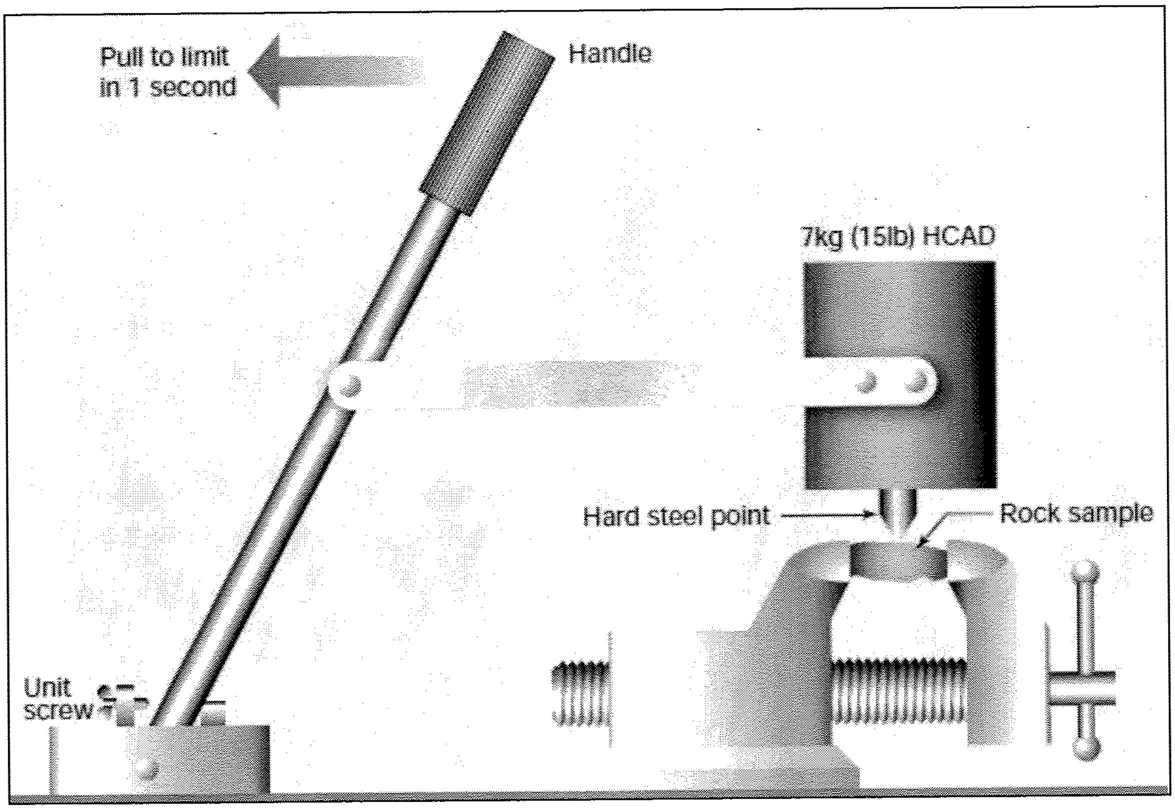
Normal wear



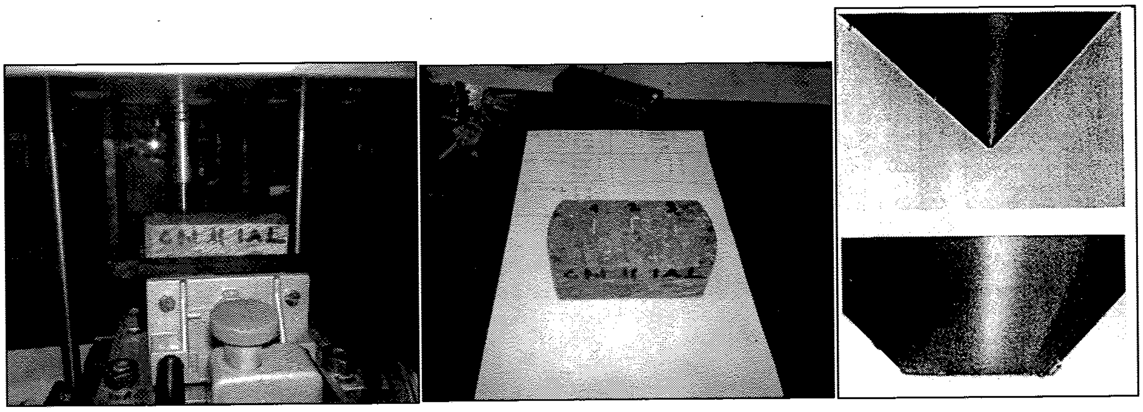
Chipping

CHECHAR ABRASIVITY INDEX (CAI)

Scheme of the test



Sample and tip during and after the test



The test may also be performed with irregular samples, but this will brings a big variation of results.
By consequence, the best is to use smooth samples, which are even easy to be obtained because samples can be very small.

The CAI index is a fundamental parameter to assess the life of one tool.

→ NTNU abrasion test

The test considers the real movements of the tool, in order to reproduce the dynamic failure - failure is not due to a single force destroying the metal.
The test gives different parameters, depending on the tool used.

→ abrasion value AV, in case of tungsten carbide cutter on rock

→ abrasion value AVS, in case of steel cutter on rock

→ abrasion value SAT, in case of steel cutter on soil

These indices represent the time dependent abrasion of the tool caused by crushed rock powder or soil.

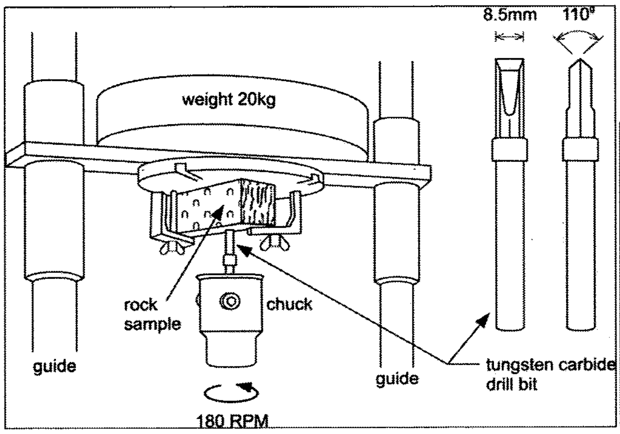
The test is performed on a rotating steel plate, where rotation speed is depending on the type of parameter we are looking for.
The sample is represented by rock or soil put in a jaw crusher, which reduces the particle size under 1 mm. Then, the material is put on a vibrating feeder which feeds the material in the plate, with a flow rate of 80 g/min.
In this way, the surface of the plate is constantly covered by material and, finally, the material is taken away by a suction device at the end of the plate.

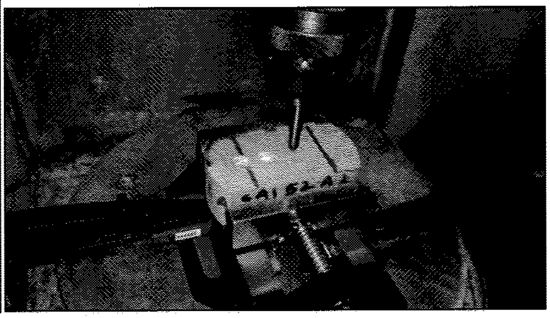
The tip is pressed against the plate and the material with a weight of 10 kg.

In this way, the test is able to reproduce the real behaviour of the tool - dynamic conditions.
Actually, the material is just like powder and the test does not reproduce rock mass continuity.

The abrasion value is given by the <u>weight loss of the cutter</u>.

