TBM tunnelling in complex rock formations

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A list of references can be found at the end of the hand-out.

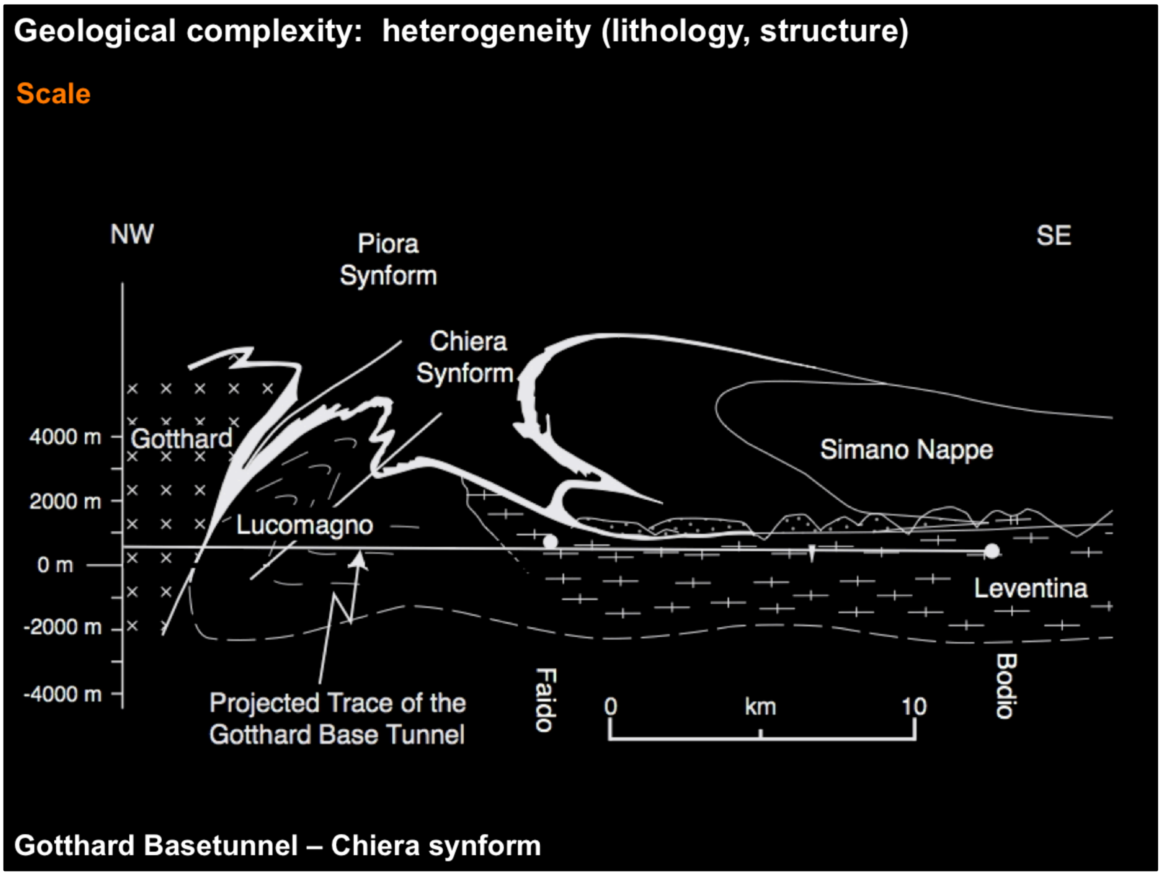
Geological complexity: heterogeneity (lithology, structure)

Scale

Gotthard Basetunnel – Chiera synform

Geological complexity is understood as heterogeneity with respect to composition or structure. Heterogeneity, and thus complexity as well, is a matter of scale and, consequently, a matter of perspective.

The scale of this photograph – that of a specimen from the so-called Chiera Synform of the Gotthard Basetunnel – may be interesting for a petrologist.

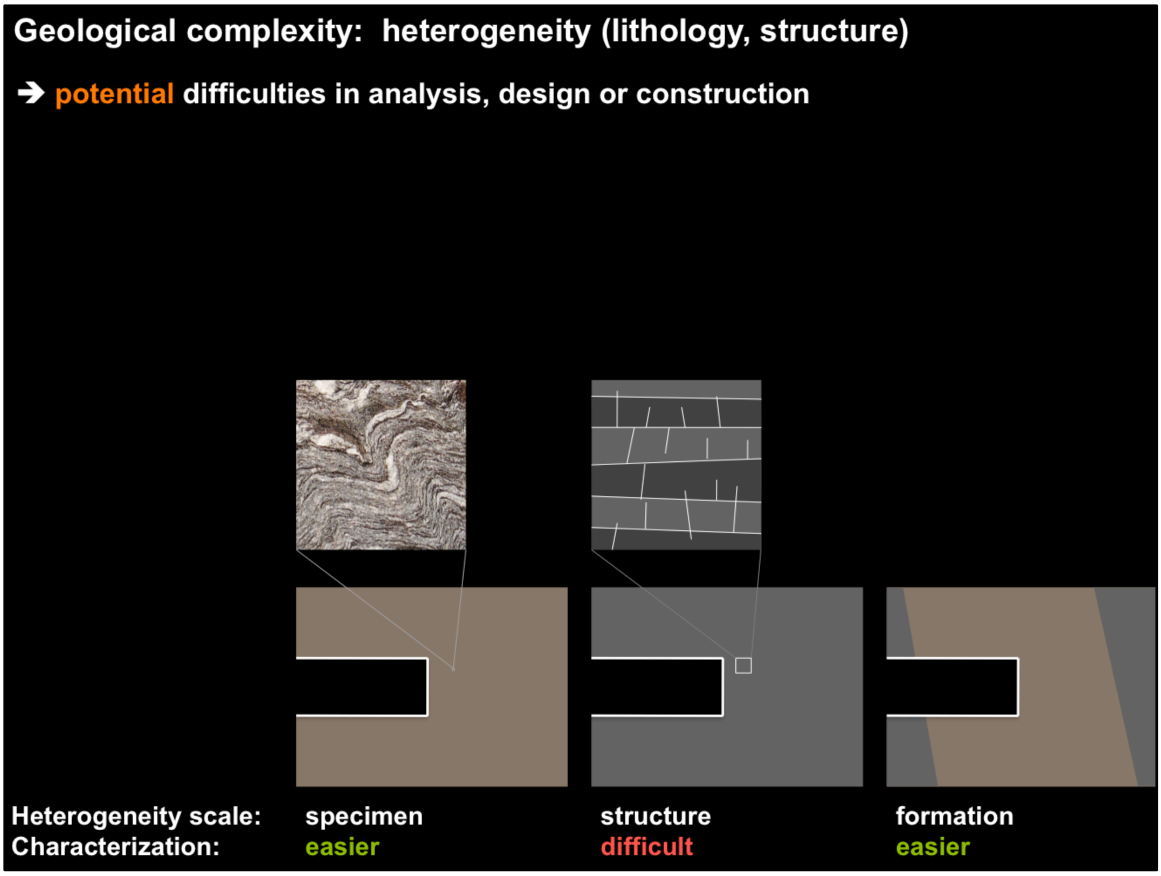


Geological complexity: heterogeneity (lithology, structure)

Scale

Gotthard Basetunnel – Chiera synform

This drawing shows the Chiera Synform in another scale – a scale, which may be interesting for a structural geologist.

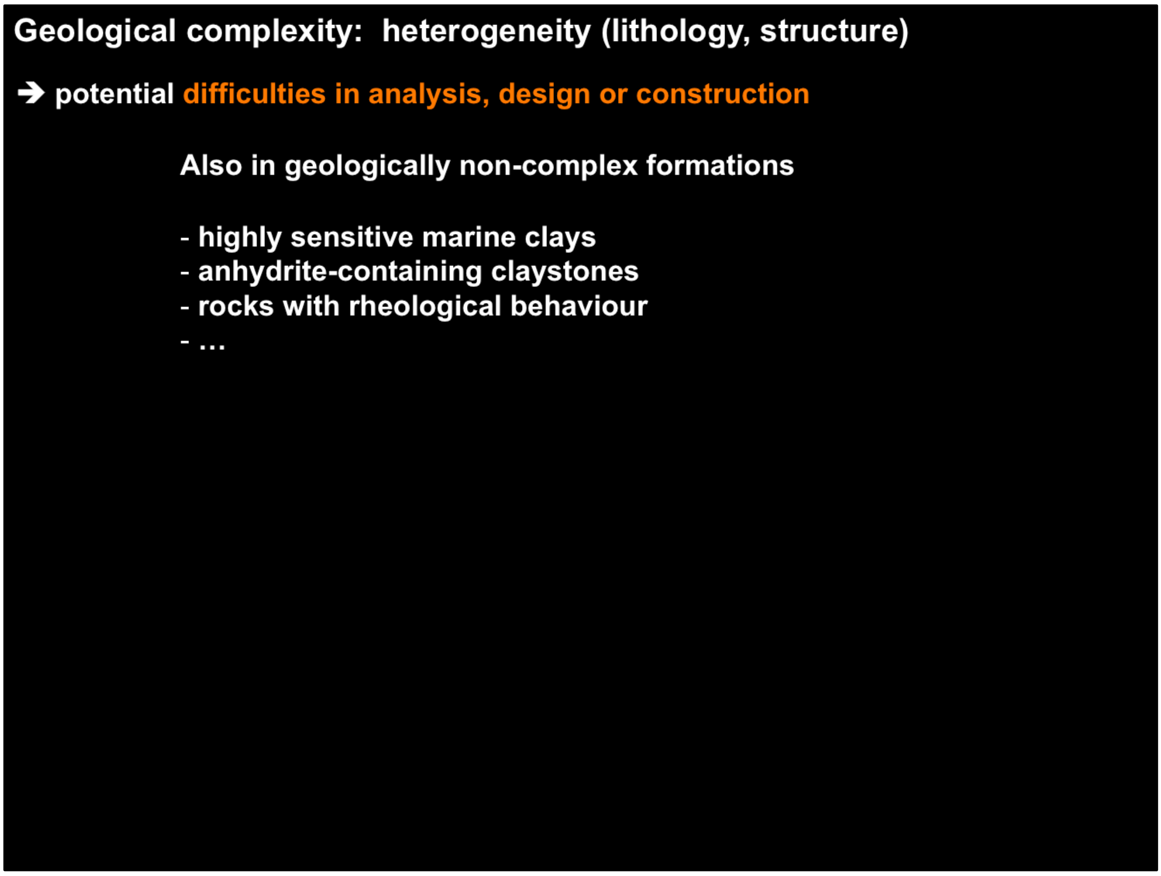


Geological complexity: heterogeneity (lithology, structure)

➔ potential difficulties in analysis, design or construction

Heterogeneity scale:	specimen	structure	formation
Characterization:	easier	difficult	easier

Depending on the scale, geological complexity may (but not necessarily will) result in analysis, design or construction difficulties.
So, for example, the geotechnical characterization of the ground is difficult, if its lithological or structural heterogeneity occurs at the scale of the tunnel cross-section.



