

Urban tunnelling in soft ground using TBM's

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Key note lecture

Urban tunnelling in soft ground using TBM's

Basic considerations

Grouted body

Basic considerations

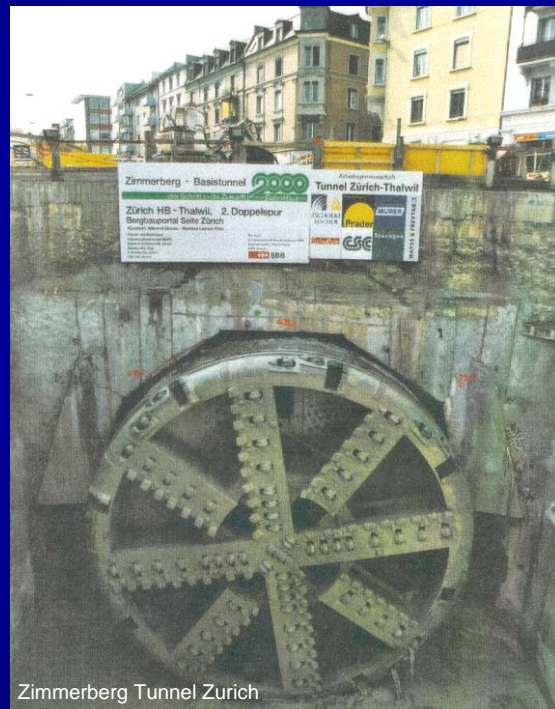
Specific features

- Urban environment
- Risk scenarios
- Ground conditions
- TBM technology
- Risk management

In the sense of basic considerations of the subject first the specific features of urban tunnelling in soil using TBM's are listed.

Urban environment

- Shallow overburden



As to the urban environment the generally prevailing shallow overburden must first be mentioned. Frequently, nowadays, low overburden is combined with a large tunnel diameter.

The photo shows the recently completed Zimmerberg Railway Tunnel in the city of Zurich with a diameter of 12.3 m.

Urban environment

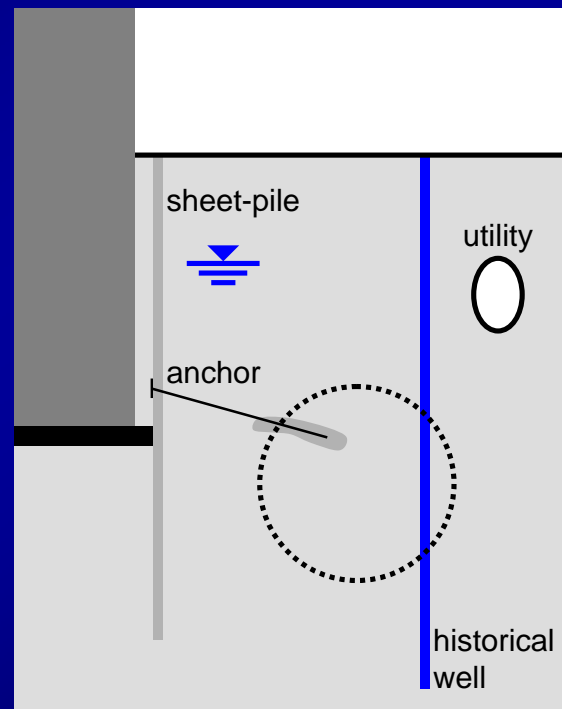
- Shallow overburden
- Structures on ground surface



Next structures of various types to be under-tunnelled have be considered. These may be buildings, roads, railroads, bridges, etc. The sensitivity of these structures to ground settlements as well as the potential damage to ground collapse may vary within extremely wide ranges.

Urban environment

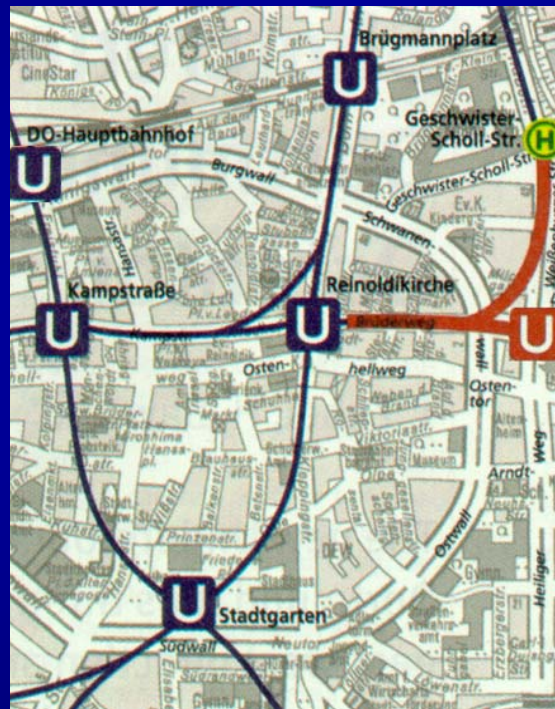
- Shallow overburden
- Structures on ground surface
- Foreign objects in ground



The presence of frequently hidden foreign objects in the ground is also one of the specific features of urban tunnelling. We mention here historical wells, ground anchors, sheet-piles, abandoned utilities such as for gas and sewage, but also tree trunks, artificial fillings, etc.

Urban environment

- Shallow overburden
- Structures on ground surface
- Foreign objects in ground
- Constraints for alignment



There are generally major constraints in the selection of the horizontal and vertical alignment. As a rule it is generally preferable to run the tunnel in public ground under main roads or streets. However, under-passing buildings, roads and other structures is as a rule unavoidable.

Urban environment

- Shallow overburden
- Structures on ground surface
- Foreign objects in ground
- Constraints for alignment
- Restriction for
 - Place of attack, material transport, access to TBM



Also the serious restrictions when selecting places of attack and planning material transport from and to the site are of great practical importance.

Urban environment

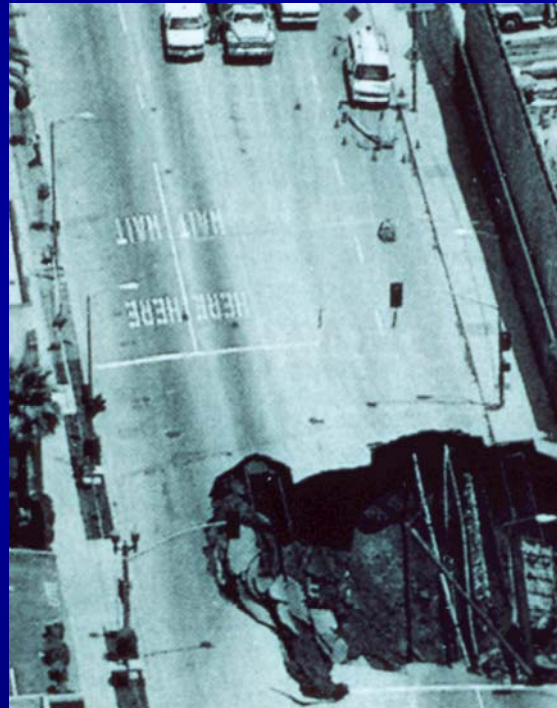
- Shallow overburden
- Structures on ground surface
- Foreign objects in ground
- Constraints for alignment
- Restriction for
 - Place of attack, material transport, access to TBM
 - Exploration and auxiliary measures (ground water, consolidation)



Such restrictions also apply to sinking drill holes for explorations, for ground water control or ground consolidation.

Urban environment

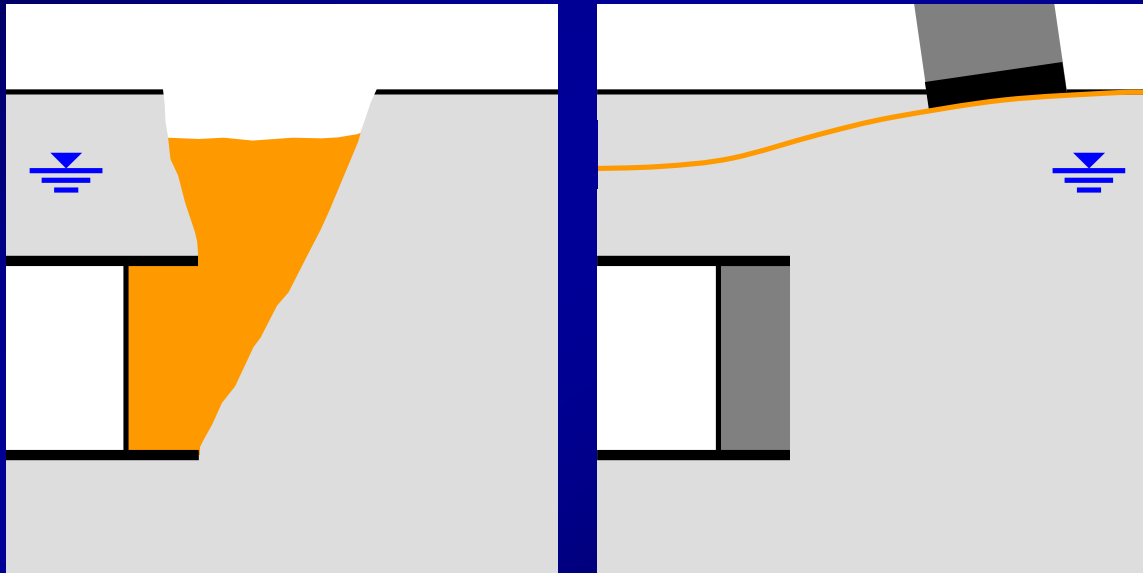
- Shallow overburden
- Structures on ground surface
- Foreign objects in ground
- Constraints for alignment
- Restriction for
 - Place of attack, material transport, access to TBM
 - Exploration and auxiliary measures (ground water, consolidation)
- High visibility of damage (risk aversion)



In the urban environment damage to buildings and roads has a high visibility. The risk aversion is very pronounced, which may lead to a strong opposition to further underground projects in towns or even elsewhere. The loss of public confidence in the technology can be looked upon as a kind of damage.