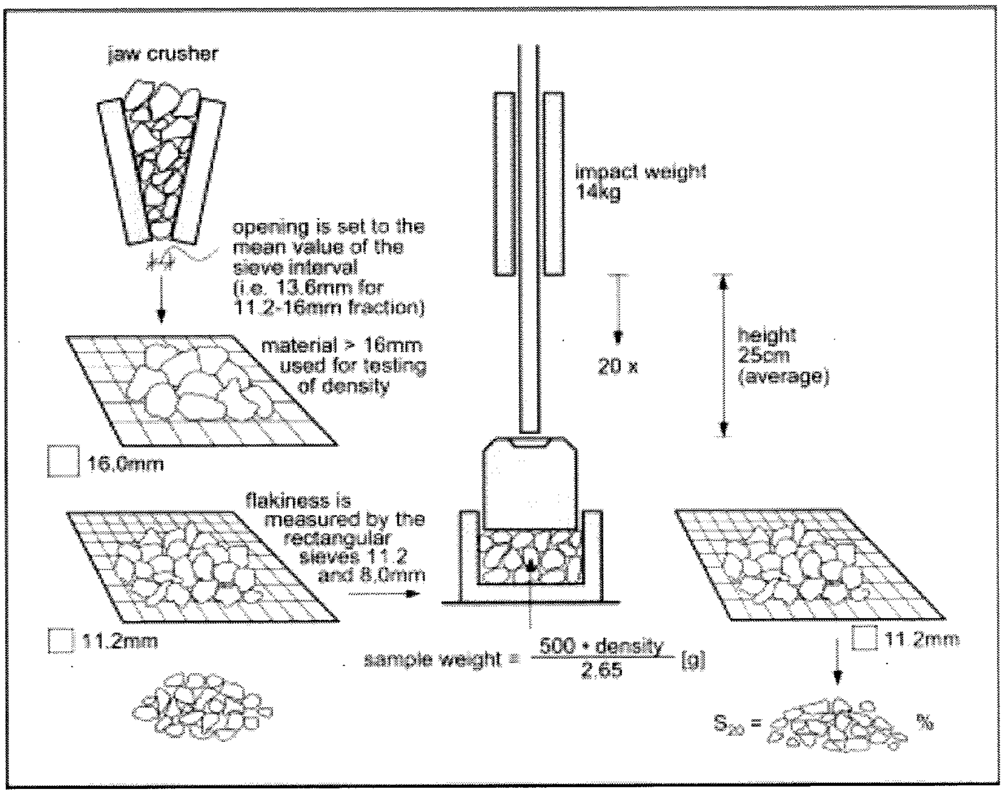
SIEVERS' MINIATURE DRILL TEST





BRITTLENESS TEST

Scheme of the test



The impacts reduce the size of the material.
Then, the material is put again on sieve and we have new some passing part.

The Brittleness Value S_{20} is equal to the percentage of the material passing the 11,2 mm mesh after the aggregate has been crushed.

$$S_{20} = \% P_{after\ crushing}$$

The test is not exactly perfect and needs to be repeated 3 ÷ 5 times.

→ NCB cone indenter test

It is a statical test, taken from metal industry.

The test evaluates rock hardness from measuring the resistance to indentation by a tungsten - carbide cone.

The device presents a thin steel strip to which a cone is applied.
The cone is subjected to certain weight and is connected to a ~~st~~gauge ("micrometro") to measure indentation.
The plate is thin in order ~~to~~ not to have too much resistance and to bend properly and, if there is not the sample, the plate will bend and the cone will lower down with the same displacement, as in the metal-metal contact there is no penetration.
If the sample is placed in the middle, part of the displacement is taken by the sample itself and the difference corresponds to the indentation.

These tests are useful to assess the performance of the excavation and each one gives different indication for different models of performance prediction.

From the results, we derive some drillability indices

→ drilling rate index (DRI), depending on Siever's test and brittleness value.

$$DRI = f(S_{20}; S_J)$$

→ bit wear index (BWI), depending on DRI and abrasion value AV;

$$BWI = f(DRI; AV)$$

→ cutter life index (CLI), very important.

$$CLI = f(S_J; AUS)$$

ABRASIVENESS AND DRILLABILITY

CORRELATIONS BETWEEN LABORATORY TEST RESULTS AND MECHANICAL ROCK PARAMETERS

Following the determination of the abrasiveness parameters, the next step is their understanding in order to reach a more global view of the rock mass conditions and then evaluate the effect of abrasiveness.

CERCHAR ABRASIVITY INDEX

The Cerchar test is a very quick and simple testing method for rock abrasivity classification.
Yet, some technical factors have a reasonable impact on the results of the Cerchar scretch test.
As consequence, in order to obtain good and comparable results, there are some recommendations for the procedure.

- Use testing pins with standard materials properties.
- Assess the flat area to evaluate the pin wear flat diameter.

Test results can be compared with standard CAI values determined on broken surfaces by using an empirical correction equation.
The comparison with "standard" rock parameters gives rise to supposition that the abrasiveness index CAI is mainly influenced by two factors.

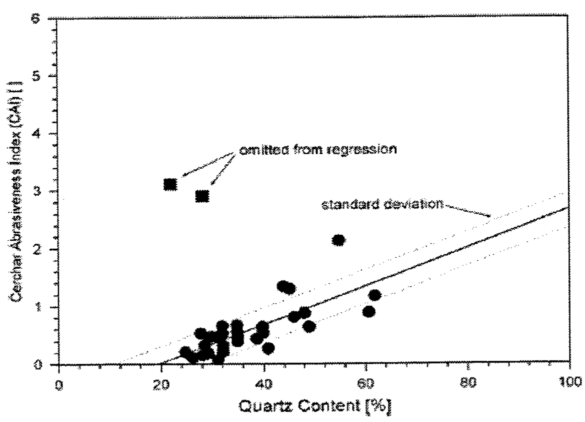
- *Rock deformability.*
- *Content of abrasive minerals*, especially quartz.

The typical range is the following.

$$CAI = 0{,}3 \div 5{,}6$$

Several studies give the correlations between the abrasiveness index CAI and other wear parameters.

- Correlation CAI – quartz content.
  West proposed the quartz content being the main geomechanical parameter influencing the CAI value. Actually, quartz content is also affecting the deformability modulus of the rock mass and so the link between the two parameters is not so much direct.



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NCB CONE INDENTER TEST

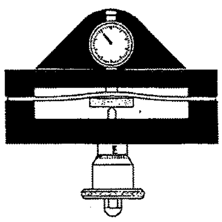
The NCB Cone Indenter Test is a handy and cheap test, where we perform just a penetration and an indentation.
The test does not require the preparation of accurately shaped specimens, as it consist just of a penetration and it determines rock hardness, by measuring its resistance to indentation by a hardened tungsten carbide cone.

The cone indenter hardness value is obtained by dividing the force, i.e. spring deflection D, necessary to cause penetration of the specimen by the amount of penetration P that has occurred.

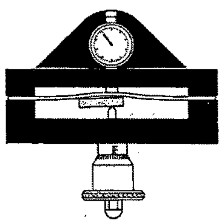
$$I = \frac{D}{P}$$

The cone indenter has so far been found suitable for all rocks with a grain size of less than 0,05 mm, the limit at which grains just become visible to the naked eye. Otherwise, penetration might occur inside a grain and not in rock mass.
It is possible to use the indenter to test coarser-grained rocks, but the indentation should be between grains rather than one them; if the reading are made on a quartz grain, the standard cone indenter number will be between 8 and 12.
Furthermore, the micrometer must be screwed slowly clockwise until the spring deflection, as indicated by the dial gauge, is equivalent to a load of 40 N – this should be 0,635 mm approximately.
Finally, in case of large specimen, it is also necessary to control the position of the sample within the test apparatus. If the specimen is loaded in the middle, it will cause excessive deflection of the plate and the gauge will not give the correct indication. By consequence, we have to load the sample close to the edge.
The best solution would be to use a small sample, if possible.