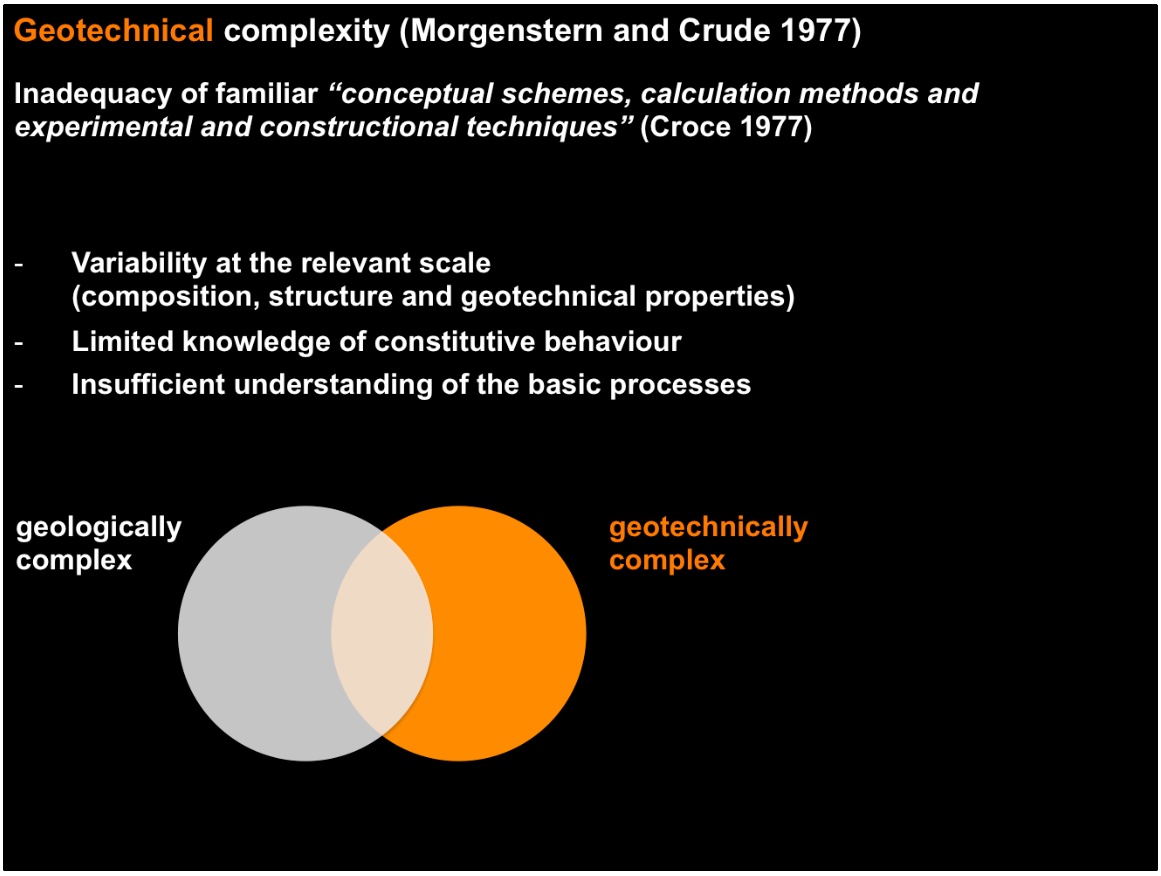
Geological complexity: heterogeneity (lithology, structure)

➔ potential **difficulties in analysis, design or construction**

Also in geologically non-complex formations

- highly sensitive marine clays
- anhydrite-containing claystones
- rocks with rheological behaviour
- …

However, analysis, design or construction difficulties may occur even in geologically non-complex formations – for example, when the constitutive behaviour of the ground or the underlying physical-chemical processes are poorly understood.



Geotechnical complexity (Morgenstern and Crude 1977)

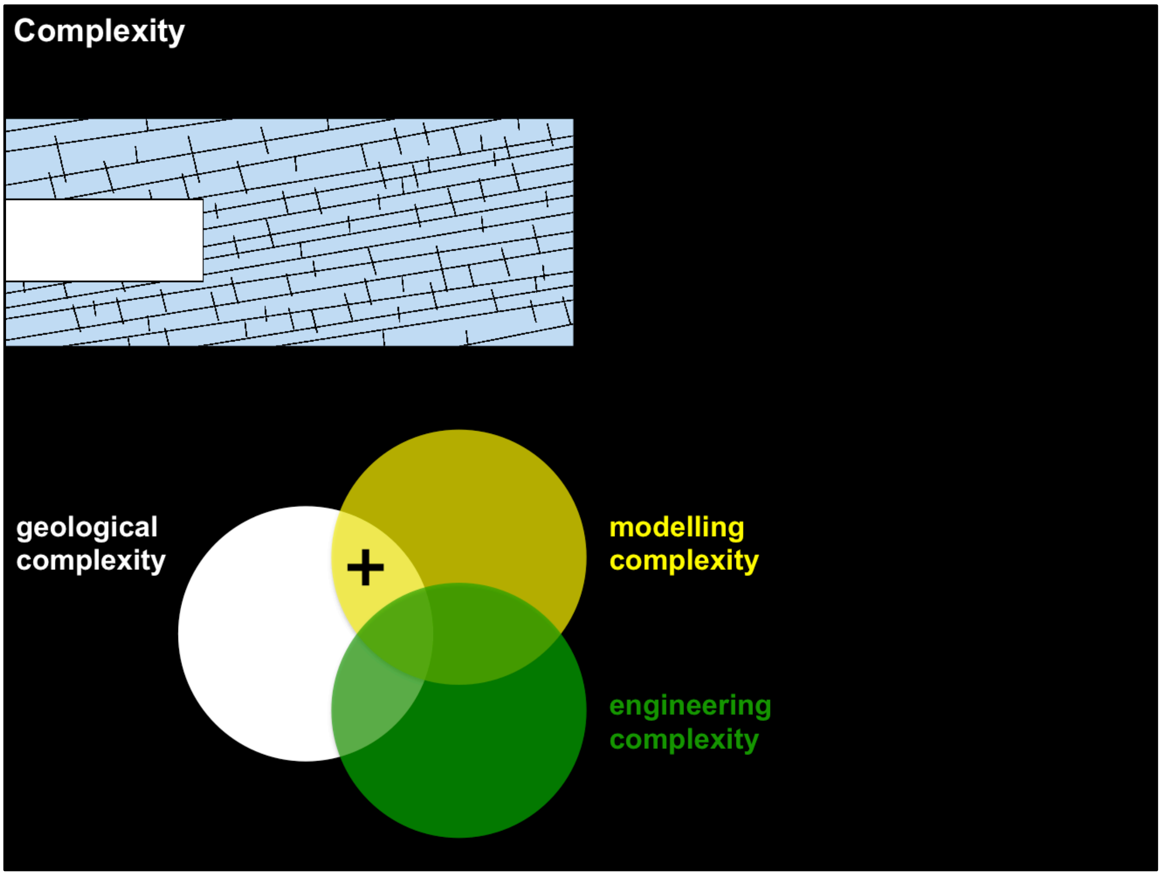
Inadequacy of familiar *"conceptual schemes, calculation methods and experimental and constructional techniques"* (Croce 1977)

- **Variability at the relevant scale**
  (composition, structure and geotechnical properties)
- **Limited knowledge of constitutive behaviour**
- **Insufficient understanding of the basic processes**

geologically complex

geotechnically complex

As geological complexity does not always result in geotechnical complexity and, on the other hand, geotechnical complexity may occur also in geologically non-complex formations, Morgenstern and Cruden [1] introduced the notion of geotechnical complexity. The latter is characterized by an inadequacy of familiar conceptual schemes, calculation methods, experimental and constructional techniques [22]. Variability of a formation at the relevant scale, limited knowledge as to its constitutive behaviour, insufficient understanding of the basic processes, certainly justify the attribute of "complex", at least from a modelling perspective.