Risk scenarios

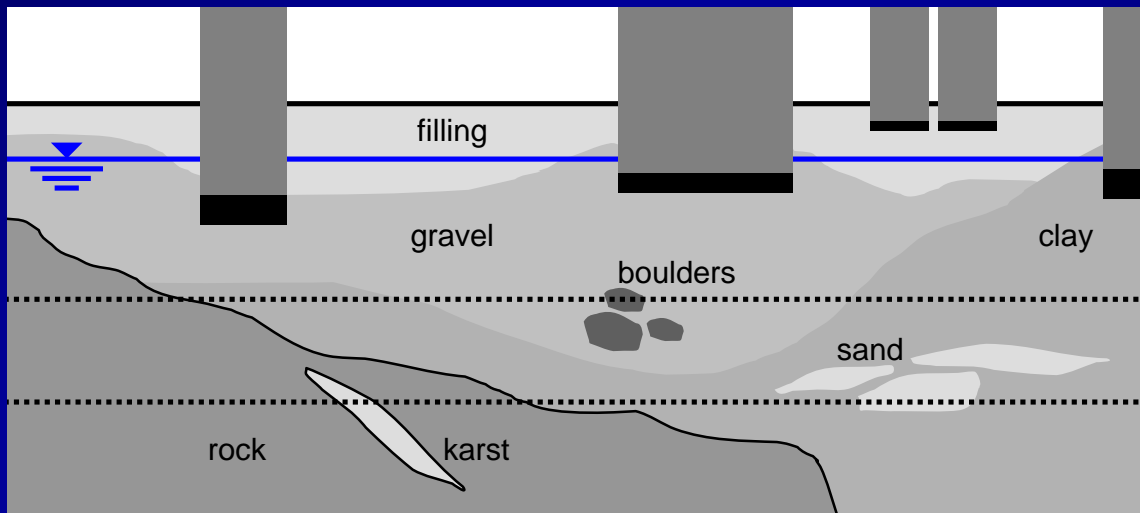
- Collapse up to surface
- Damage due to ground deformations (settlements)



There are two major risk scenarios in urban tunnelling as shown in the picture: collapse up to the surface and damage due to ground settlements.

Ground conditions

- Recent geological formations
- Frequently changing conditions
- Presence of ground water



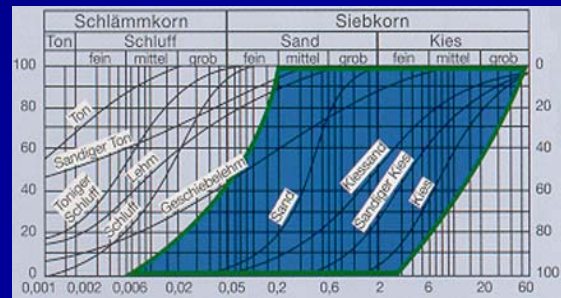
The ground conditions in urban tunnelling have also several important common features.

In most cases near the ground surface in general recent weak geological formations are encountered. There are frequently changing conditions due to the presence of lenses, layers, boulders, etc. and in rock open joints and in limestone even karsts.

A water table situated above the tunnel or crossing the tunnel profile requires particular attention.

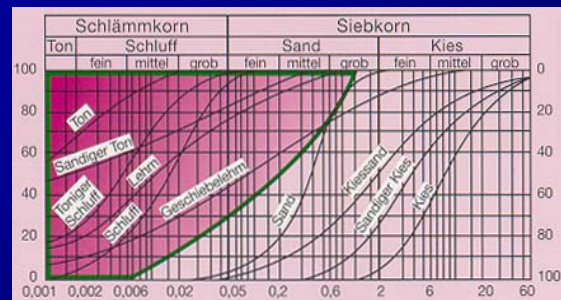
Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution



slurry shield

Herrenknecht (2001)



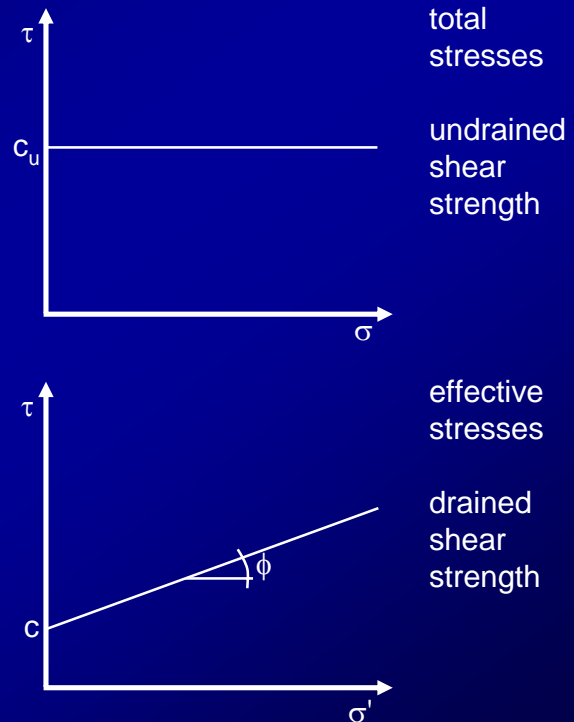
EPB shield

Herrenknecht (2001)

In soil the grain size distribution is one of the decisive factors when selecting the type of TBM shield to be applied. One is familiar with the diagrams shown above indicating schematically the preferred ranges of application of slurry and EPB shields.

Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution
 - Shear strength

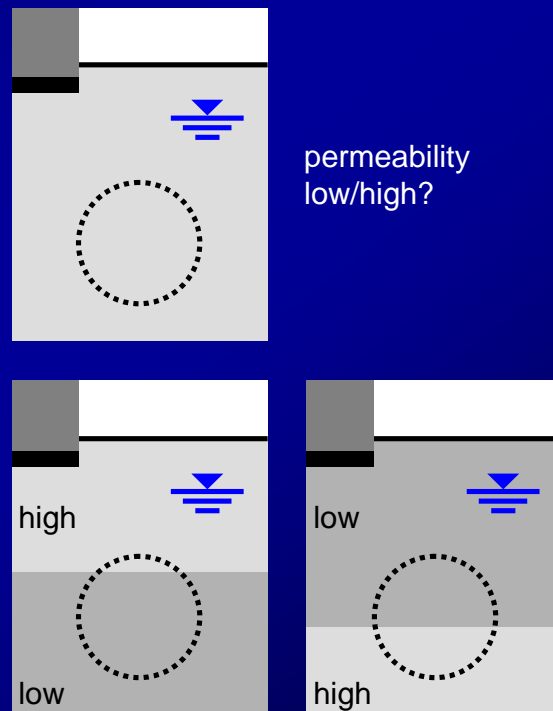


Apart from the grain size distribution the shear strength of the material on a large scale is very important. In clay the undrained cohesion c_u and in sand and gravel the drained cohesion c is of interest.

Because of the very low stress level in the ground already small values of cohesion are generally decisive in the appraisal of the stability of the working face. In any case, we have unfortunately no means of determining such low values of cohesion based on exploratory boreholes and laboratory tests. As a rule one assumes the extreme case of zero cohesion.

Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability



In the presence of groundwater the permeability of the ground is of great practical interest. The questions are:

- Is the permeability of the ground low or high?
- Is there any relevant heterogeneity and what is the distribution of the individual formations with the various permeabilities?

Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability
- Rock and weak rock properties
 - Discontinuities



For the sake of completeness we also look at possible rock formations paying special attention to discontinuities.

Ground conditions – Relevant for TBM drive

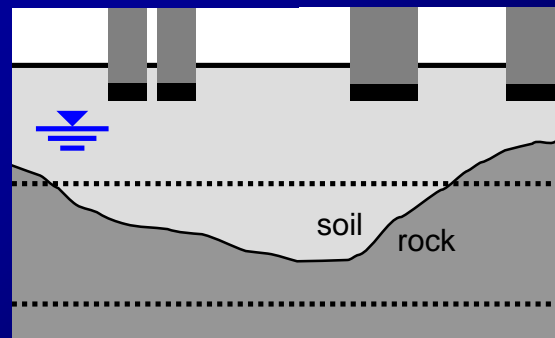
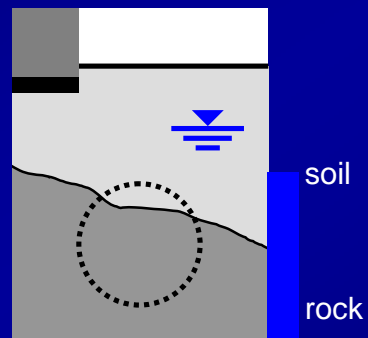
- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability
- Rock and weak rock properties
 - Discontinuities
 - Weathering



One also has to consider the degree of weathering of the rock.

Ground conditions – Relevant for TBM drive

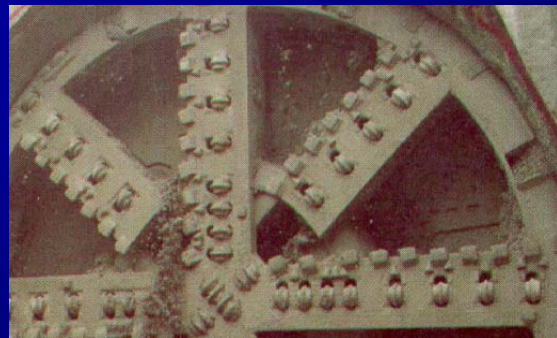
- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability
- Rock and weak rock properties
 - Discontinuities
 - Weathering
- Ground properties
 - Occurrence of mixed face



The occurrence of a so called "mixed face" – i.e. the simultaneous presence of rock and soil – frequently causes major difficulties for the stability of the face. Apart from this guiding the machine may also become difficult.

Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability
- Rock and weak rock properties
 - Discontinuities
 - Weathering
- Ground properties
 - Occurrence of mixed face
 - Quartz content

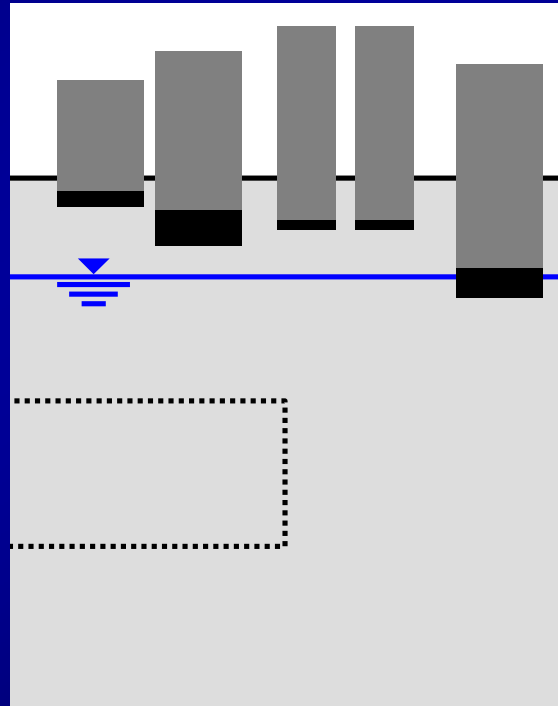


For the sake of completeness let us also mention the influence of the mineral content which may determine the degree of wear of the tools or may even lead to damage of the cutting head.

Here one can see the head of the slurry type TBM (Herrenknecht) of the Zimmerberg Tunnel at the start and after the completion of the drive.

Ground conditions – Relevant for TBM drive

- Soil properties
 - Grain size distribution
 - Shear strength
 - Permeability
- Rock and weak rock properties
 - Discontinuities
 - Weathering
- Ground properties
 - Occurrence of mixed face
 - Quartz content
- Piezometric level

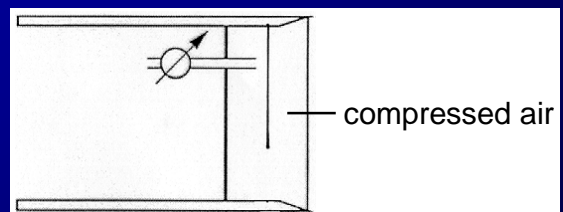
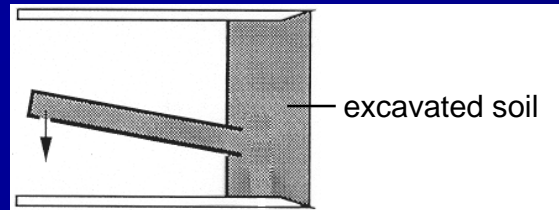
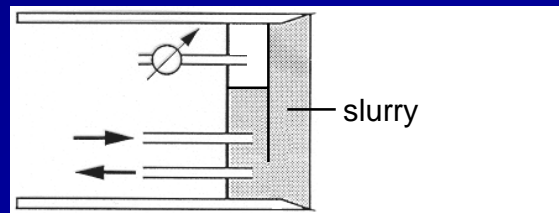


Finally the piezometric head with respect to the tunnel as an important factor for the stability of the face as well as for a successful permeability reduction of the ground must be mentioned.

Also the required air pressure during maintenance in the working chamber strongly depends on the piezometric head in the ground.

TBM technology

- Face support

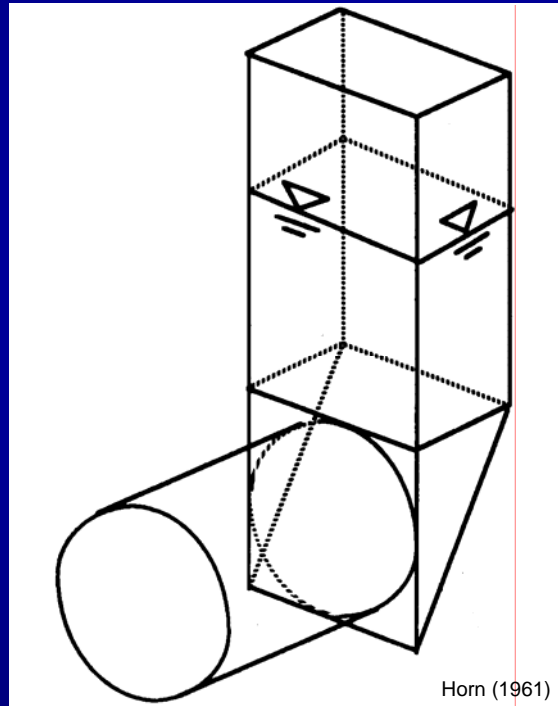


The three ways to support the face are: by slurry, by excavated soil and by compressed air.

The extraction of the muck is carried out in the first case through a pipe and in the two other cases by a screw conveyor. Slurry shields at the entrance of the sucking pipe are generally provided with a rock crusher.

TBM technology

- Face support
- Failure mechanism

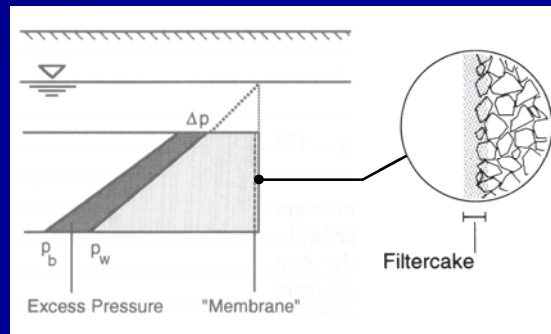


Any study of the stability of the face begins with the assumption of a simplified failure mechanism in the ground ahead of the face.

The three-dimensional model of Horn (1961) is close to reality and is simple to handle. It consists of a wedge and a prism in the state of limit equilibrium. The model is basically an extension of Janssens's silo theory to three dimensions. The mobilized shear strength along the failure surfaces is one of the key factors in the statical calculations.

TBM technology – Slurry shield

- Stabilizing effect of slurry
 - Without infiltration

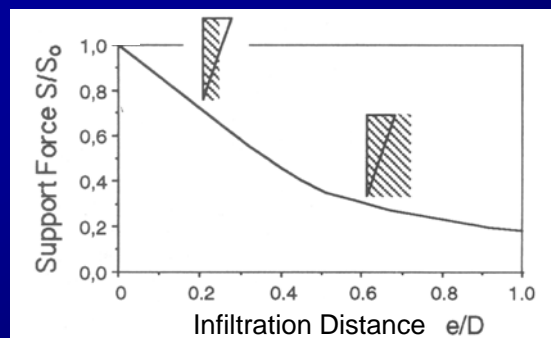
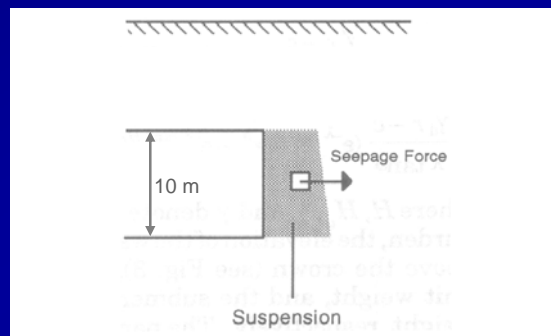


The figure demonstrates the stabilizing effect of the slurry at the face. Due to the excess pressure Δp the so called filtercake is formed on the surface of the face having the function of a membrane. It prevents the infiltration of the slurry into the ground. The formation of the filtercake requires the presence of sufficient fines in the ground and, depending on the applied excess pressure Δp , a critical limit of the permeability of the soil.

The photo below shows such a filtercake on the tunnel face in a fluvial gravel.

TBM technology – Slurry shield

- Stabilizing effect of slurry
 - Without infiltration
 - With infiltration



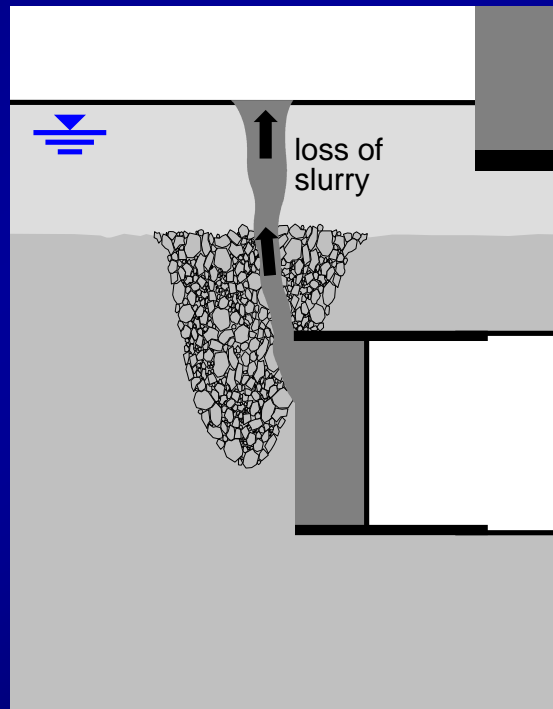
If the slurry is allowed to infiltrate into the ground its supporting effect rapidly diminishes with increasing distance.

The above shown wedge/prism model allows the reduction of the support force to be calculated. For a given set of parameters if the penetration e of the slurry reaches half of the tunnel diameter D the value of the supporting force S falls to approximately 40 % of its initial value S_0 .

Appropriate conditioning of the suspension and reduction of excess pressure may prevent breaking through the filtercake or considerably reduce the infiltration of the slurry into the ground.

TBM technology – Slurry shield

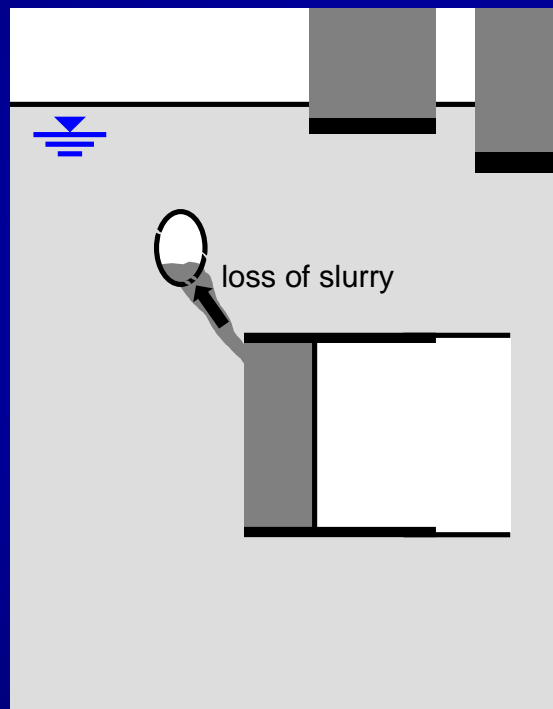
- Stabilizing effect of slurry
 - Without infiltration
 - With infiltration
- Influence of
 - Ground permeability



Sudden loss of slurry may occur due to an unexpected high permeability of the ground resulting in a drop in the excess pressure in the chamber. The figure illustrates the example of traversing an artificial filling.