Not recommended
(loading in the middle)



Recommended
(loading near the edge)



Even if the test is simple, the accuracy of the cone indenter may be verified by using it on a suitable material of known strength.

The values obtained using the cone indenter have a strong correlation with the uniaxial compressive strength of similar rocks UCS.

$$UCS\ [MPa] = 24{,}8I \pm 13{,}8$$

Table 1. AVS classification for rocks based on the NTNU/SINTEF database of 1590 rock samples

Category	% of Total	AVS
Extremely low	5	<1
Very low	10	2–3
Low	20	4–2
Medium	30	13–25
High	20	26–35
Very high	10	36–44
Extremely high	5	>44

Table 2. AVS values for some sedimentary rocks and quartzite tested at NTNU/SINTEF

Rock Type	Number of Samples	AVS
Limestone	17	0.2–1.4
Shale	17	0.4–10
Siltstone	4	0.4–44
Sandstone	36	0.4–52
Quartzite	20	17–63

Based on rock testing, the content of quartz and other hard minerals like garnet and epidote have a major impact on the abrasion on the test pieces, but grain shape and grain binding may also contribute substantially.
The test results, however, provide a good basis for comparing the abrasiveness of the respective soils, and by comparing the results with those for rock, useful indications of relative abrasiveness may be obtained.

SIEVERS' MINIATURE DRILL TEST

The Sievers' drill test gives a measure for the surface hardness (or the resistance to indention) of the rock, by performing different tests in a single sample.

The Sievers' J-value S_J is the mean value drill hole depth after 200 revolutions, measured in 1/10 mm, from 4 to 8 holes.
The S_J value measured parallel to the foliation is use to find the Drilling Rate Index DRI; if the S_J value for drilling perpendicular to the foliation differs from the value for drilling parallel to the foliation, the drilling rate will most likely vary with direction to the foliation.

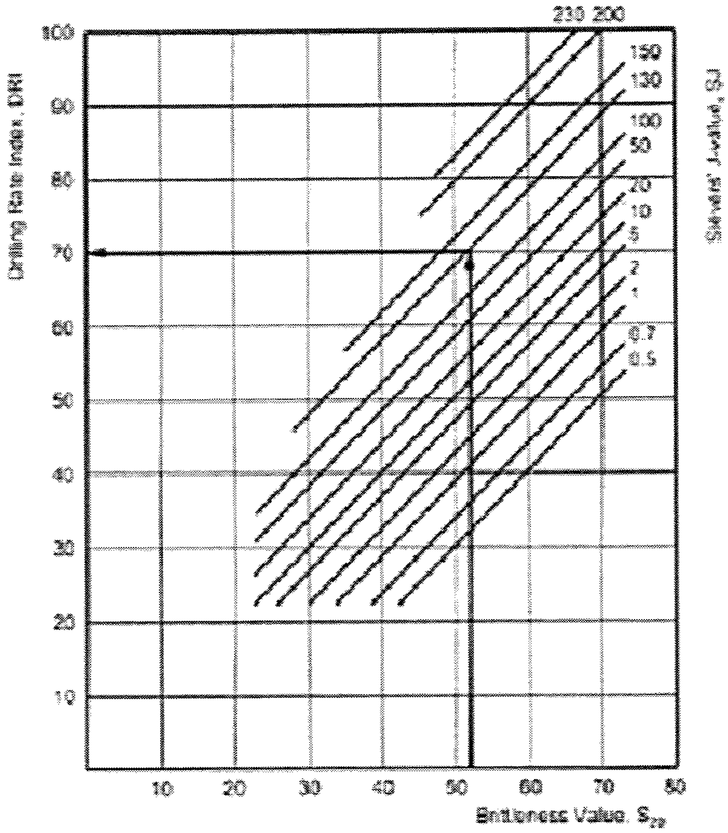
This parameter helps us to notice a significant difference in the surface hardness between a quartzite sample, where there is no penetration, and limestone sample.

CALCULATION OF THE DRILLABILITY INDICES

Drillability indices are used in the performance models of excavations.

DRILLING RATE INDEX

The Drilling Rate Index DRI is calculated from the Brittleness value S_{20} and the Sievers' J-value S_J, by using a plot.
In the plot, we enter with a certain Brittleness value S_{20}, we intercept a curve corresponding to the known Sievers' J-value S_J and we read the Drilling Rate Index DRI on y axis.



Depending on the Drilling Rate Index, we have some classification categories of rock mass, ranging from 0 to 100. Actually, the extremities are very hard to be reached.

Category	DRI
Extremely low	≤ 25
Very low	26 -32
Low	33 - 42
Medium	43 - 57
High	58 - 69
Very high	70 - 82
Extremely high	≥ 93

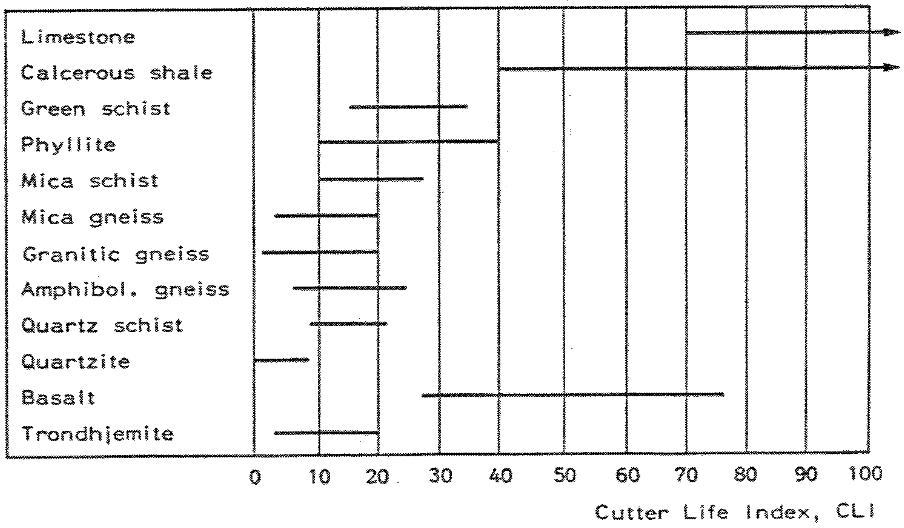
In addition, we can identify a correlation between the Drilling Rate Index DRI and the uniaxial compressive strength of rock UCS, for different kinds of rock mass.

CUTTER LIFE INDEX

The Cutter Life Index CLI is an important parameter in TBM excavation and expresses life in boring hours for cutter rings of steel on tunnel boring machine.
It is calculated on basis of Sievers' J-valueS_J and the Abrasion Value Steel AVS.

$$CLI = 13{,}84\left(\frac{S_J}{AVS}\right)^{0{,}3847}$$

Each rock type has a range of variation of Cutter Life Index, referred to bored tunnels in Norway.



RELATION BETWEEN THE DRILLABILITY INDICES

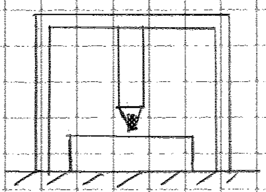
On the background of the original classification done by Lyen and Selmer-Olsen, in 1960s, and more than 2000 samples that later have been tested in the laboratory, the following intervals are recommended for the rock categories.

Category	DRI	BWI	CLI
Extremely low	- 25	- 10	< 5
Very low	26 - 32	11 - 20	5.0 – 5.9
Low	**33 - 42**	**21 - 30**	**6.0 – 7.9**
Medium	**43 - 57**	**31 - 44**	**8.0 – 14.9**
High	**58 - 69**	**45 - 55**	**15.0 - 34**
Very high	70 - 82	56 - 69	35 - 74
Extremely high	82 -	70 -	≥ 75

We can also analyse the correlation between the Bit Wear Index, the Drilling Rate Index and the quartz content, divided into 7 different categories.