Complexity

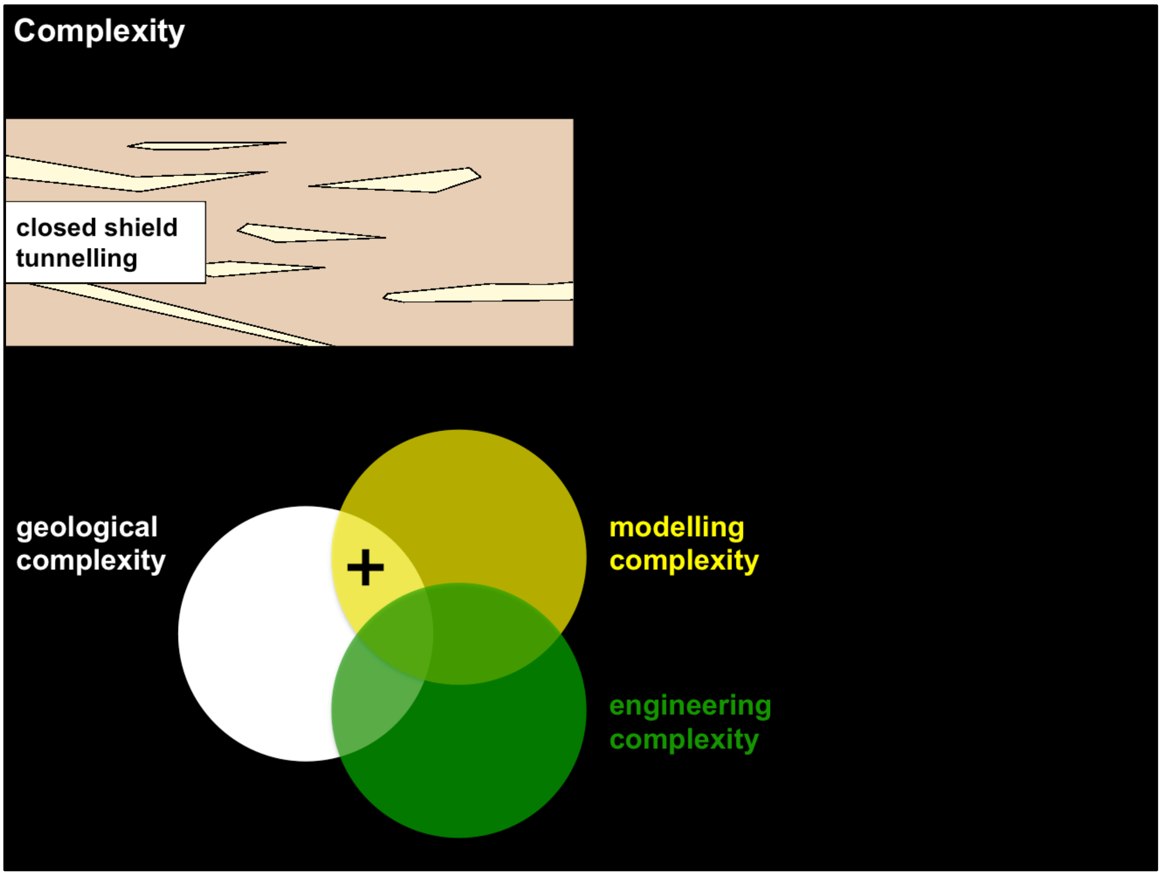
geological complexity

modelling complexity

engineering complexity

+

However, a formation that is complex from a geological or modelling perspective is not necessarily complex from an engineering perspective. For example, tunnelling through jointed sedimentary rocks is in most cases routine.



Complexity

closed shield
tunnelling

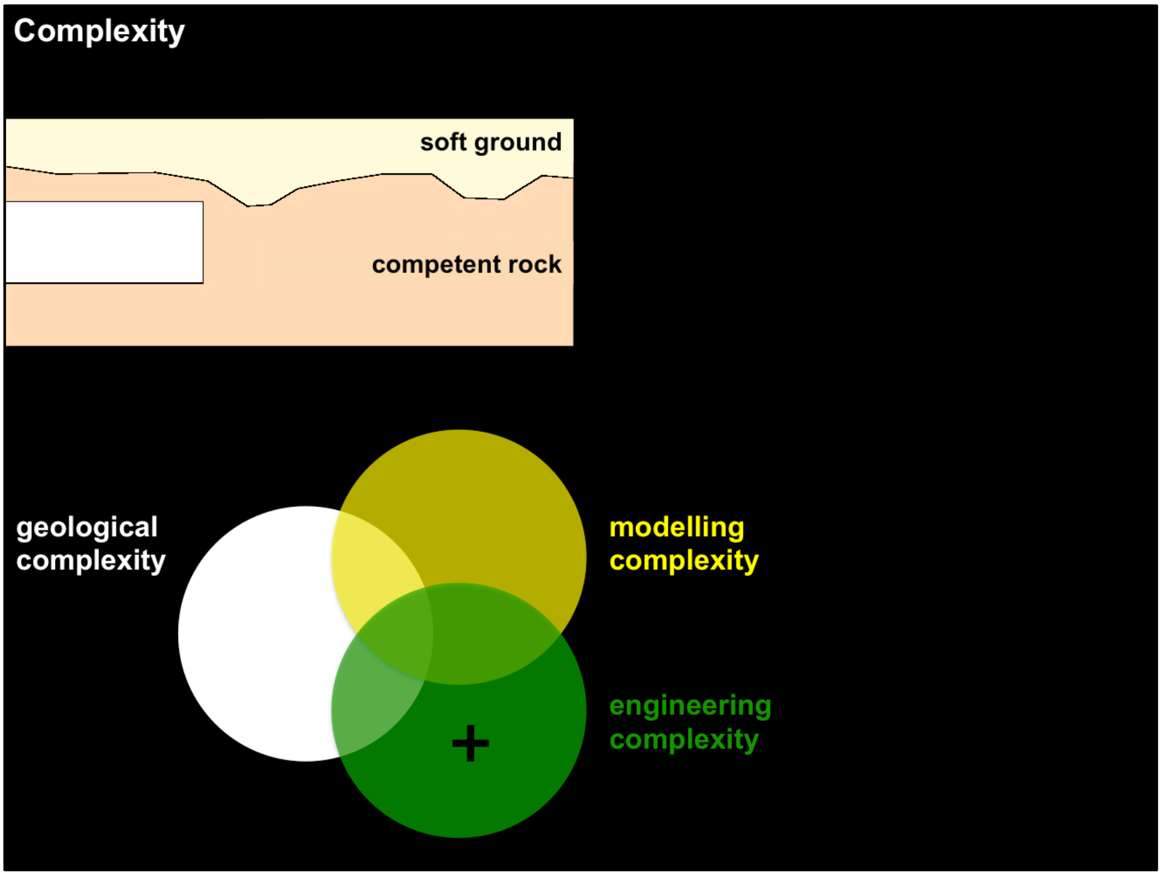
geological
complexity

+

modelling
complexity

engineering
complexity

As another example, consider closed shield tunnelling through heterogeneous quartenary deposits. In this case, the selection of a suitable construction method eliminates the effect of geological or modelling complexity.



Complexity

soft ground

competent rock

geological complexity

modelling complexity

engineering complexity

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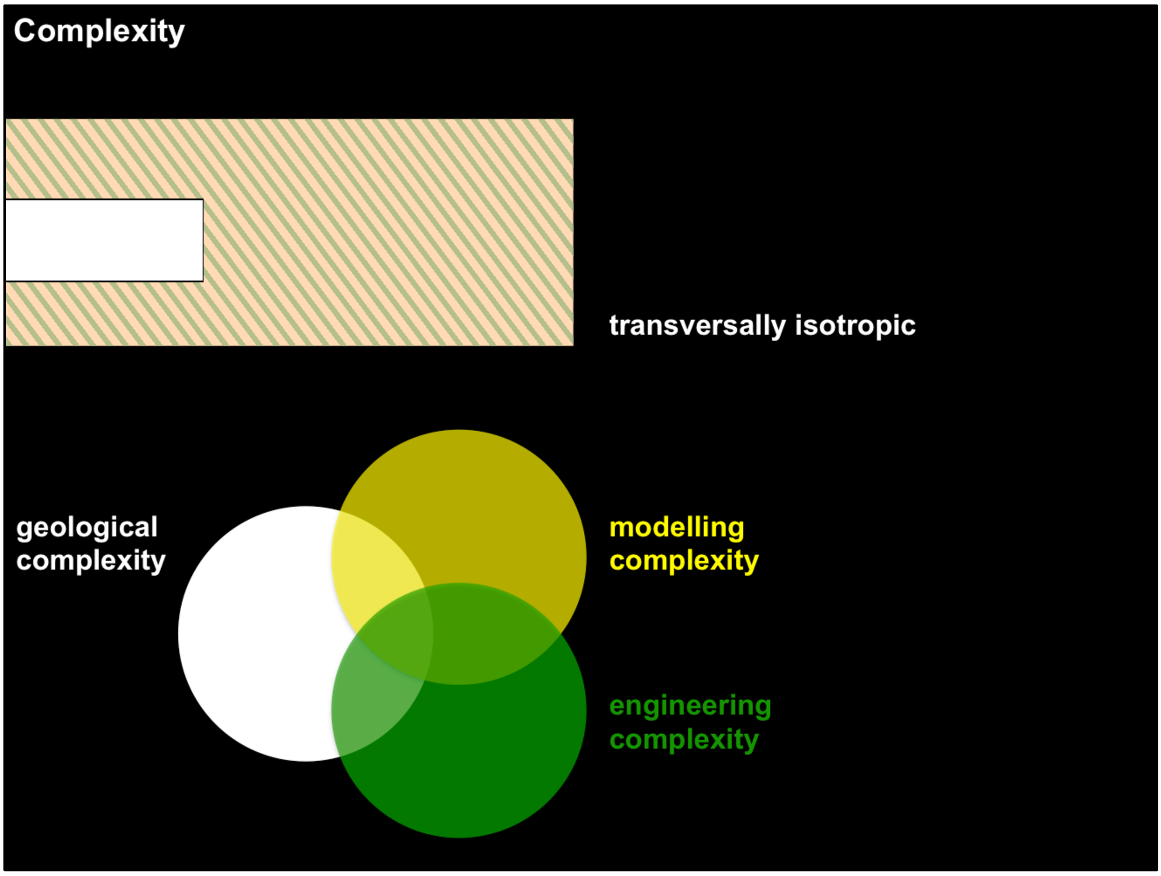
On the other hand, engineering complexity may arise even if the formation does not exhibit geological or modelling complexity – for example, in conventional or mechanized tunnelling at the interface between soil and rock.