TBM technology – Slurry shield

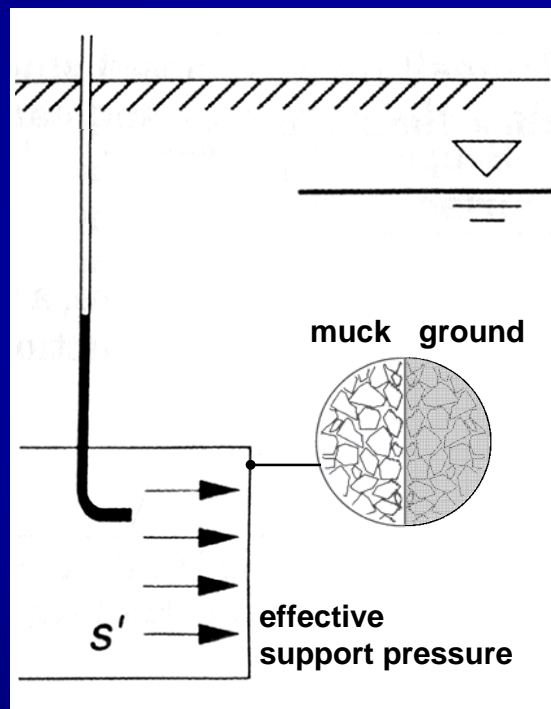
- Stabilizing effect of slurry
 - Without infiltration
 - With infiltration
- Influence of
 - Ground permeability
 - Foreign objects



The same thing can happen due to foreign objects in the tunnel profile or in the vicinity of the tunnel.

TBM technology – EPB shield

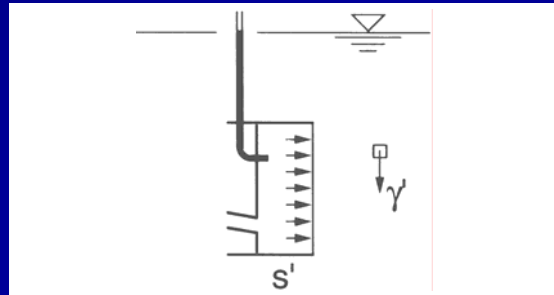
- Stabilizing effect of excavated soil



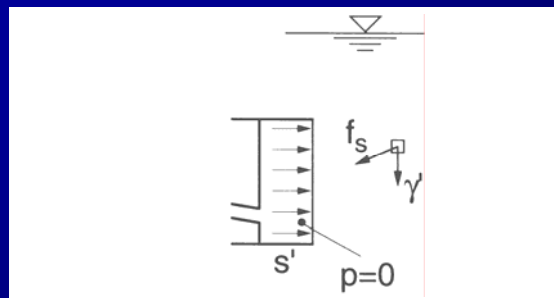
Face stabilization with an EPB shield relies on the effective grain to grain pressure (effective stress s') at the interface between muck and ground as well as on the control of the piezometric head in the working chamber.

TBM technology – EPB shield

- Stabilizing effect of excavated soil
- Influence of ground water
 - Seepage forces



without seepage



with seepage

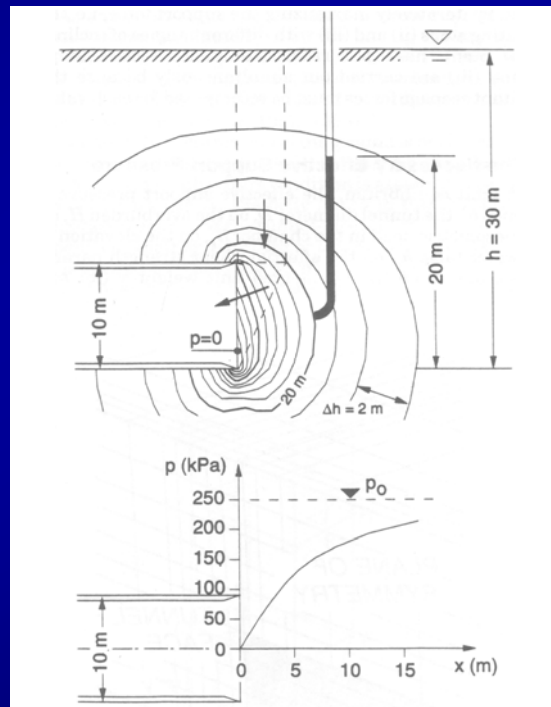
Consider two extreme cases regarding the piezometric head occurring in the chamber.

The upper figure illustrates the case in which there is hydraulic equilibrium between the muck and the ground.

In the lower figure the extreme case of an atmospheric pressure ($p = 0$) in the working chamber is shown. As a result of a hydraulic gradient seepage into the chamber occurs causing seepage forces f_s in the ground. These forces may strongly affect the stability of the face and must be taken into consideration when calculating the necessary support pressure s' .

TBM technology – EPB shield

- Stabilizing effect of excavated soil
- Influence of ground water
 - Seepage forces



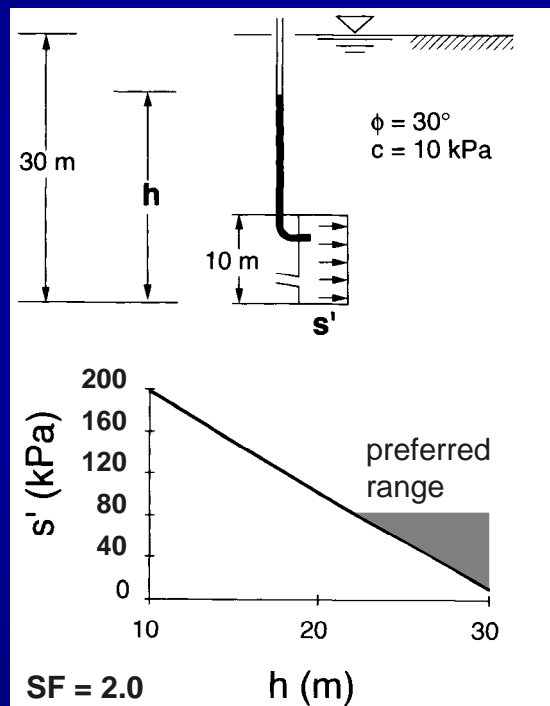
In order to calculate the seepage forces in the ground a numerical flow analysis has to be carried out.

The upper figure shows results of such calculations. The contour lines of piezometric head indicate high gradients at the face resulting in increasing seepage forces.

In the lower diagram the decrease of the piezometric head along the tunnel axis with decreasing distance to the face can be seen.

TBM technology – EPB shield

- Stabilizing effect of excavated soil
- Influence of ground water
 - Seepage forces
 - Support pressure



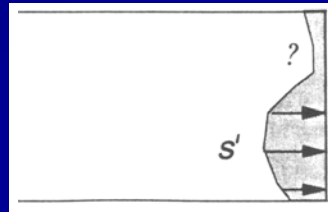
The considerable influence of the piezometric head h in the working chamber is illustrated in this figure.

For a tunnel with a diameter of 10 m, an overburden of 20 m and for the selected shear strength parameter (c and ϕ) a decrease of the necessary effective support pressure s' with increasing piezometric head h results. For a piezometric head of $h = 10 \text{ m}$ the effective support pressure s' will be 200 kPa. For $h = 30 \text{ m}$ – i.e. in case of hydraulic equilibrium – practically no effective pressure is needed. The calculations were carried out with a safety factor SF of 2.0.

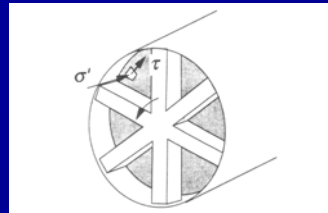
In practice low values of the support pressure s' are preferable – as shown in the diagram.

TBM technology – EPB shield

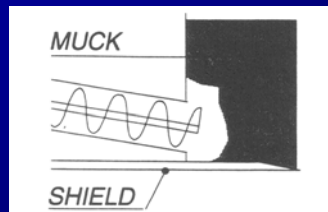
- Stabilizing effect of excavated soil
- Influence of ground water
 - Seepage forces
 - Support pressure
- High effective support pressure
 - Problems



uncontrollable
support
pressure
distribution



excessive
cutter wear
and torque

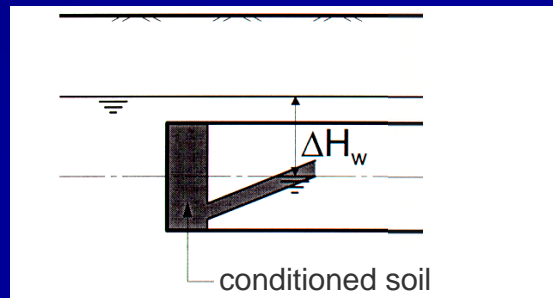


arching at the
entrance of
the screw
conveyor

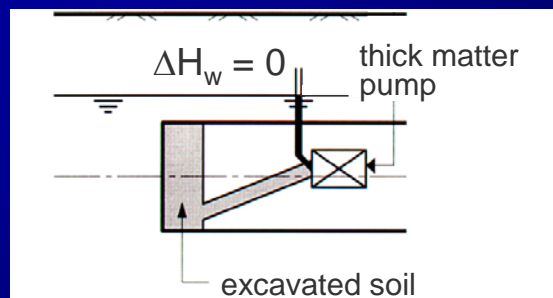
Problems caused by a high effective support pressure s' resulting in high internal friction in the muck are illustrated by these figures.