3 Colorado School of Mines method (CSM method)

It is an analytical penetration model based on the linear cutting test with a detailed consideration of cutter disc.



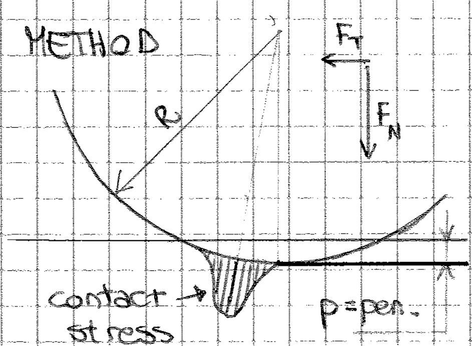
The linear cutting test uses a rotating cutting tool over a rock sample, which is fixed to a big frame. The tool is moving longitudinally along the block and applying a pressure, so that it creates some traces.
The test tries to reproduce the behaviour of a tool on the excavation face, even if actually it does not find a wall but a face with fractures → it is quite a theoretical test.

INPUT PARAMETERS

→ geotechnical parameters, as compressive strength UCS and tensile strength BTS

→ TBM parameters
- → maximum thrust per cutter
- → cutter number, width, diameter and spacing
- → cutterhead diameter and rotation speed

METHOD



The method uses a model resembling the physical behaviour of the interaction between the tool and the ground:

the tool receives certain thrust and is penetrating into the rockmass.
We can notice a peak of contact stresses and the resultant can be decomposed in radial force and tangential force.

Starting from this physical model, they defined some calculation steps.

(I) Assumption of penetration

We assume a value of penetrations, in terms of angle of contact area φ.

Geometrical design of the segment lining

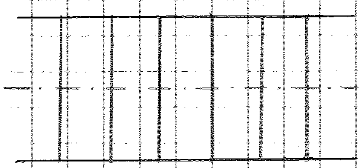
We know that the segments of the final lining are pre-cast in place elements assembled together behind the shield by a machine, called segment erector.

THICKNESS: the thickness depends on the tunnel diameter and, for normal metro tunnels ($\phi = 6 \div 10$ m), thickness is

$$t = 30 \div 45 \text{ cm}$$

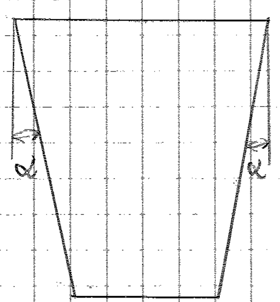
In case of big diameter tunnels, thickness can go up to 70 cm.

SHAPE



In STRAIGHT ALIGNMENTS, all the rings can be cut orthogonal to the axis.

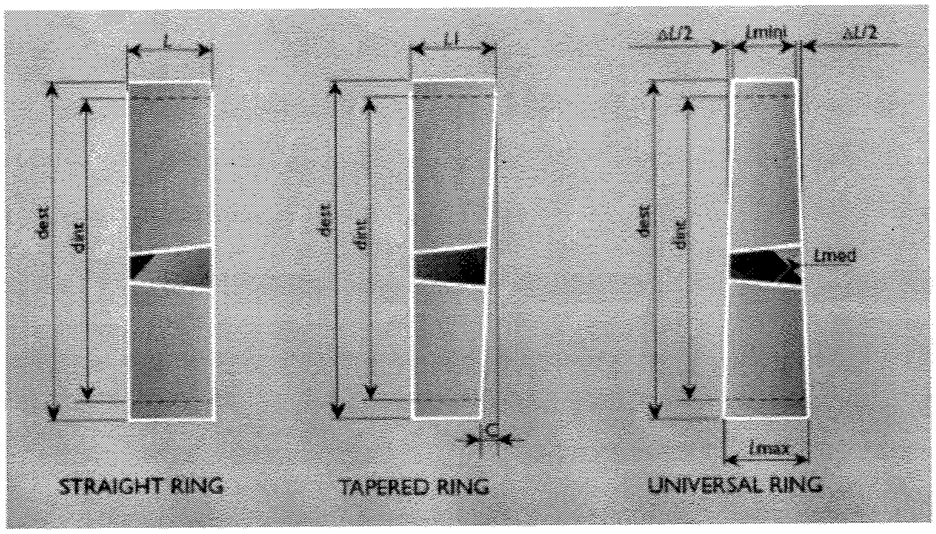
In CURVED ALIGNMENTS, the shape of the ring is not regular because they are shorter in the inner side and longer in the outer side.
If the alignment has many curvatures, we will have to use lots of different types of segments and the plant will become complicate to be managed.



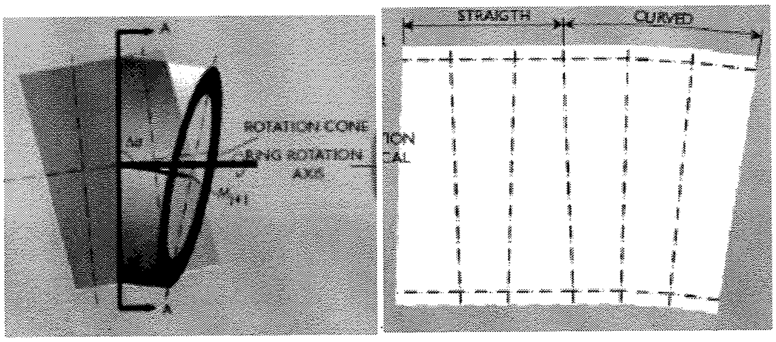
That's why we normally adopt the universal ring, which is a ring made of segments cut in certain way in the transversal part, with an angle of $1 \div 2°$ on the two sides.
With the universal ring, if we are going straight, we will have to put one segment in one direction and the other segment rounded in the opposite direction.
In making a curvature, the second segment is not completely rotated but just of certain degree.
Thanks to this degree of rotation, we can do different curvature radius.

The main consequence is that we need <u>just one set of formworks</u>, i.e. a unique set of formworks for the ring.
Of course, the assembly should be done knowing exactly where the machine is.

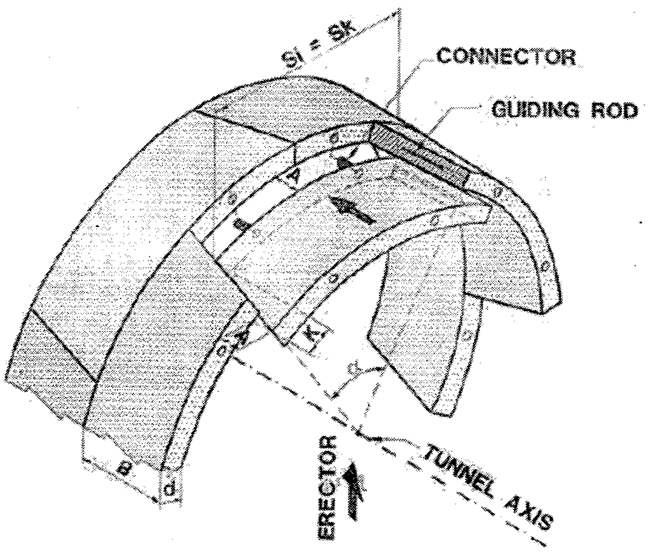
SEGMENT SHAPES



Universal ring

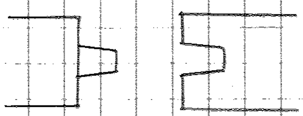


Keistone condition



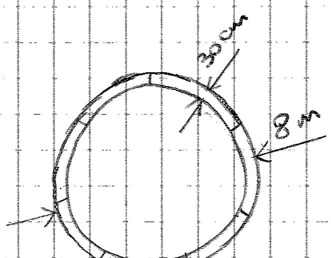
Design of the connection between two segments

In the assembly, the guidance rod is used between segments of the same ring and allows them to be guided into its position and functions as a shear pin.