Complexity

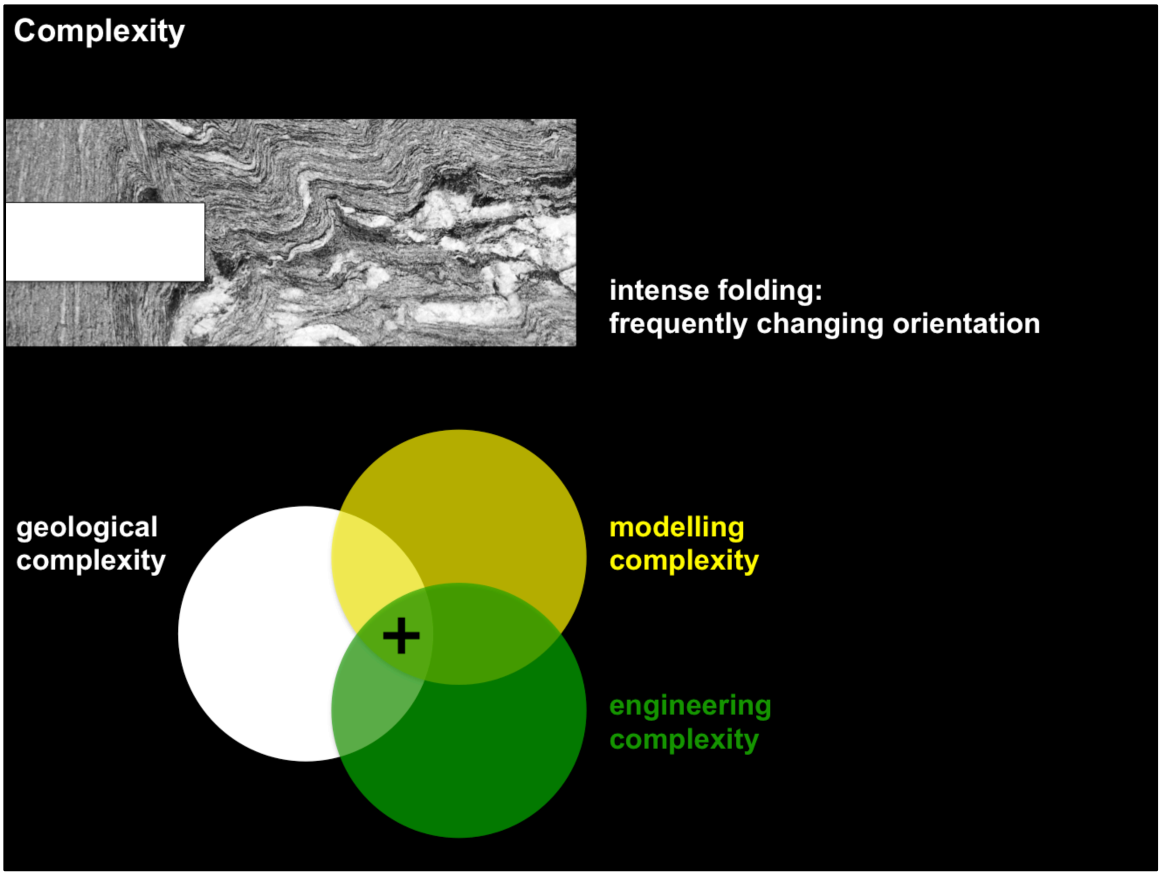
transversally isotropic

geological complexity

modelling complexity

engineering complexity

As most rocks exhibit transversal isotropy, anisotropy *per se* often does not increase complexity considerably.



Complexity

intense folding:
frequently changing orientation

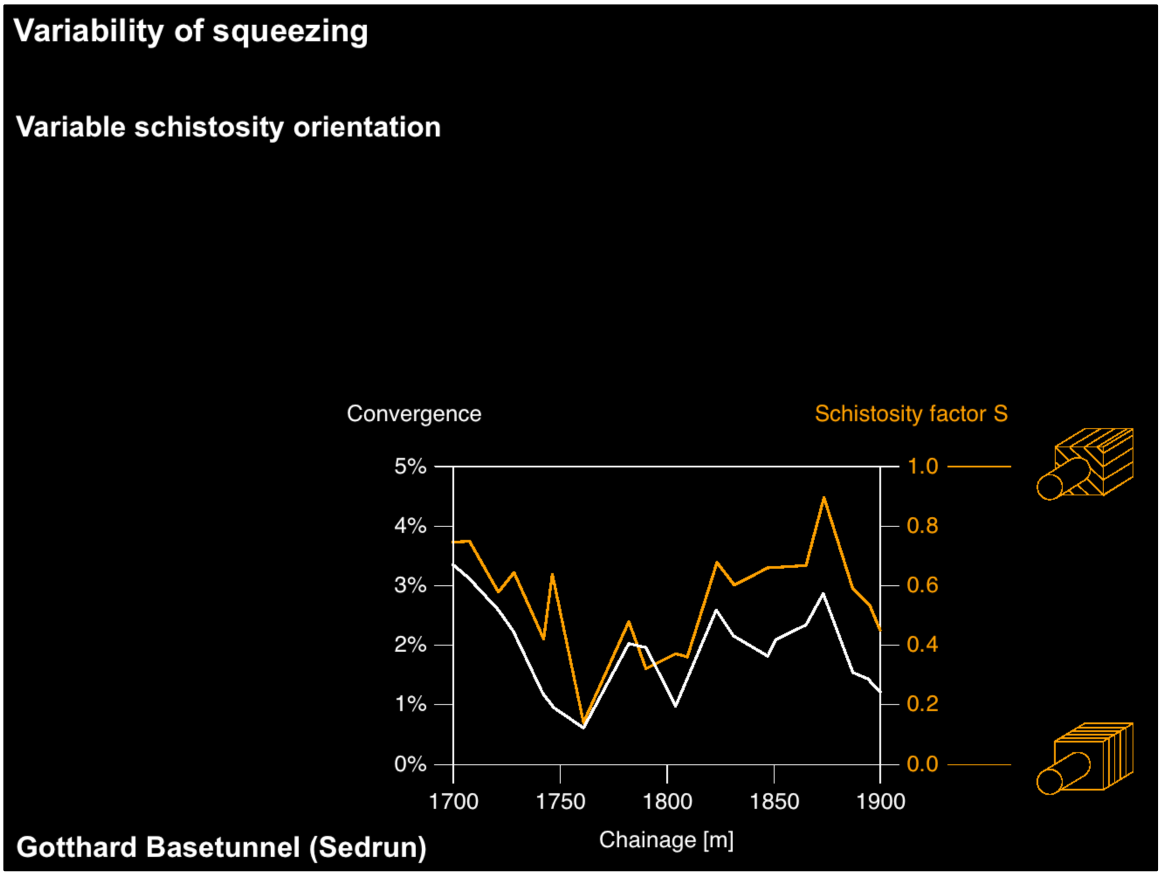
geological
complexity

+

modelling
complexity

engineering
complexity

However, in combination with intense folding, anisotropy may lead to a highly variable behaviour during tunnelling.



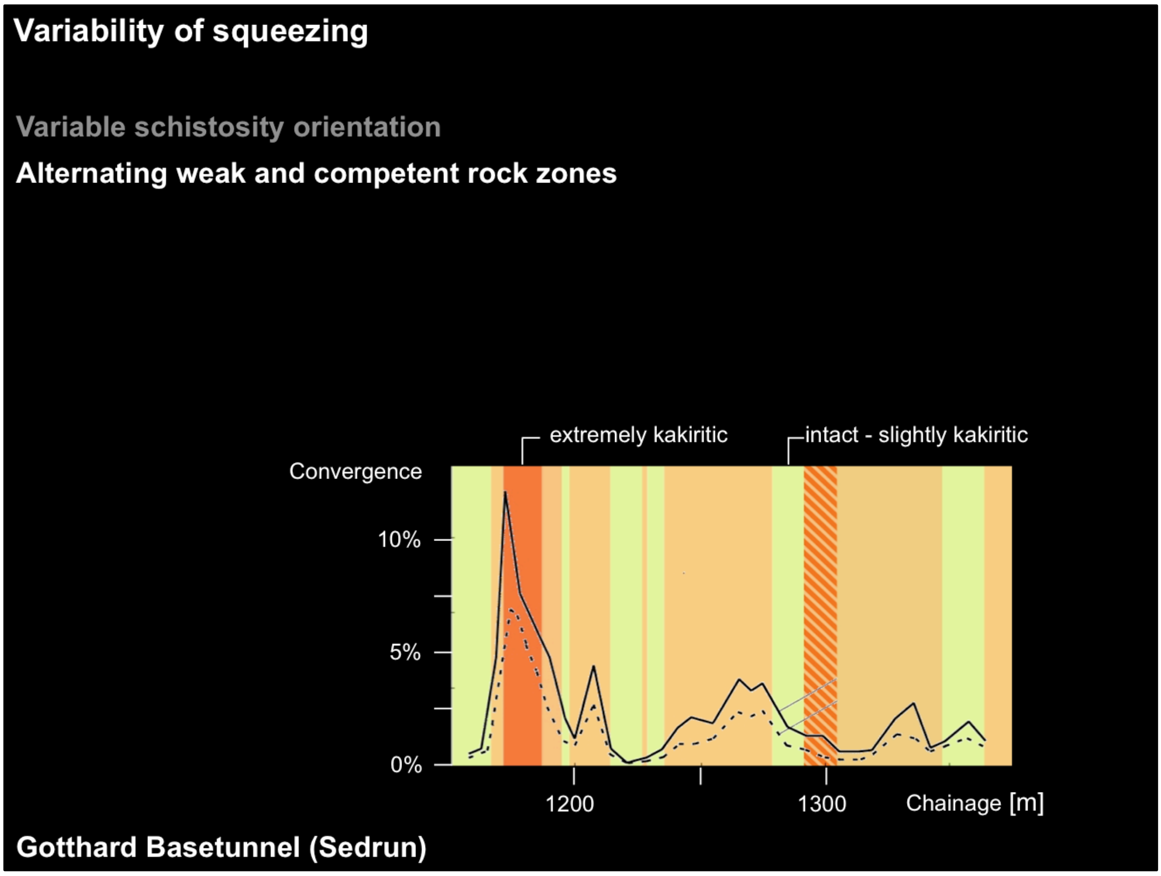
Variability of squeezing

Variable schistosity orientation

Gotthard Basetunnel (Sedrun)

This is observed, for example, when tunnelling through squeezing rocks.
The white line in this diagram shows the measured convergences in a section of the Gotthard Basetunnel with uniform support, uniform lithology and uniform degree of shearing, but variable schistosity orientation.
The orange line shows the so-called schistosity factor – a measure for the schistosity orientation [2]. This factor is defined such that it is equal to zero in the most favourable case (schistosity perpendicular to the tunnel axis), and becomes equal to one in the most unfavourable case (schistosity strike parallel to the tunnel axis).
The diagram shows that the convergence correlates well the schistosity orientation.

The variability of squeezing intensity is one of the main causes of construction setbacks. TBMs are particularly vulnerable to squeezing because the available space for deformations is very limited. It is, therefore, worth to spent a few minutes to this point.