TBM technology – EPB shield

- Stabilizing effect of excavated soil
- Influence of ground water
 - Seepage forces
 - Support pressure
- High effective support pressure
 - Problems
 - Countermeasures



muck conditioning

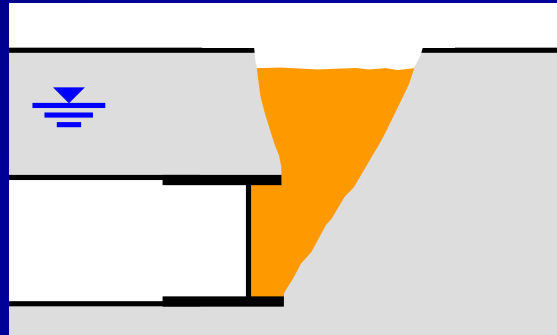


thick matter pump

The frequently used countermeasures against the seepage of water into the working face may consist of the conditioning of soil – both in the working chamber and in the screw conveyor – and/or of the installation of a thick matter pump at the end of the screw conveyor.

Risk management

- Typical patterns of ground failure

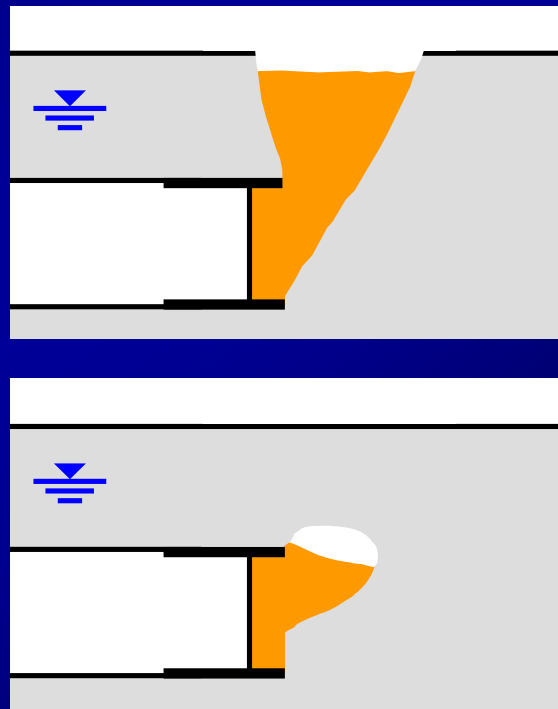


The greatest concern is a face collapse reaching up to the ground surface.

In the case of a slurry shield the collapsed ground fills up the working chamber and the slurry rises to take its place. The photo shows such a crater filled with slurry – fortunately not under urban conditions.

Risk management

- Typical patterns of ground failure

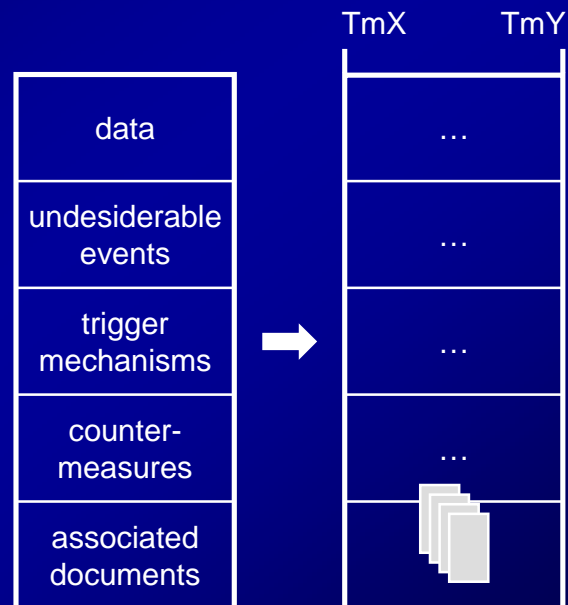


Such collapses can also occur with the application of an EPB shield when inadvertently more material is extracted than the corresponding theoretical excavated volume of the tunnel.

The created opening (see the lower figure) – if it remains unfilled – may collapse with a time delay – possibly resulting in the formation of a crater at the ground surface.

Risk management

- Typical patterns of ground failure
- Safety plan
(systematical procedure)



(valid for time t)

Risk management requires a systematic and well-structured procedure. For this purpose the *safety plan* provides the best instrument. To a large extent it involves a visualisation of the objects it deals with, whereby for a clear cut system or subsystem the facts, assumptions, scientific knowledge, operational instructions, etc. are presented on a plan – as schematically shown in the figure.

The first step is to define the tunnel section that should be subjected a risk analysis by specifying the kilometric distances $T_m X$ and $T_m Y$. The system can comprise a whole construction lot or just a part of it, as for example, when passing under a building, bridge foundation or important traffic arteries.

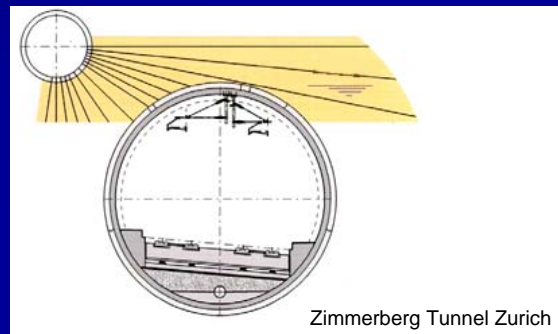
The data to be represented comprise the topography, the structures on the ground surface, geology, groundwater conditions, foreign objects located within the projected tunnel profile, exploratory boreholes and specific aspects of the construction method.

As shown in the figure, apart from the category of undesired events (risk scenarios), all possible triggering mechanisms and finally the foreseen countermeasures with the associated separate documents are presented.

The safety plan has to be constantly updated according to the actual state of knowledge; therefore it is valid only for a given time period.

Risk management – Reduction of risk

- Constructional measures
 - Ground improvement

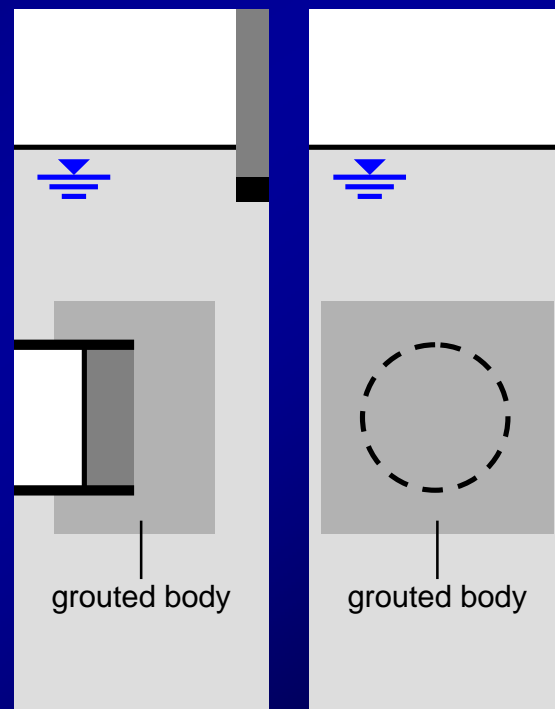


One of the most important constructional measures to reduce risk consists of grouting operations. They aim at increasing the strength and stiffness and/or reducing the permeability of the ground. The figure above shows a completely injected body, the grout holes being drilled from a parallel running gallery.

The photo illustrates one of the drillhole equipments in operation in such a gallery.

Risk management – Reduction of risk

- Constructional measures
 - Ground improvement
 - Prepared stations for TBM

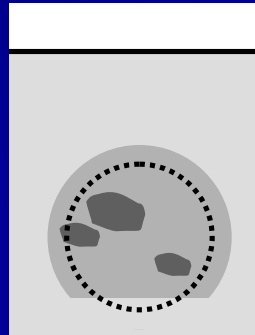


If the EPB or slurry shield has to underpass a densely urbanized area on a long stretch and under difficult geotechnical conditions stopping the TBM for maintenance purposes is generally inevitable. In such cases it is advantageous to prepare at predetermined locations and in good time one or more *stations*.

These can provide safe conditions even without pressurized air for rapid maintenance work in the chamber. Such *stations* may also be important to avoid a time delay in the completion of the tunnel.

Risk management – Reduction of risk

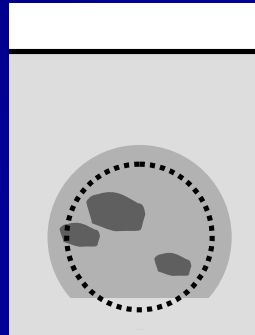
- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization



In some geological formations loosened blocks between the head and the face may present a major problem. The tools for the head may be damaged and the face over-excavated leading to local instabilities. Already modest grouting operations to keep the blocks in place during cutting by the disks generally provide a satisfactory solution.

Risk management – Reduction of risk

- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization

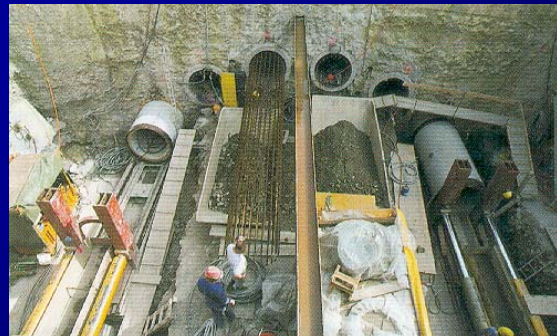
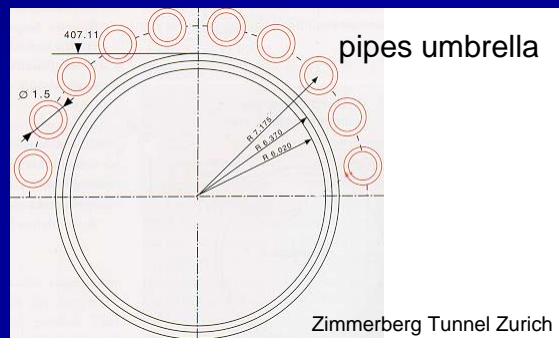


The photo shows an intact block between a disk and the face which became loose and was carried around by the head of the TBM.