In addition to the guidance rod, the connection between segments is realized with pins.
Their goal is just to stabilize the segments and avoid them falling down during the assembly, but they do not have any structural effect on the global behaviour and on long term stability.

Pins must be designed in order to have adequate flexural strength up to the closure of the ring.



For instance, in a tunnel of 8 m of diameter with a lining made with 7 segments 30 cm thick, each segment will be 3 tons heavy.
In installing the elements connected with pins, pins have to resist to the flexural load before the closure because the lining will work as a ring only when closed.
Before the closure, the elements work as a cantilever and pins have to support them.

On the other side, pins are just assembly elements and they do not have any long term structural function.

Design of the waterproofing system

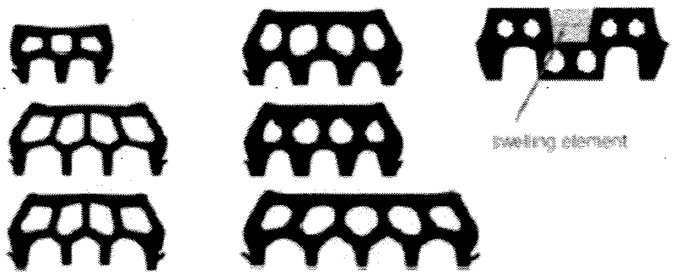
The waterproofing system of the joints is realized with gaskets, which are sealing elements positioned in grooves placed on each single side of all the segments close to the extrados, both between two segments between two rings and between two segments in one ring.
The elements are then pressed one against the other and, thanks to this, we have IMPERMEABILIZATION and water will not go through.

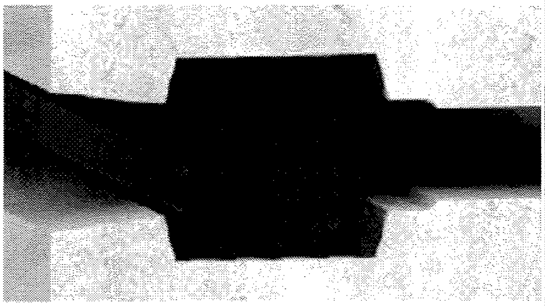
During the installation, the two seals are pressed against each other and there is perfect contact and maximum closure, due to the predominant force of the thrusting jacks.
When jacks are released, the seals tend to open due to elastic reaction, but the movement is opposed by the presence of pin connector.
Finally, an equilibrium is reached and, if the seal has been well designed, it will guarantee the impermeabilization.

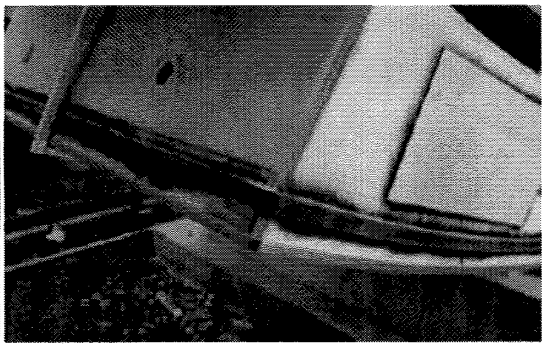
Actually the assembly procedure is dangerous towards the perfect sealing of the elements because, during this, we can damage

WATERPROOFING SYSTEM

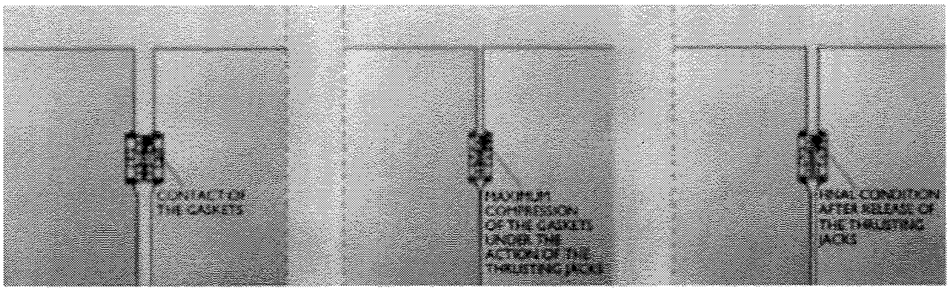
Gaskets



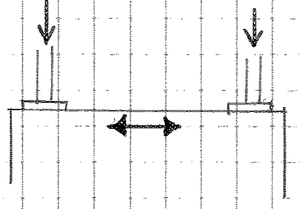




Gaskets' behaviour



→ advancement of the TBM, which is usually the heaviest load which a segment has to fulfil.



Indeed, in order to make the TBM to advance, jacks apply a pressure on the segments. The thrust force of the jacks creates some stresses inside the segment, including bursting tensile stresses, which can be evaluated with a structural numerical model.

In this step, an important design parameter to be introduced is the maximum eccentricity acceptable of the jack system because, if excessive, it may lead to the failure of the segment.

→ design of the ring as a whole, considering several aspects.

→ longitudinal injection, i.e. backfilling, which is a radial injection applying a pressure.

→ exit of the TBM, which is quite critical in the curves because the tail of the shield hits the segments.

→ long term stability of the ring, the segments and the joints – normal geotechical design.

The correct design requires, with the geotechnical properties, some characteristics of the TBM

→ excavation cutter-head diameter

→ length and diameter of the shield

→ thrust system: number of jacks, number and size of the thrust shoes, maximum total thrust force, maximum eccentricity of the jacks, maximum stroke, etc.

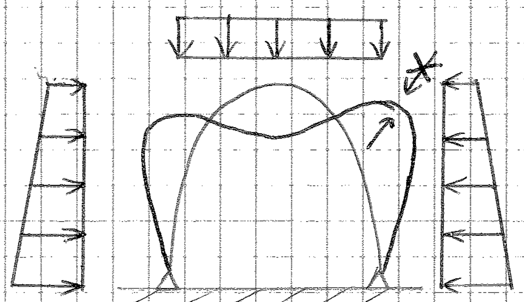
→ segment lifting system:

normally, erector is working as a vacuum but, in small machines, it still acts as mechanical erector, where segment pins are inserted in a mechanical connection – the mechanical connection create a lot of shear forces and reinforcement has to be designed with care.

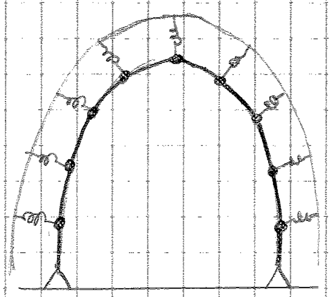
→ DEEP TUNNEL (depth > $(5 \div 6) \cdot \varnothing$)

We can use the CONVERGENCE - CONFINEMENT METHOD, giving us indications on the maximum load acting on the tunnel. Actually, we often use the coupled method, in this case.

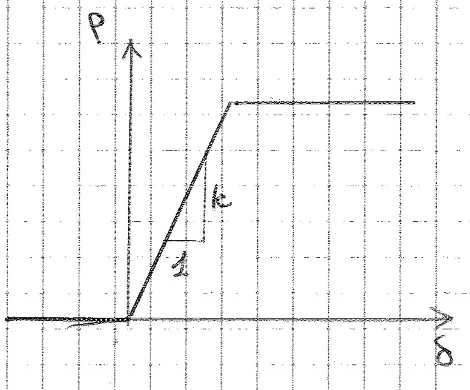
Then, after having assessed all the loads, we make the structural design.
In this step, we make a schematization of the lining.



In case of horse-shoe tunnel, we model the lining as an arch on two hinges - the simplest hypothesis.
Under the loads, the arch will deform and, due to this deformation, we will get a diagram of bending moment, axial force and shear.