Variability of squeezing

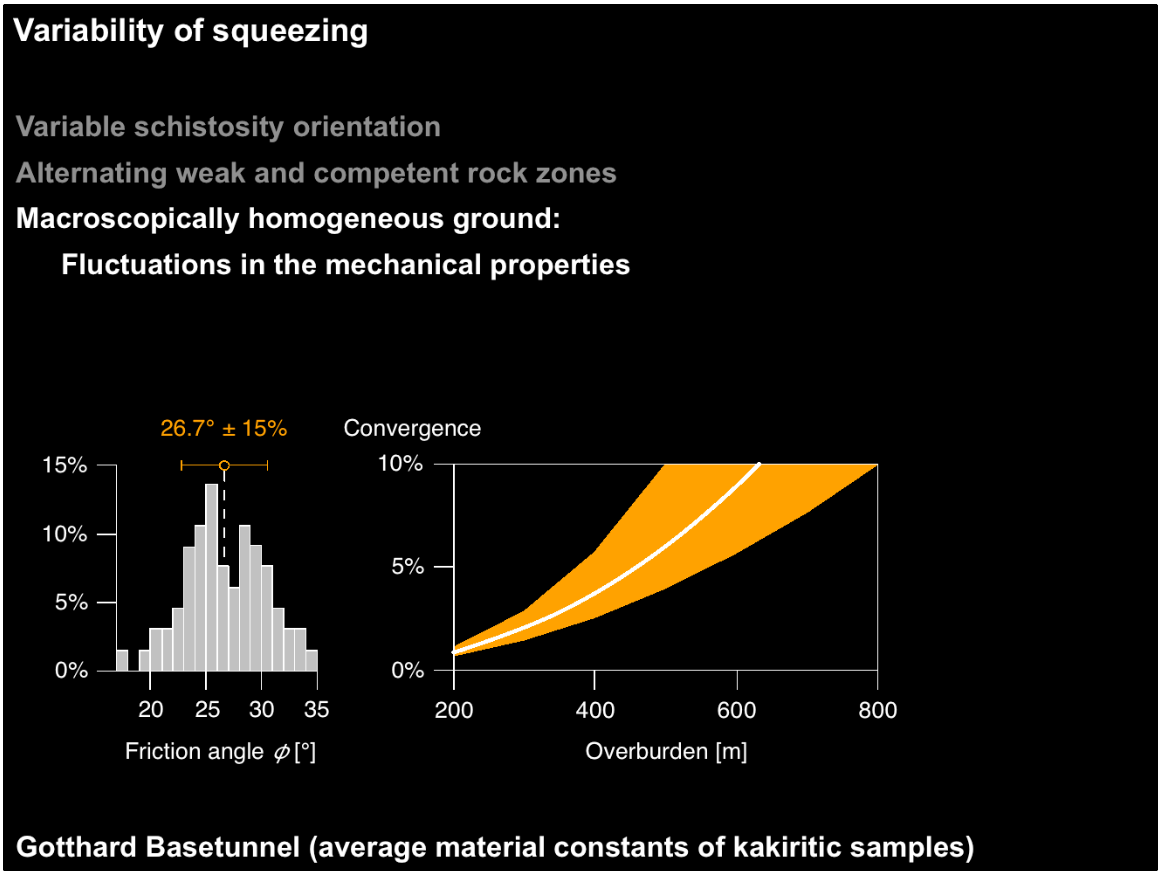
Variable schistosity orientation

Alternating weak and competent rock zones

Gotthard Basetunnel (Sedrun)

Another cause for the observed squeezing variability is a variable degree of shearing of the rocks.

The diagram shows the convergence along a section of the Gotthard Basetunnel, where the formation consisted of more or less tectonized rocks. The red colour shows the more intensively sheared zones, the yellow colour the more competent units. One can recognize a rough correlation between squeezing deformation and degree of shearing.



Variability of squeezing

Variable schistosity orientation

Alternating weak and competent rock zones

Macroscopically homogeneous ground:

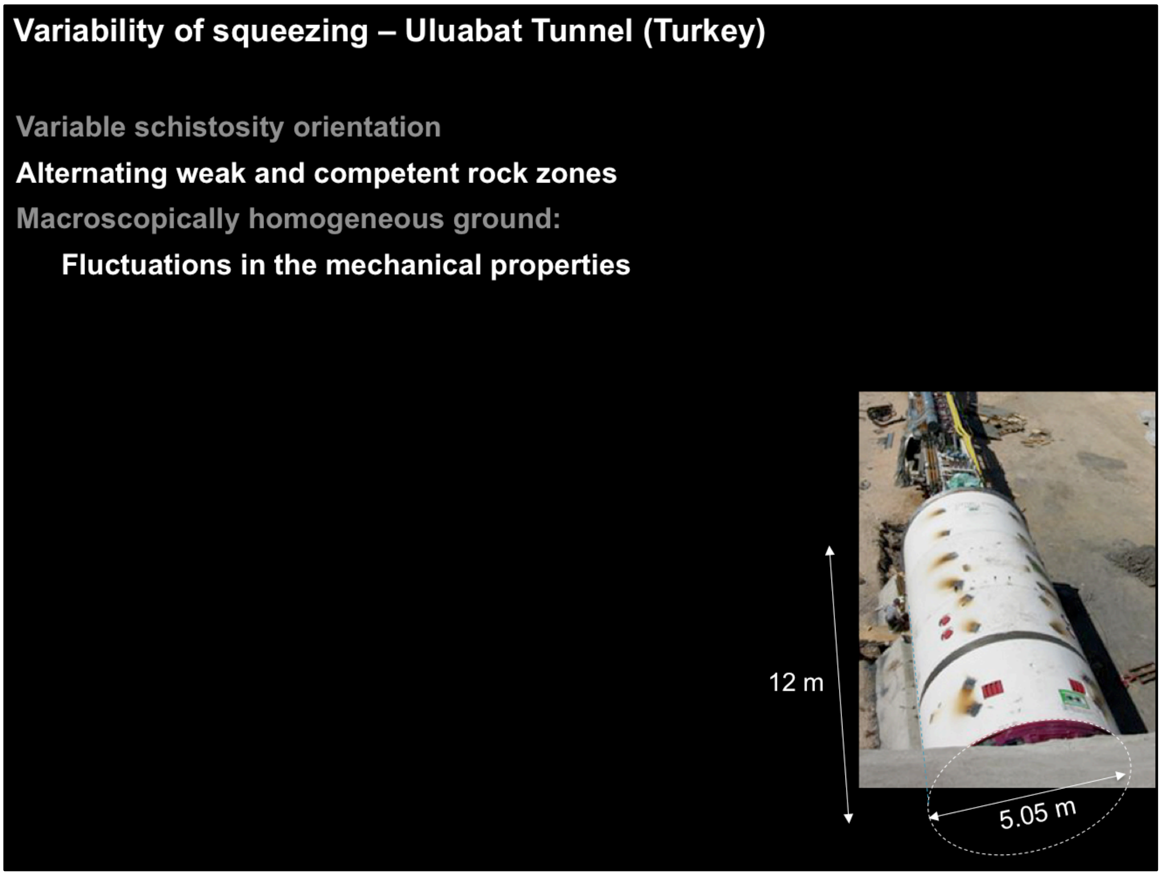
Fluctuations in the mechanical properties

Gotthard Basetunnel (average material constants of kakiritic samples)

Often the intensity of squeezing is highly variable even within apparently homogeneous rock stretches. The observed variability is probably due to a high sensitivity of the rock behaviour with respect to variations of its mechanical parameters.

The white line in this diagram shows the computed convergence as a function of the overburden, assuming the average parameters of kakiritic rocks [3]. The orange area shows the variation of this relationship when varying the friction angle by just 15% (and keeping all other parameters fixed).

The diagram illustrates, that a small change in the mechanical parameters may result in a significantly lower or higher convergence, particularly at great depths of cover.



Variability of squeezing – Uluabat Tunnel (Turkey)

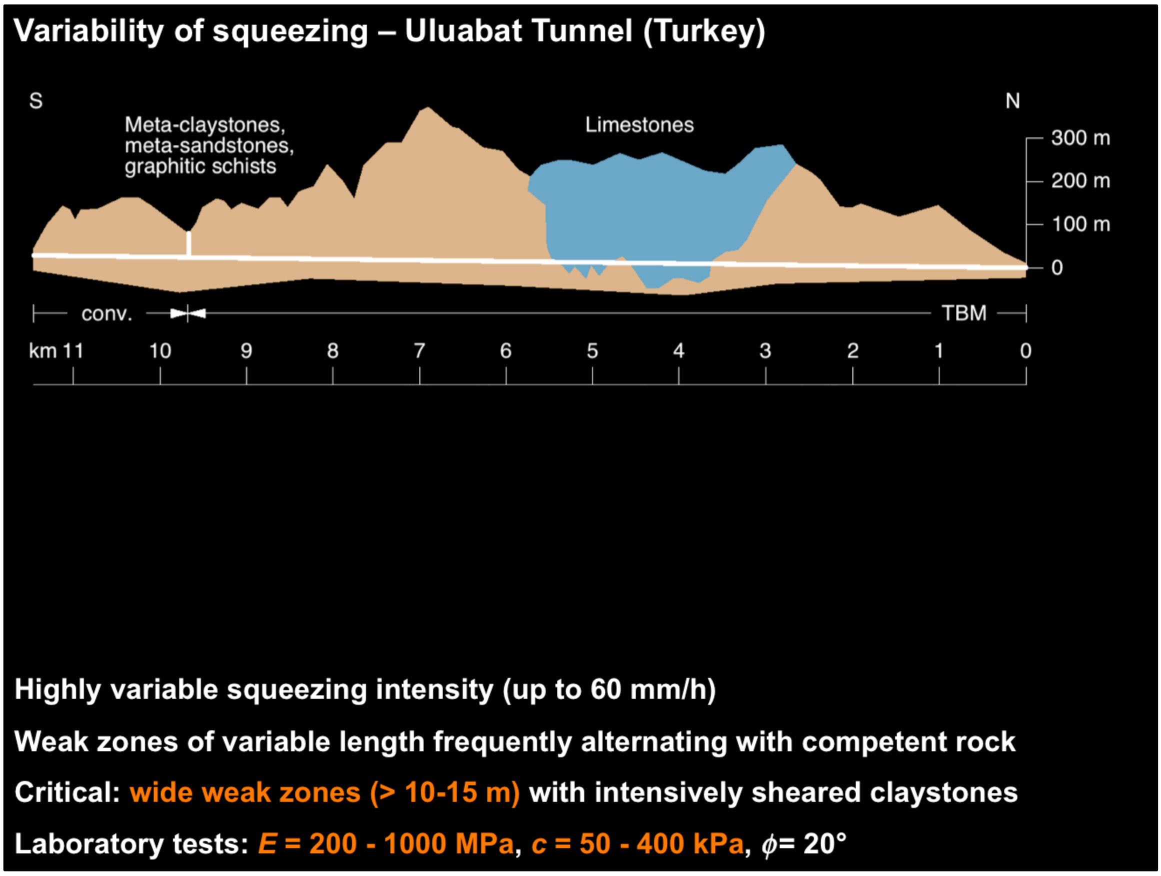
Variable schistosity orientation

Alternating weak and competent rock zones

Macroscopically homogeneous ground:

Fluctuations in the mechanical properties

In the following, the practical significance of these aspects for mechanized tunnelling will be illustrated by making reference to Uluabat tunnel – a hydraulic tunnel about 100 km south of Istanbul. It was constructed by a single-shield TBM. The boring diameter was equal to 5 m and the shield was 12 m long.