If the size of the block is greater than the opening of the crusher of a slurry machine only manual work in the chamber can deal with it.

Risk management – Reduction of risk

- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization
 - Structures

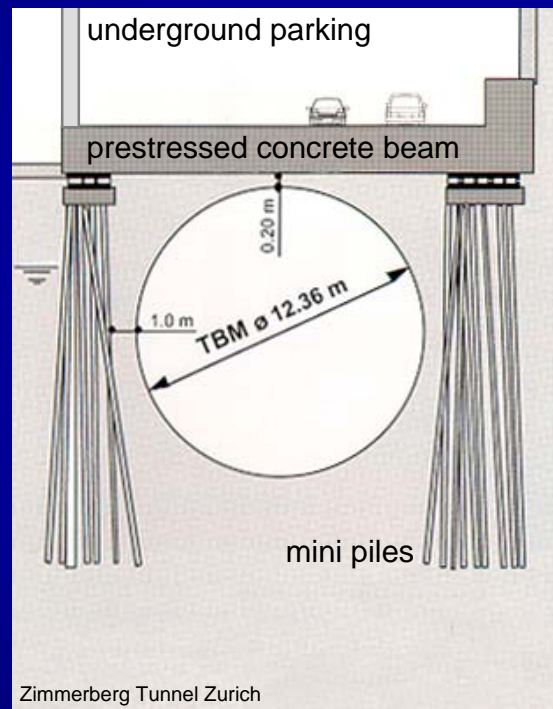


In some situations only the construction of real underground structures allows an adequate reduction of risk.

Here an umbrella over the roof of the large diameter Zimmerberg Tunnel is shown made by pipe jacking of a series of tubes filled up by concrete. The overburden was in this case so small that the execution of a grouted body in the roof became impossible.

Risk management – Reduction of risk

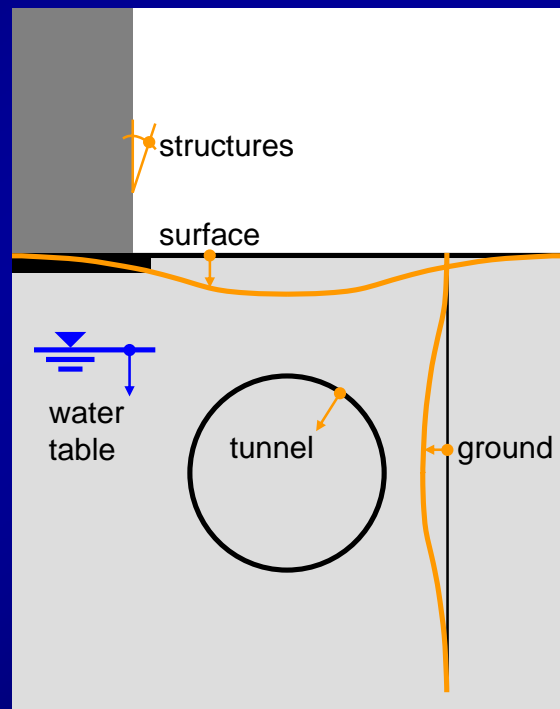
- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization
 - Structures



Another example illustrates the construction of a prestressed concrete beam founded on each side on so called micro-piles for under-passing – in river gravel with the presence of ground water – the underground car park of a complex tall building. As seen in the figure the distance of the shield to the concrete beam was only 0.20 m. Thanks to the additional grouting measures carried out during the underpinning work on the building, an ordinary slurry mixture with very low pressure could be applied.

Risk management – Reduction of risk

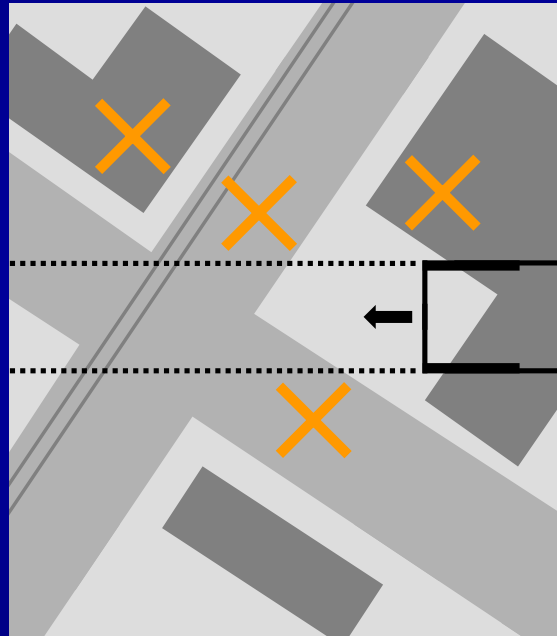
- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization
 - Structures
- Monitoring



Systematic monitoring of ground deformations including settlements, the behaviour of the nearby urban structures, the groundwater table and the machine performance forms an integral part of any *safety plan*.

Risk management – Reduction of risk

- Constructional measures
 - Ground improvement
 - Prepared stations for TBM
 - Grouting for block stabilization
 - Structures
- Monitoring
- Additional measures

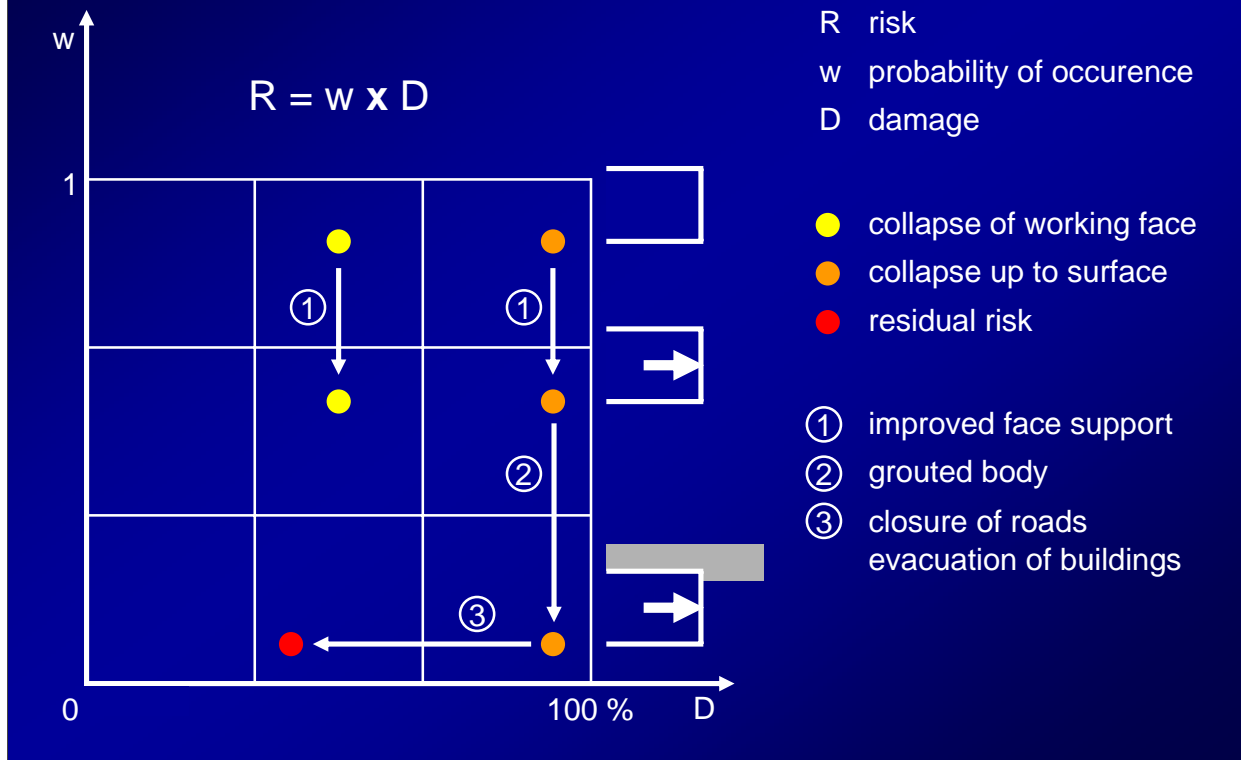


closure of roads
evacuation of buildings

In addition to the above discussed constructional measures the risk can be further reduced by reducing the amount of damage.

The picture shows as an example the case of the temporary closure of roads to be under-passed and the evacuation of buildings.

Risk management – Reduction of risk



Here a visual representation is given of how different measures can produce a reduction of the risk for a face failure and its possible propagation up to the ground surface.

According to its definition risk has two components: probability of occurrence w and amount of damage D . In a quantitative appraisal the product of these two factors defines the risk: $R = w \times D$.

In the graph the case of an urban tunnel with the possibility of face failure and a possible triggered collapse up to the ground surface is discussed. The probability of occurrence of these undesired events is assumed to be the same. But as seen from the graph the associated amounts of damage is different.

In order to reduce the probability of both events the support of the face might be improved by a better conditioning of the slurry or the muck in the chamber (①).

If the corresponding decrease of the risk is not sufficient one can, in addition, create an injected body in the roof of the tunnel resulting in a drastically reduced probability of ground failure up to the surface (②).

If a further risk reduction is required the possible amount of damage can be reduced by closing roads or/and evacuating buildings (③). The corresponding point in the graph indicates the accepted risk.