Actually, even if in safety, this scheme is making a big mistake because it is not taking into account that the structure is embedded in soil.
Thus, when structure tends to deform, the reaction of soil will prevent this deformation.
If we do not consider the soil reaction, the deformation and bending moment are magnified.
As consequence, we introduce the beam-spring method, where the lining is made of beam connected to springs, which simulate the action of the soil.



In this method, the big geotechnical problem is the definition of the springs' properties, since they do not exist and we have to go from soil's properties to properties of artificial elements.
The model assumes no reaction in tension - soil will not react if tensed - and reaction in compression with stiffness k.

This type of model can be solved with any structural code.

Nowadays, the trend is to use the steel cage with less steel, which is replaced by fibers.
The fibers' goal is mainly to avoid local breaking of segments and so they do not affect the stability of the tunnel but the quality of the final product, in terms of aesthetics and necessity of restorations.

Production plant

Segments are generally is normal pre-casting plant, by using prefabrication moulds

→ moulds for normal segments (more than 1 to increase production)

→ mould for counter-key segment

→ mould for key segment

In each working cycle, we insert the steel cage into the moulds, cast and harden with steam-curing cycles, extract the segment and store it in an area and then we transport it to the machine.

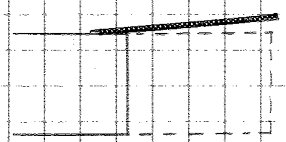
The forecast production is a design parameter because, if we make the wrong forecast of the production of the prefabrication plant, we will have to stop the excavation because the plant is not able to provide all the segments to the machine.

Presupports technology

1 The presupports technology can be applied both in conventional tunneling and mechanized tunneling, but it has been developed mainly for conventional tunneling.

2 Presupports:

presupports are defined as all the technologies used to reinforce the ground ahead of the face.



When it is impossible to make an advancement step of reasonable length, in the presupport we excavate with something launched ahead of the face.

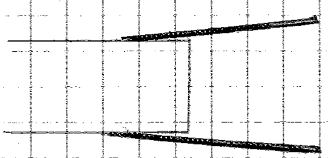
We have two possibilities to create the presupports

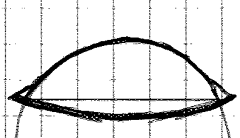
→ introduction of structural elements, like steel bars or steel pipes

→ use of improvement technologies, i.e. techniques able to change the ground properties, improving the mechanical behaviour.

These technologies create something ahead the face, in order to make a bigger advancement step.

3 Structural elements

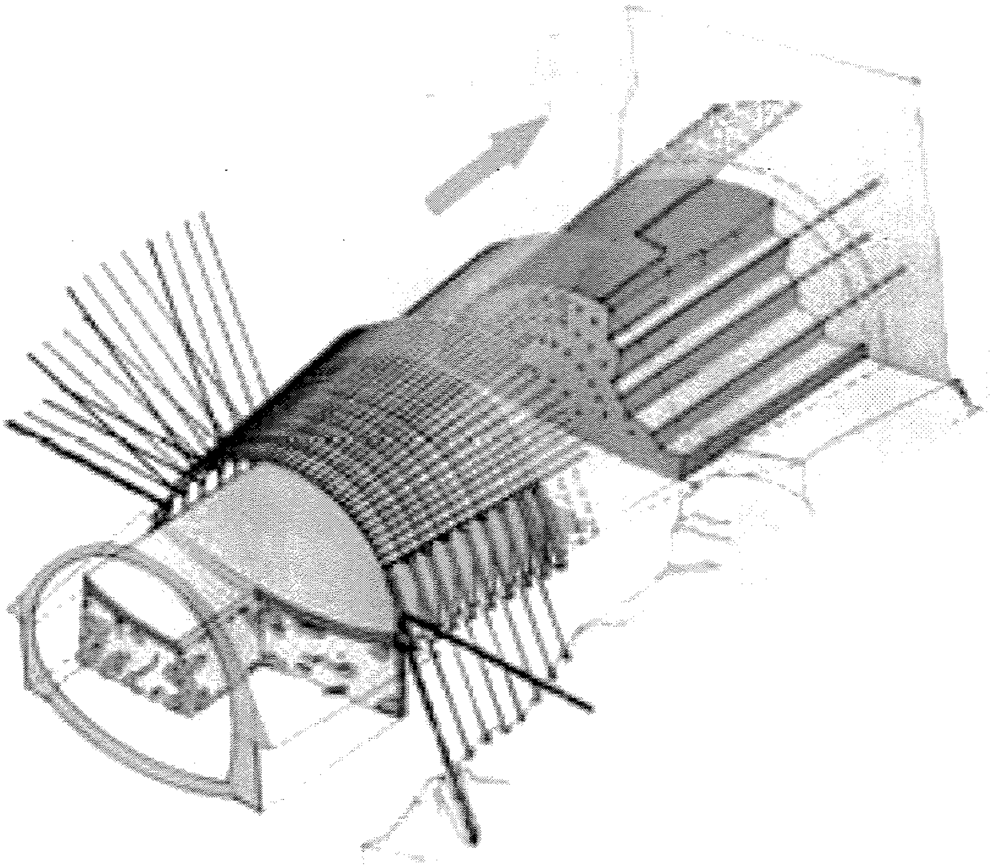




In the typical configuration of excavation of a tunnel, each steel arch corresponds to an advancement step.
The excavation is done according to the bench-invert scheme and the bench has a temporary invert. This element closes the arch if subjected to heavy horizontal loads because they tend to open the arch and bring it to collapse - we add also some bolts to counterbalance the horizontal load.

Then, we launch some structural elements ahead the face, in order to support the advancement step.
Finally, we may apply a face reinforcement, by using fiber-glass elements, which are fully grouted.

Presupports geometry



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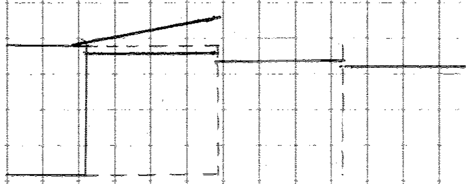
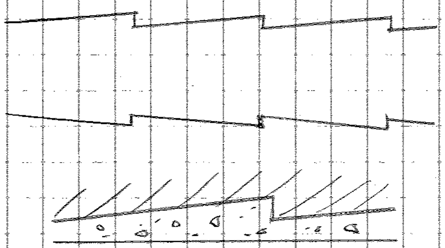
We can notice that pipes - and bolts - are drilled with certain inclination and the angle of opening of the steel pipes ahead of the face is

$$\alpha = 5 \div 10°$$



Indeed, the machine has certain thickness and, with sub-horizontal holes, the tunnel will get narrower during the advancement. By consequence, we need to diverge the pipes.

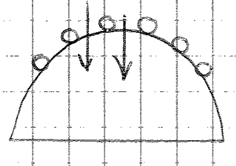
Sub-horizontal holes can be done only in special cases, e.g. we excavate just one advancement step.



As consequence, each advancement step has truncated cone shape and the tunnel shape will be tooth-saw shape ("forma a dente di sega") because, at each step, the size rises up and then reduces. Then, when we cast the final linings, the tunnel shape will become regular.

This aspect implies the use of different steel ribs - with different curvature radius - along the excavation. This is unavoidable with this system, but it is accepted.
Of course, we will compute just the bigger steel ribs, as they are the weakest, and we will buy the same profile for all the ribs.

An important aspect in steel pipe umbrella is that each steel pipe is independent and they are not linked together.



By consequence, we have to care that soil will not flow between one pipe and the other and the system will work well

→ in soils with minimum cohesion, which guarantees a small arch effect between the pipes and prevents the flow.
In loose clean sands, unless injection, the system is not good

→ above the water table

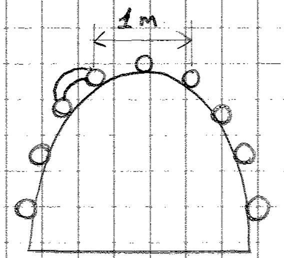
OBSERVATION: we have to take into account that the operation of installation of structural elements will enter in the cycle.