Variability of squeezing – Uluabat Tunnel (Turkey)

Highly variable squeezing intensity (up to 60 mm/h)

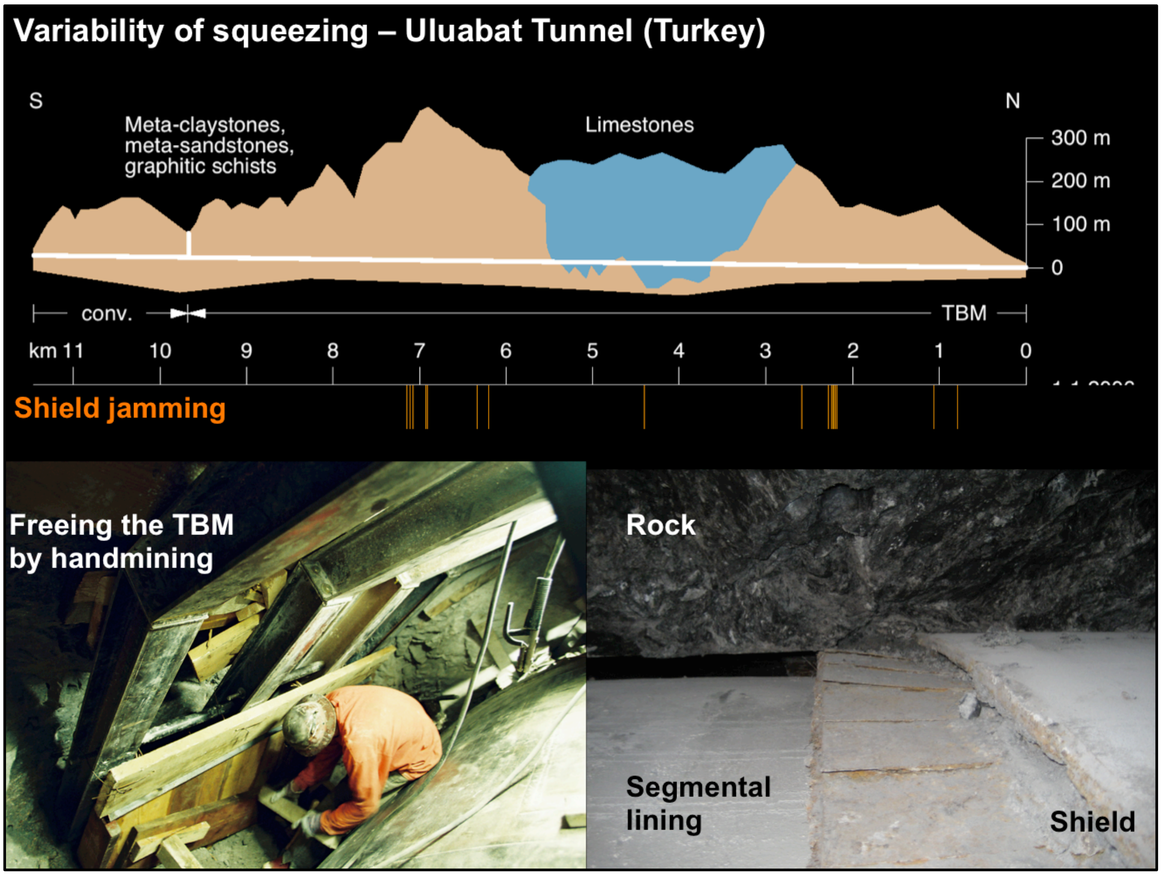
Weak zones of variable length frequently alternating with competent rock

Critical: wide weak zones (> 10-15 m) with intensively sheared claystones

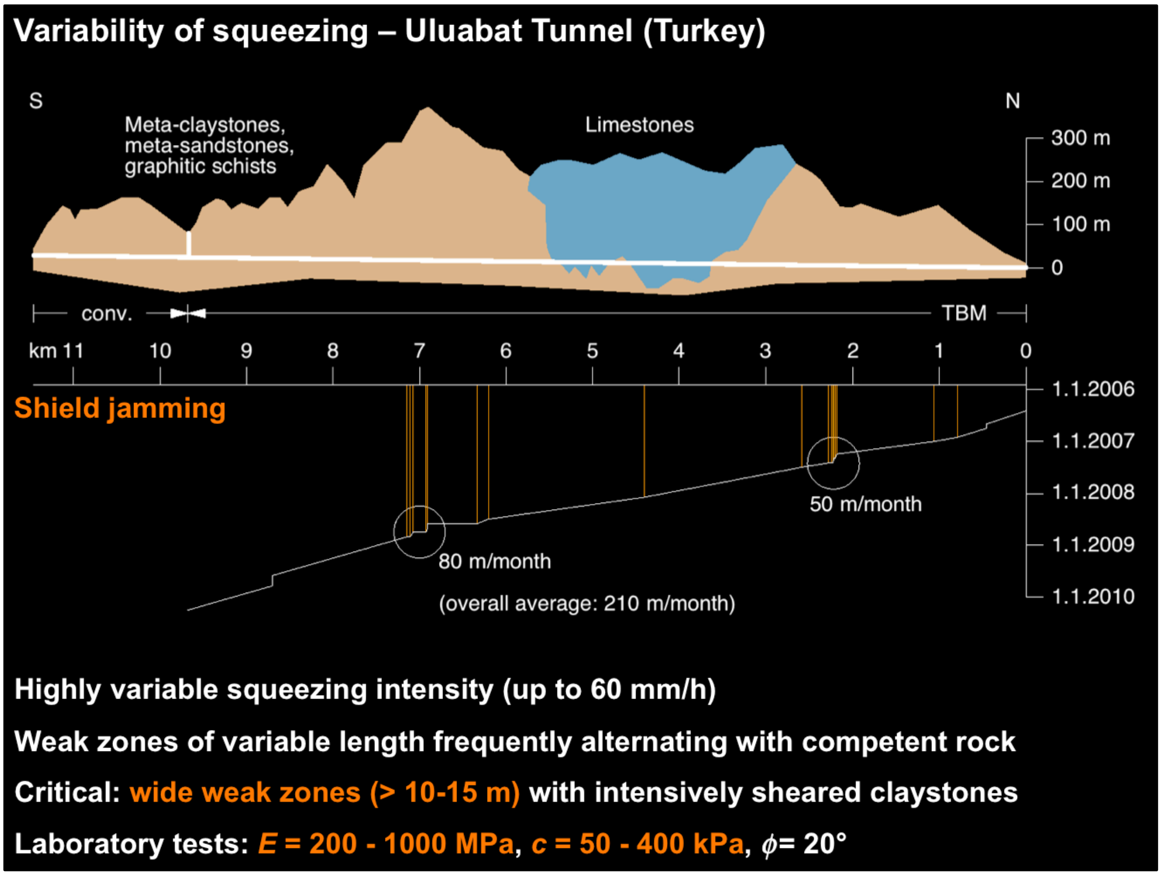
Laboratory tests: E = 200 - 1000 MPa, c = 50 - 400 kPa, ϕ= 20°

The tunnel crosses mainly Triassic, slightly metamorphic sandstones, claystones and graphitic schists (overlain by Jurassic limestones in the middle of the alignment) containing locally weak zones of variable thickness [4]. Severe squeezing conditions were encountered in the Triassic formation characterized by convergence rates of up to 60 mm per hour.

Variability of squeezing – Uluabat Tunnel (Turkey)



The TBM was stuck due to squeezing several times. Demanding hand-mining works were necessary in order to free the TBM. The photograph at the right was taken during such works and shows the extrados of the shield tail and of the segmental lining. The ground has closed the gap around the shield, but has not yet established contact with the lining.



Variability of squeezing – Uluabat Tunnel (Turkey)