Grouted body

Grouted Body

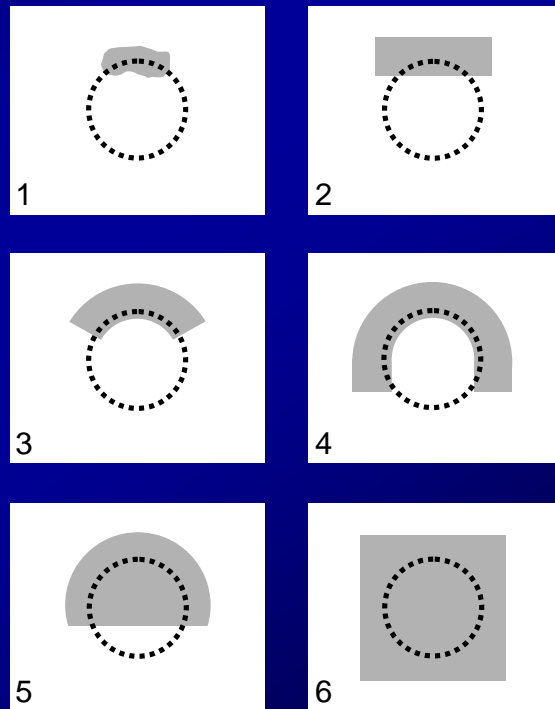
- Planning and execution
- Design

After the general overview on urban tunneling in soft ground using TBM's we turn now to the discussion of key aspects of grouted bodies. We have seen that the grouted body in many cases forms an integral part of a TBM drive with EPB and slurry shields.

First the issue of planning and execution will be discussed followed by design considerations.

Planning and execution

- General layout

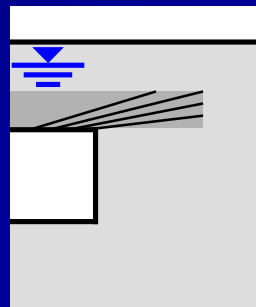


In a ground with a sufficient average cohesion (considered at the scale of the cross-section of the tunnel) but with locally and erratically occurring inclusions of materials having no cohesion a modest grouting in the roof area is generally sufficient (case 1). In the absence of ground water such a measure in many cases allows to work in open mood with a EPB or with low excessive pressure with a slurry machine. Such a consolidated body will not have neither a well defined shape nor a prescribed minimum cohesion. Therefore, such measures are not the object of statical calculations.

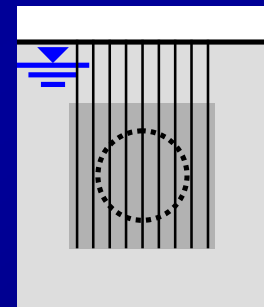
In the other cases (2-5) a well defined shape and size of the grouted body with clearly defined shear strength parameters are aimed at. The most important and most frequently applied body is presented by case 2 and 3. For practical reasons case 2 is generally preferred. Grouted bodies according to the cases 4 and 5 are extremely work intensive and costly. Additionally, from statical point of view they can hardly be justified. The case 6 shows the above mentioned *stations* for the preplanned maintenance work in the chamber.

Planning and execution

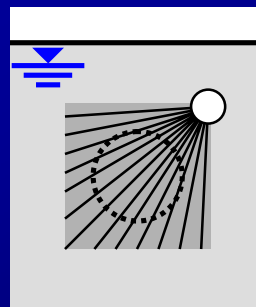
- General layout
- Execution



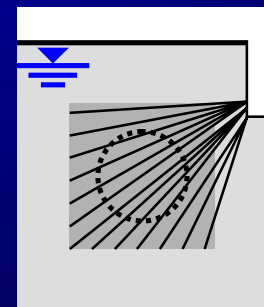
TBM



surface



auxiliary tunnel

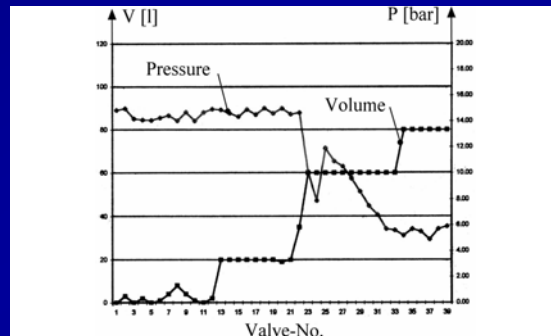


shaft

For practical reasons systematic grouting operations are generally carried out from outside the TBM. Drilling and grouting from the ground surface does not require special measures against ground water pressure like in the other cases shown in the figure.

Planning and execution

- General layout
- Execution
- Grouting technology



type
amount
pressure
intervals

Zimmerberg Tunnel Zurich

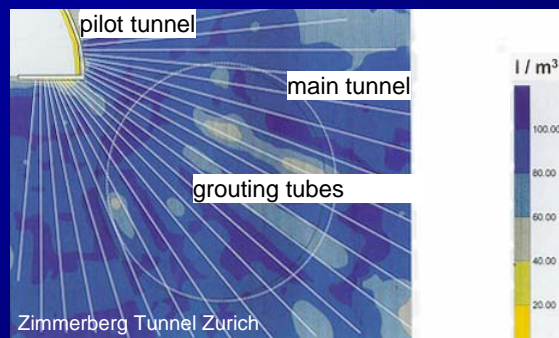
The most important factors in the planning and execution of grouting operations are the layout of the drill holes with the distance between the valves along it as well the composition of the grout, the applied pressure and the grouted volume per valve. Depending on the nature of the ground and the required mechanical properties (strength and/or permeability) several successive grouting operations from the same valve must in many cases be carried out.

Planning and execution

- General layout
- Execution
- Grouting technology
- Requirements

➡ minimum required strength

➡ satisfactory homogeneity

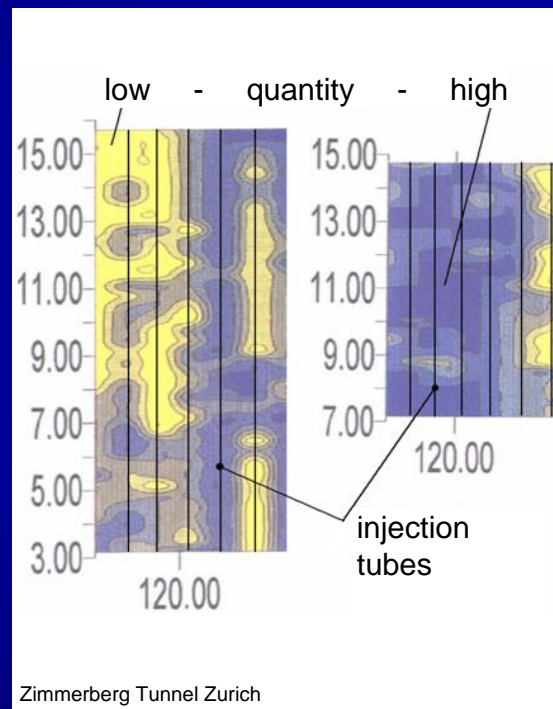


In order to achieve the minimum required shear strength and a satisfactory homogeneity of the grouted body it is necessary to apply advanced methods of data registration and data processing.

The lower figure shows an example of the visualization of the absorbed grout quantity for a *station*.

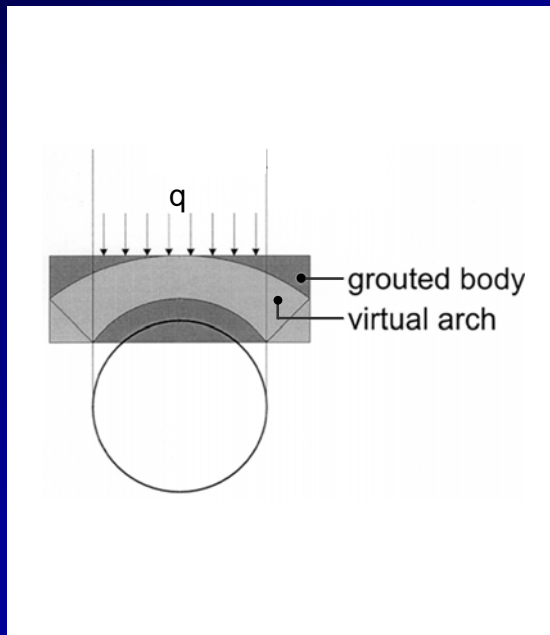
Planning and execution

- General layout
- Execution
- Grouting technology
- Requirements
- Monitoring

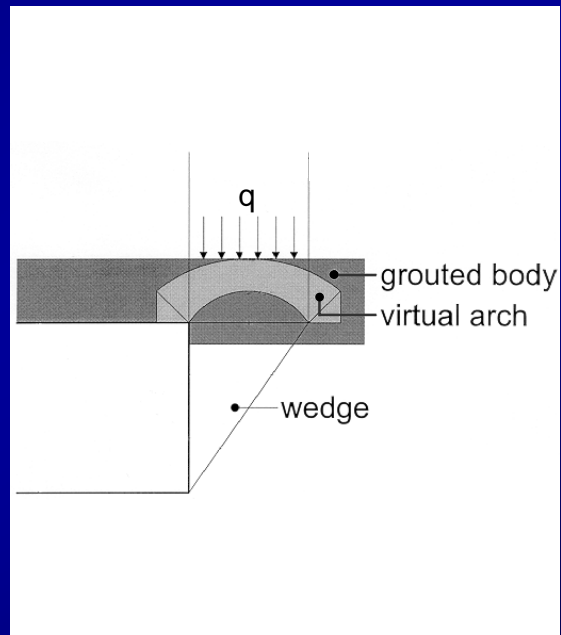


Another example illustrates the results of data monitoring revealing areas with the necessity of further grouting campaign and the density of grout after the completion of the work.

Design



statical action
transverse direction

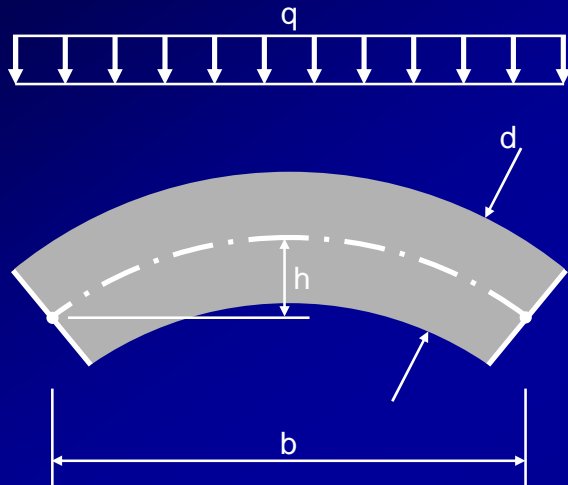


statical action
longitudinal direction

A grouted body above the tunnel acts statically both in the lateral and longitudinal directions.