DESIGN PARAMETERS

→ interax between pipes

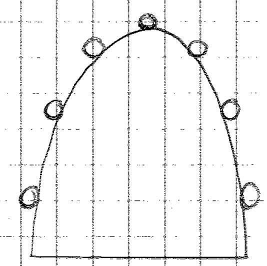
In normal soils, we use

3 pipes/m (max 4 pipes/m)



Indeed, we have certain precision in drilling the pipes and, if we made them closer, one would touch the other steel.

We may assess the interaxis from the risk of the soil to go through and calculate the arch effect between one pipe and the other.



If the load is mainly vertical, going down with the arch we can increase the interaxis because the load is smaller in the bottom part. The interaxis can rise up to $40 \div 45$ cm.
In case of important horizontal loads, also the pipes will be close to each other in the lateral side and interaxis will have to be homogeneous.

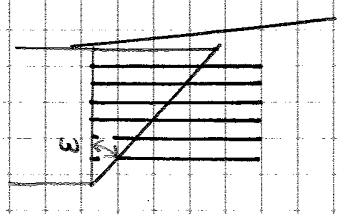
→ length of the pipes

It strongly depends on the MACHINE available on site but the minimum reasonable value is 12 m.
If there are only small machines, we will have to stop too much and this technology will not be convenient.
The biggest machines can drill up to 24 m but, in such a long perforation, we may have problem of diversion. Thus, we will stay within 15 m.

$$\ell = 12 \div 15 \text{ m}$$

→ overlapping

The assessment of the overlapping is performed through the face stability evaluation.



With reference to Anagnostou & Kovari method, the overlapping should be bigger than the critical angle ω, otherwise we will see the creation of the body.

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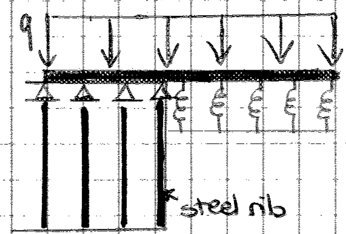
30 cm.

Thus, the design length is quite bigger than the interaxis between the steel arches.

$$L = d + (3 \div 5 \text{ cm}) + (20 \div 30 \text{ cm})$$

→ model of beam with springs



We imagine the beam like a foundation supported by springs and hinges - steel ribs.

The model brings to more precise results but the definition of the geotechnical properties of the springs is quite complex.
It is generally suggested to use the values given by Winkler theory for foundations.

As regards the evaluation of the LOADS, we can face different situations

→ LOW OVERBURDEN TUNNELS (depth < $(1 \div 1,5)D$):

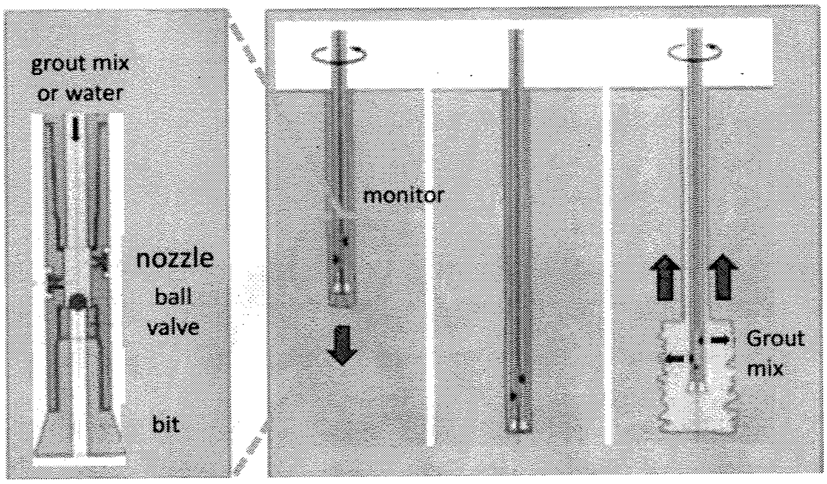
the most conservative approach supposed that the arch effect can not be created and it applies the full vertical load.

→ AVERAGE DEPTH TUNNELS:

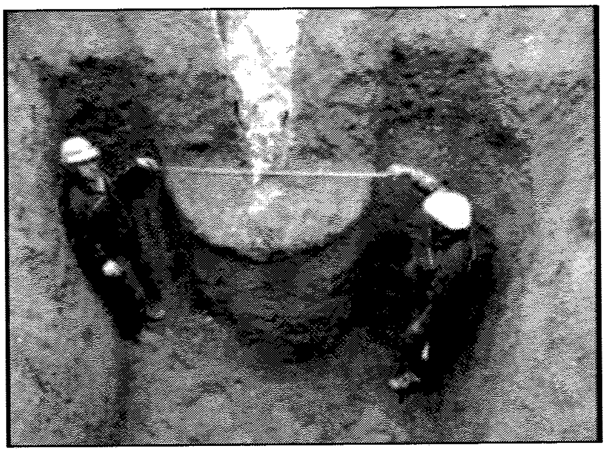
we can use the dead-load approach, like Terzaghi law. Furthermore, it is suggested to apply just $50 \div 75$ % of the load evaluated in this way, thanks to the rise of the 3D effect at the tunnel face. Indeed, part of the vertical load is absorbed by the face.

JET GROUTING CANOPY

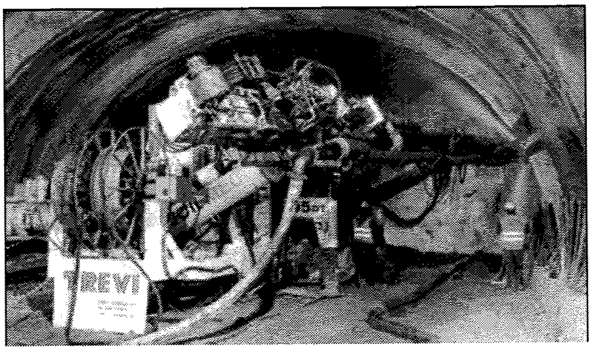
Jet grouting

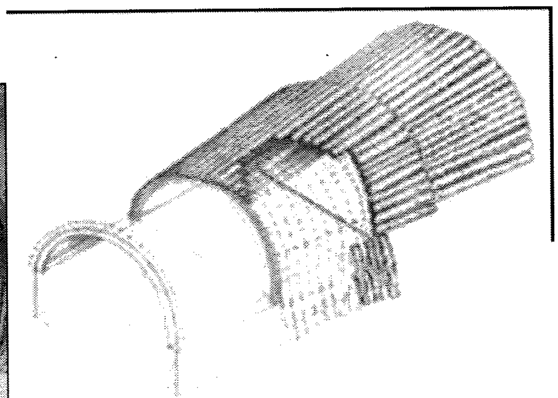


Final result



Realisation of the jet grouting canopy and final result





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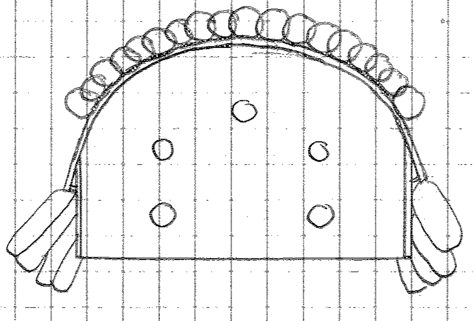
→ speed of lifting up

→ rotation speed

→ type of ground: in sand and gravels we get the best results.