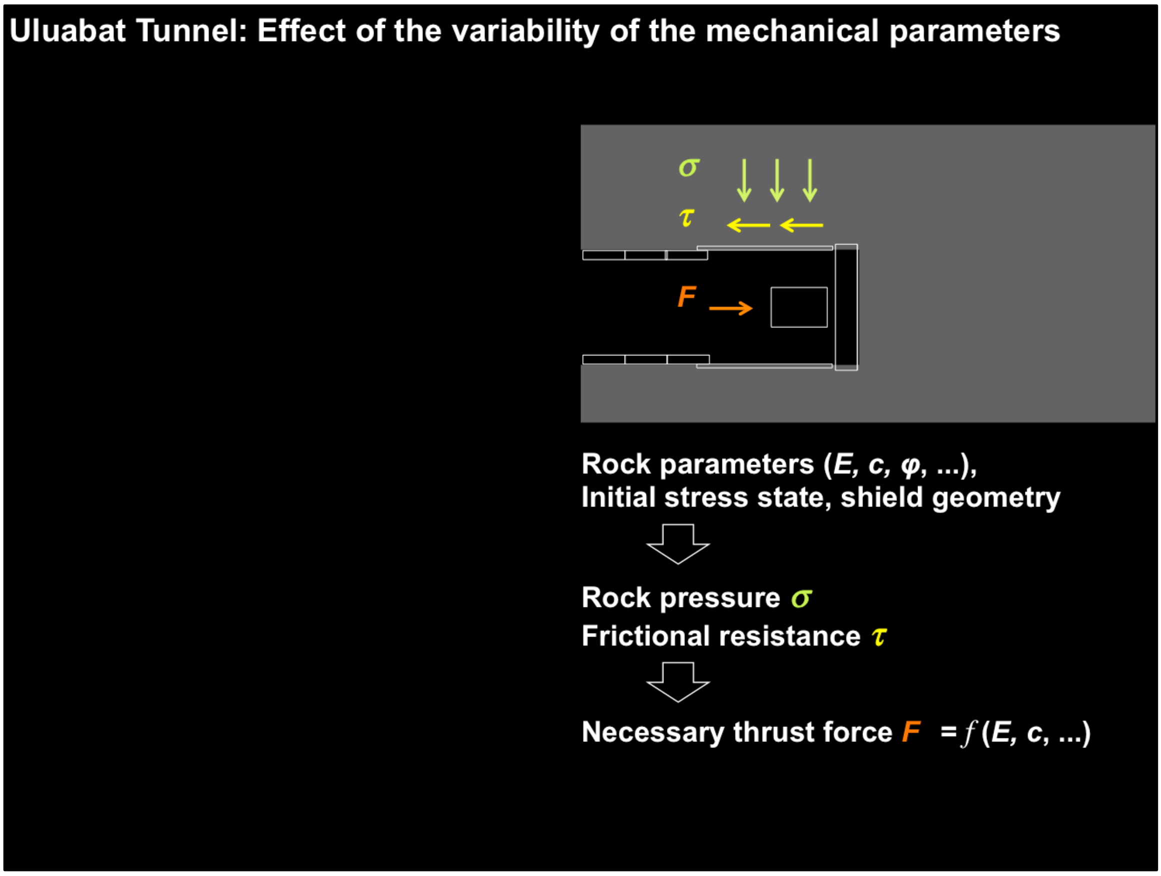
Highly variable squeezing intensity (up to 60 mm/h)

Weak zones of variable length frequently alternating with competent rock

Critical: wide weak zones (> 10-15 m) with intensively sheared claystones

Laboratory tests: *E* = 200 - 1000 MPa, *c* = 50 - 400 kPa, ϕ= 20°

In the critical stretches, monthly production dropped to 50 – 80 m only. It is, nevertheless, remarkable, that in spite of all these problems the TBM reached an overall monthly production of 210 m.



Uluabat Tunnel: Effect of the variability of the mechanical parameters

Rock parameters (E, c, φ, ...),
Initial stress state, shield geometry

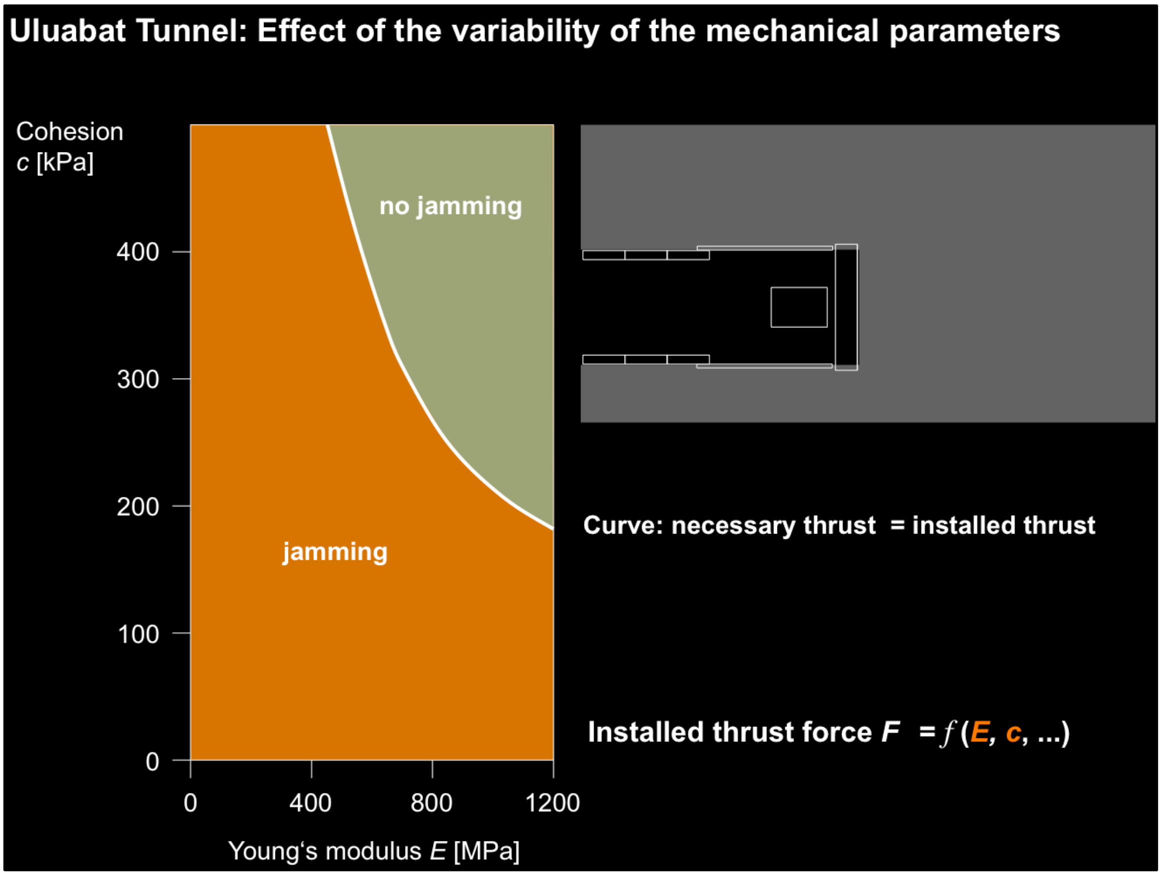
⇩

Rock pressure σ
Frictional resistance τ

⇩

Necessary thrust force F $= f(E, c, \ldots)$

Subsequently, first the effect of the variability of the mechanical parameters of the ground will be discussed.
For given rock parameters, initial stress field, shield geometry etc. one can estimate numerically the rock pressure acting upon the shield, the shield skin frictional resistance and thus the thrust force that is necessary in order to overcome friction [5].
The necessary thrust force depends thus on the rock modulus and cohesion (all other parameters being fixed).



Uluabat Tunnel: Effect of the variability of the mechanical parameters

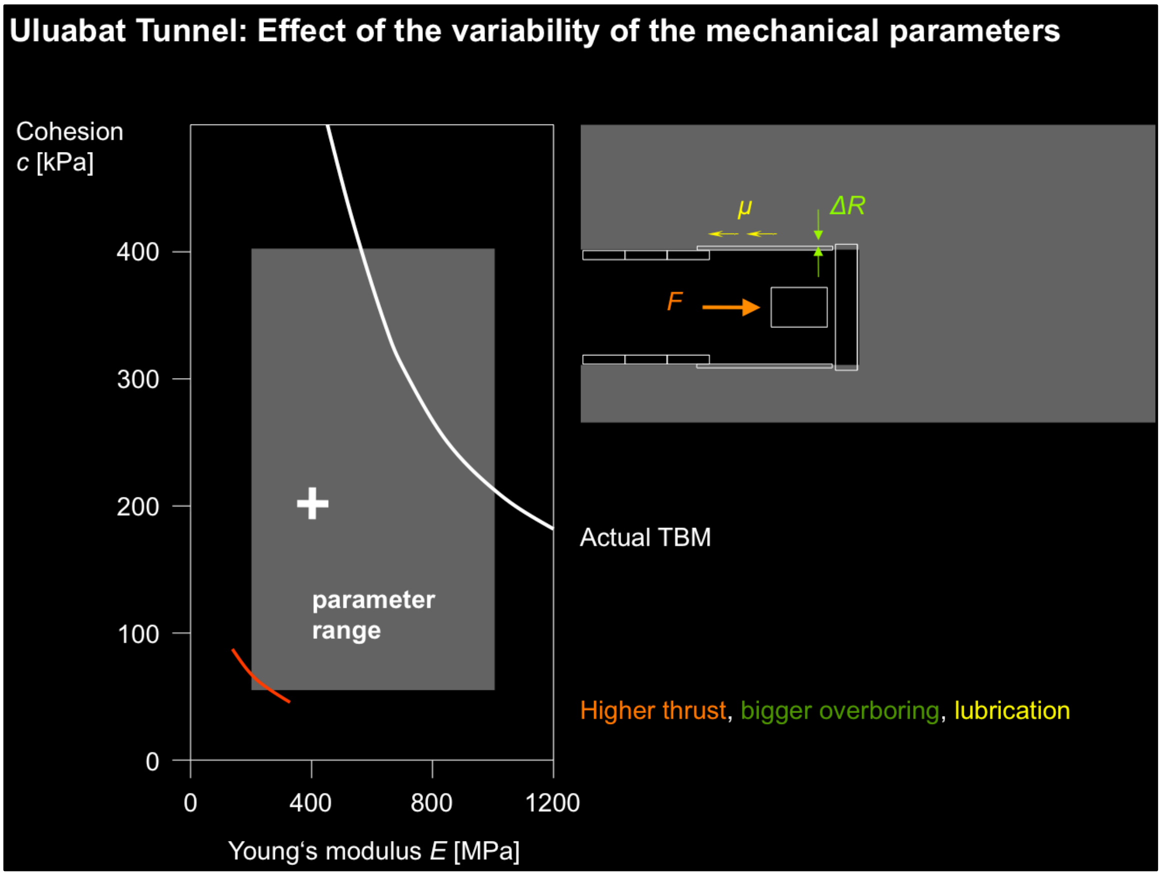
Curve: necessary thrust = installed thrust

Installed thrust force $F = f(E, c, \ldots)$

By fixing the value of the thrust force equal to that of the installed thrust, a relationship can be determined between the critical cohesion and modulus of the rock. The diagram shows this relationship [5].

For rock parameters above the curve, the necessary thrust force would be lower than the installed one.

For rock parameters below the curve, the installed thrust would be insufficient to overcome friction, which means that the shield would get stuck.