Within the slab virtual arches can be assumed provided the material is stressed to its limit state. Thus, under a uniformly distributed vertical load the state of stress in such an arch is defined by the uniaxial strength of the grouted body.

Design – Virtual arch in failure state



State of limit equilibrium:

- Uniaxial strength σ_c
- Load in limit state q^*
- Factor of safety FS

$$q^* = 8 \sigma_c \frac{h d}{b^2}$$

$$FS = \frac{q^*}{q_{\text{eff}}}$$

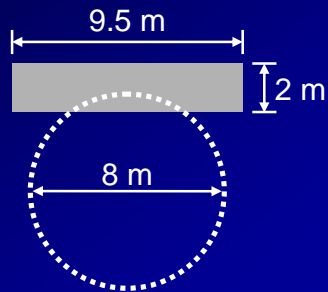
For an arch under these conditions simple relations exist between the geometrical parameters b , d and h as well as the magnitude of the load q and the uniaxial strength σ_c of the body.

The formula can easily be obtained by the assumption that the bending moments at the supports and in the centre of the arch are zero. It shows that the load bearing capacity q^* is proportional to the height h , thickness d and uniaxial strength σ_c of the body and inversely proportional to the square of the span b .

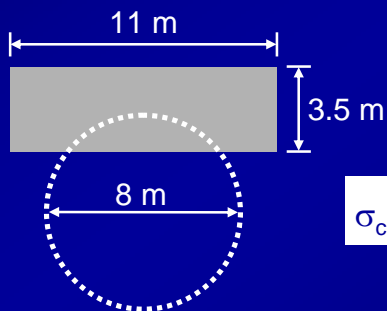
The factor of safety SF can be defined as the ratio of the maximum possible load q^* to the effectively acting load q_{eff} .

Design – Relation geometry/strength

$q = 100 \text{ kN/m}^2$, $SF = 1.5$



$$\sigma_c = 1.5 \text{ MPa}$$



$$\sigma_c = 0.6 \text{ MPa}$$

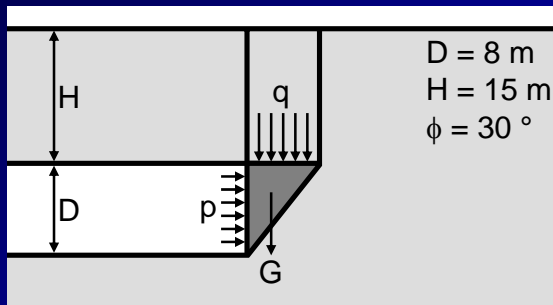
Factors:

- Shape and size
- Strength
- Degree of homogeneity

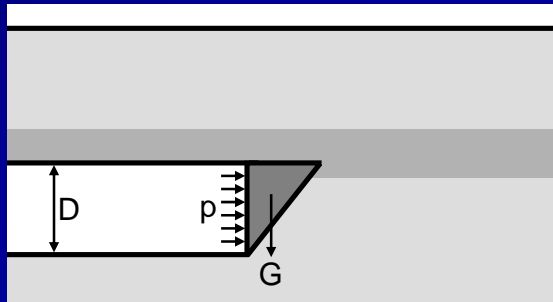
The simple formula permits the study of the relative importance of the shape and size of the grouted slab with respect to its uniaxial strength σ_c .

The two examples in the figure indicates that for a given load q and a factor of safety SF it can be beneficial to increase the size of the body in favour of a reduction of the requested uniaxial strength σ_c of the body.

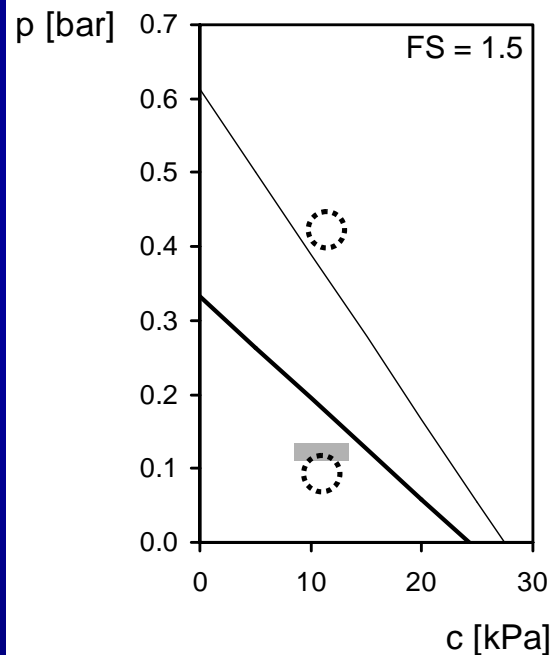
Design – Support pressure



without grouted body



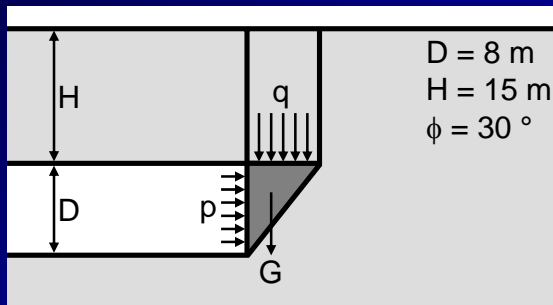
with grouted body



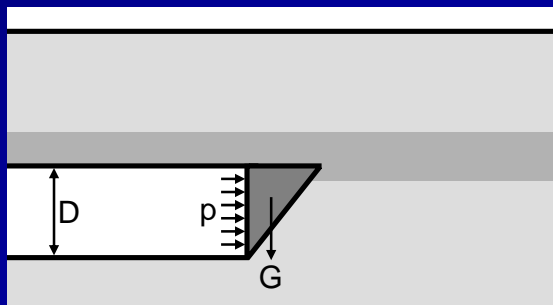
Consider now the effect of the grouted body on the necessary support pressure p acting on the face for a given set of parameters in function of the cohesion c of the untreated ground.

As can be seen from the graph for a soil with no cohesion the presence of the grouted body reduces the necessary support pressure p by a factor 2. This is due to the fact that in case of the grouted body there is no vertical load q acting on the wedge.

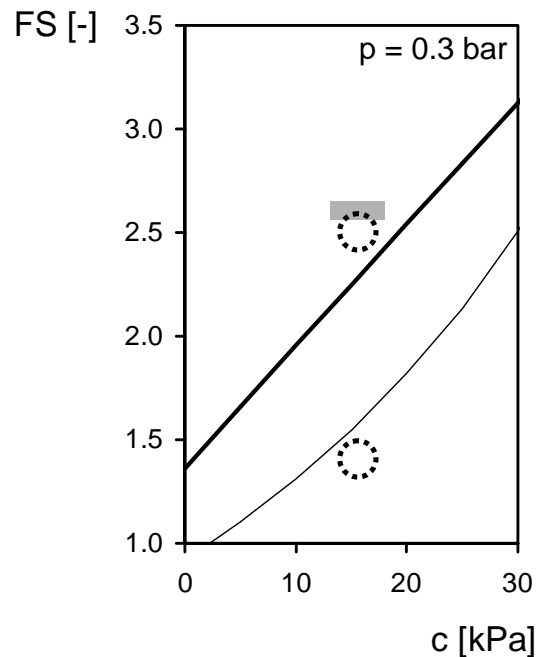
Design – Support pressure



without grouted body



with grouted body



For the same set of parameters but for a selected value of the support pressure p the factor of safety FS is given as a function of the ground cohesion c . Thanks to the grouted body already an extremely small value of the cohesion c suffices to obtain for the factor of safety FS the value 1.5.

In the case of an EPB machine above the water table and a small value of ground cohesion and without important objects to be under-passed an open mode of operation can be envisaged.

Conclusions

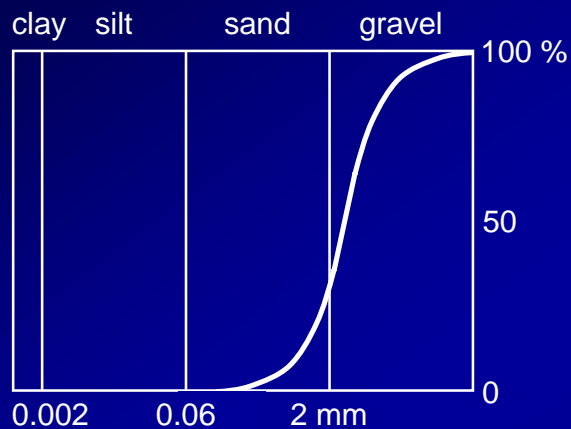
Grouted Body

- High safety against collapse
- Reduced ground settlements
- Safety during work in the chamber
- Control of time schedule

These are four major factors favoring the application of a grouted body.

In a given case the decision must first of all take into consideration the risks involved and possibly the importance of the time schedule to be fulfilled.

Grouted Body

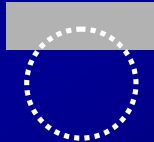


Sand and gravel without fines:

- Low cohesion
- High permeability



Mechanised tunnelling feasible with grouted body



One of the major results which has emerged from recent tunnelling experience is that in some types of ground - despite advanced techniques of conditioning - only a grouted body makes TBM drives possible.

Consider, for example sandy gravel with almost no fines as illustrated by the grain size distribution. It must also be kept in mind that in the presence of a grouted body any work in the chamber can be carried out faster than without it.

Grouted Body – Operational benefits

- Reduction of support pressure
 - Slurry shield
 - No or only little infiltration of suspension
 - EPB shield
 - Less conditioning
 - Less tool wear and torque
 - Better handling of muck

These are the possible operational benefits which may result from the application of grouted bodies in the roof area of the tunnel.

Urban tunnelling in soft ground using TBM's

- Efficient TBM technology
- Reliable design procedure
- Improved methods of conditioning
- Advanced grouting technology
- Reliable risk management

➔ Safe and economical urban tunnelling in soft ground assured

Summarizing the presentation here the main features permitting safe and economic tunnelling in soft ground under urban conditions using TBM's with slurry or EPB type of face support are listed.

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