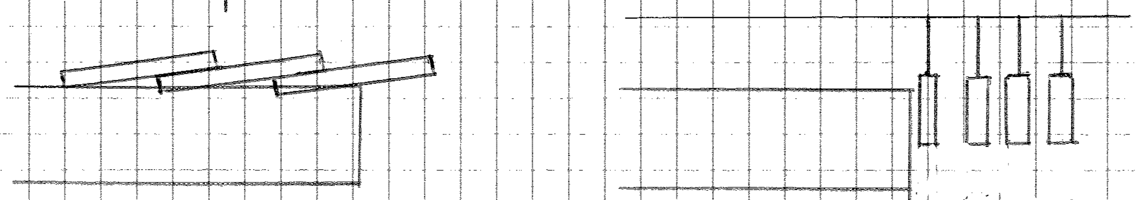
In tunnelling, jet grouting is mainly used to create a vault over the tunnel.

If needed, we can use jet grouting columns also to stabilize the tunnel face and improve the foundation of the steel ribs.

The ~~The~~ jet grouting canopy is an arch made of jet grouting columns, diverting of $5 \div 10°$ from the horizontal and with an overlapping of $6 \div 10$ m.

The machine used to create the canopy is a big machine with big booms, able to do the drilling and the jet grouting - or the drilling and the pipe installation - in one single operation.
The typical machine is single-boom or double-boom machine and can drill up to 20 m.
Moreover, the arm can rotate around an axis, so that the drilling can be done in one step.

A special application is jet grouting from the surface to create the canopy, where drilling is done from surface and the realization of the arch is independent from the excavation.



The main aspect is that the jet grouting canopy works as an arch, whereas in steel pipe umbrella each element is working as single beam.
For this reason, this system is typically employed only in cohesionless granular soils - e.g. clean sand -, where we can not control the flow of material between the pipes. We use it only in this case because canopy is <u>more expensive</u> than steel pipe umbrella.

DESIGN OF THE CANOPY

We know that the jet grouting works as an arch, i.e. the transfer of the vertical load is done through an arch action.

If we want that the system of columns works as an arch, this system has to be continuous and columns must be compenetrated. By consequence, the interax between columns is a design parameter:

knowing the diameter of the column, we design the interax in order to have a reasonable overlap - about 10 cm.

The design of the arch is developed in two steps.

(I) ASSESSMENT OF THE COLUMNS

We evaluate the design parameters of the jet grouting column

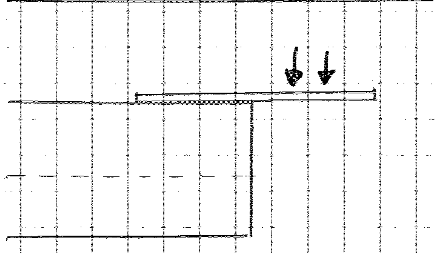
- → length, depending on the available machine, which is also the length of the canopy L.

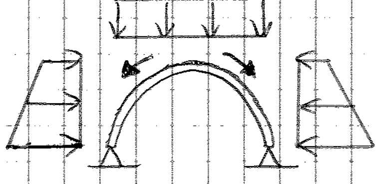
$$L = 12 \div 24\ m$$

- → diameter of the column, based on literature data or field test
- → from the diameter, we derive the interax
- → taking into account the type of soil, we estimate the strength UCS.

(II) ASSESSMENT OF THE ARCH

Using the parameters of the columns, we assess the stability of the canopy, computing the system as an arch.
For instance, in a low overburden tunnel in sand, we apply a vertical and horizontal load on the arch. Then, we estimate the compressive force acting inside it and assess if the stress is smaller than the strength.





→ permeation grouting ("iniezione per permeazione")

Grouting is injection at limited value of pressure, smaller than 60 bar in soil, in order to fill the intergranular voids with a grouting mix, which can be cement - based or chemical - based.

The goal of grouting is the improvement of soil engineering properties

→ REDUCTION OF SOIL-ROCK PERMEABILITY

→ IMPROVEMENT OF MECHANICAL PROPERTIES, through the creation of an arch allowing to make the advancement step safely.

We should be able to pump the mix inside the voids, without changing too much the intergranular voids.
For the purpouse, there are different mixes with different penetration properties.

→ cement - based mix:

it is the most used mix in tunnelling and made of

water + cement + bentonite

It is a suspension of cement grains in water and bentonite. Bentonite is in small quantity ($2 \div 3$ %) and makes the mix stable, i.e. it does not release water when stored.

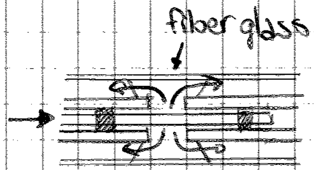
Due to the thickness of the cement grains, the mix can permeate only big voids and this will correspond to certain grain size distribution - sands and gravels.

→ microcement

This mix is made of cement more crashed than standard cement. Thanks to the smaller grain size, the mix is able to permeate fines like silts.

→ chemical - based mixes:

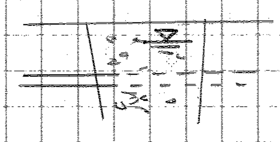
these mixes have the same ability of permeation as water and are used for smaller fines.



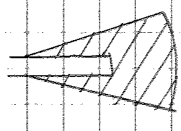
Another device used for grouting are fiber glass elements.
This device uses fiber glass elements installed around the manchette pipe and create a well grouted reinforcement.

DESIGN

We refer to a simple example.



A tunnel excavated in competent rock has to cross a fault with very fractured ground and water.
We have to impermeabilize the ground and improve its mechanical properties.



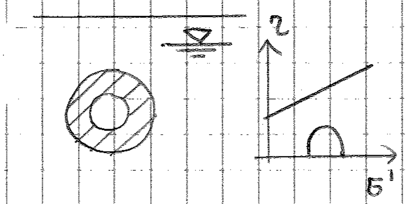
The solution consists to realize a cylinder of grouting from the tunnel, excavate inside it and so on.

The first step is the GEOTECHNICAL DESIGN, in which we have to assess

→ thickness of the ring and at face

→ mechanical properties to fulfill the stresses acting on the ring

→ type of grout to give optimal impermeabilization of the ground.



In this case, we can compute the ring as a thick ring under uniform pressure, due to water and soil.
With this model, we compute stresses inside the ring and we evaluate how they are close to the failure envelope - the one after conditioning.

After the geotechnical design, we proceed with the INJECTION DESIGN, where we decide where to place the pipes in order to make the best grouting.
Normally, the design of the grouting in soil is done according the procedure of controlled volume and controlled pressure

→ as regards the controlled volume, we know that each valve is grouting a cylinder which size depends on the penetration radius of the valve itself, depending on soil properties and mix properties.

By consequence, we have to assess the maximum pressure we can accept in soil.

The values of volume and pressure are typically given on the basis of similar case histories or experience - there are no rules - and then assessed through field tests.

The technology of permeation grouting is very flexible and can be well integrated with other technologies to reach what we want from the engineering point of view.

→ freezing ("congelamento")

This technology consists of freezing the water already present in soil, in order to excavate in frozen soil.
The goals are

→ impermeabilization

→ improvement of mechanical properties

In practice, freezing has the same goals of grouting and it is used when grouting should fail, generally when there is quickly moving underground water which can remove the grout from soil when it hardens.

Freezing is very expensive and requires very important technological approaches.
It is done by putting liquidum nitrogenum in drill holes, which creates the freezing. Once installed the lining, we remove the freezing.

PROBLEMS → freezing needs time to realize a completely frozen arch.

→ we have to design the optimal pipe interaxis

→ workers have to work in an uneasy environment, with temperature below 0° C

→ when we defreeze soil, we reduce its properties because the increase of volume linked to freezing destroyes the structure, typically reducing cohesion. By consequence, in the lining design, we refer to worse geotechnical parameters with respect to the original conditions