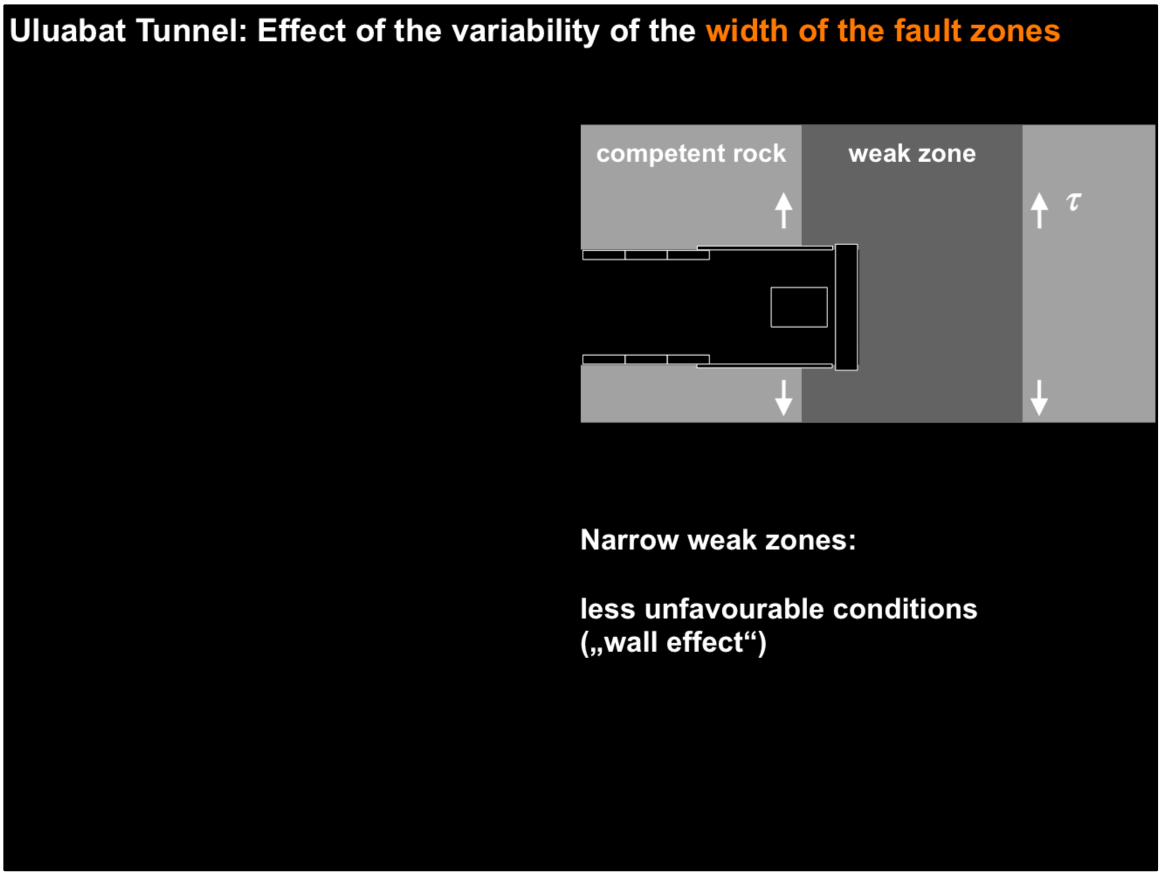


Uluabat Tunnel: Effect of the variability of the mechanical parameters

Higher thrust, bigger overboring, lubrication

The grey rectangle shows the actual parameter range. Variations in the ground quality within this range would result to an extremely variable behaviour: the TBM might get stuck or not.
With a combination of TBM improvements (such as installing a higher thrust force, a bigger overcut and lubrication of the shield extrados), the critical line would move to the bottom of the grey rectangle: the effect of geological complexity and ground variability can be eliminated by suitable construction measures.

Next, the situation in narrow weak zones will be discussed, exhibiting the parameter set that is marked by the cross.

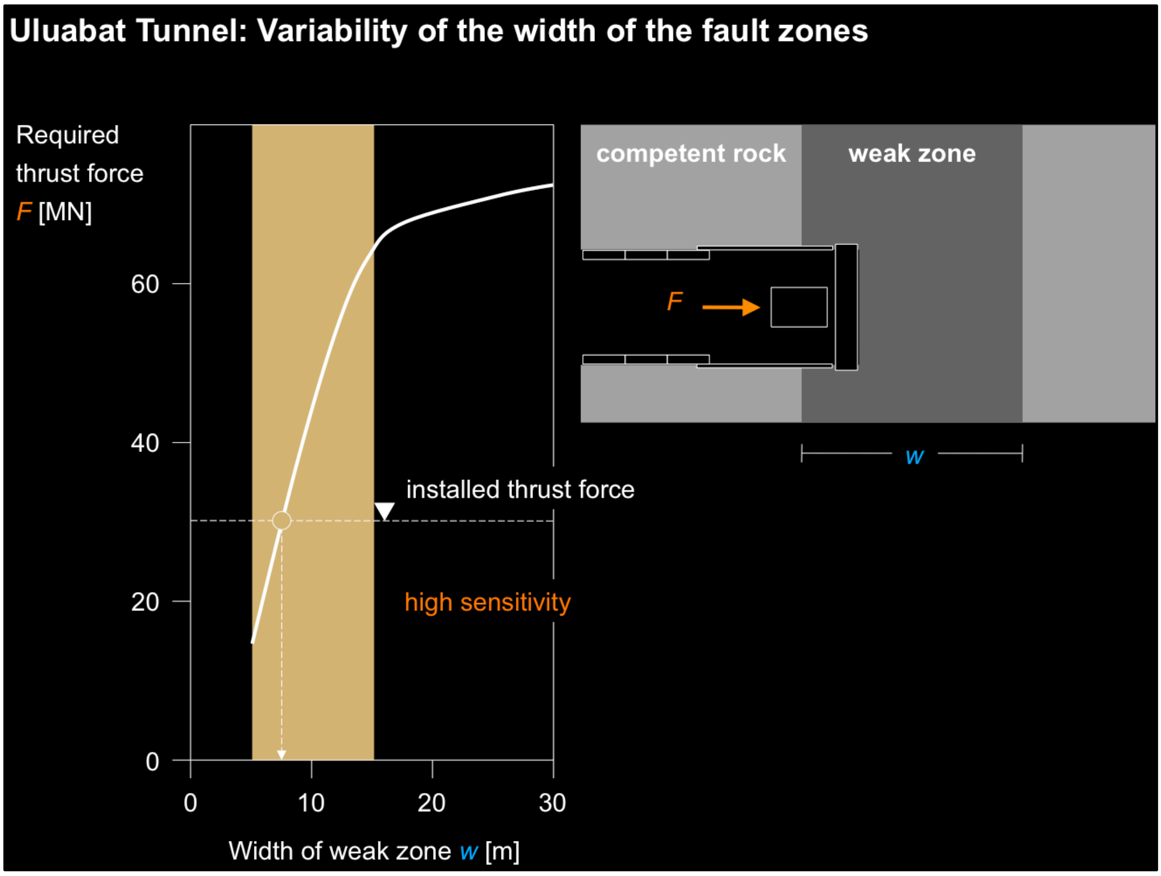


Uluabat Tunnel: Effect of the variability of the width of the fault zones

Narrow weak zones:

less unfavourable conditions („wall effect“)

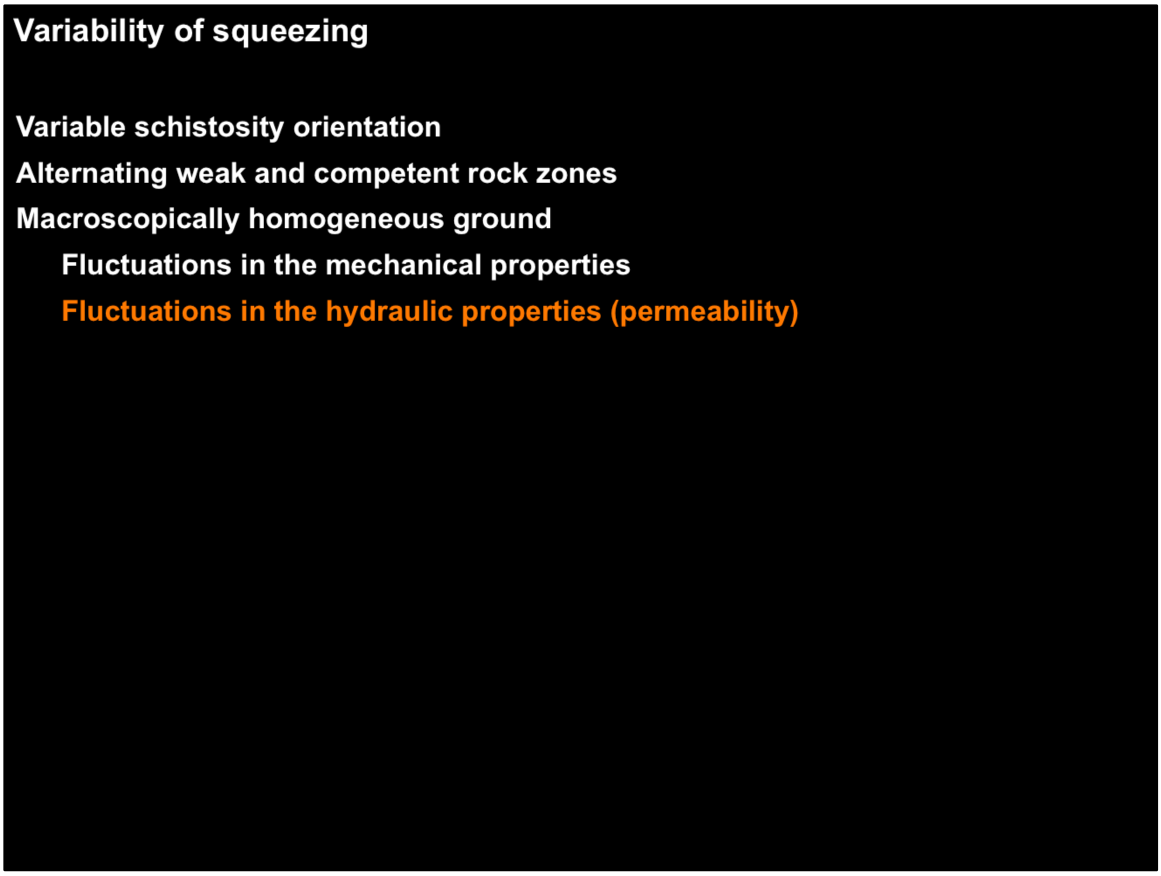
In the case of alternating weak and competent rock zones, the convergence distribution along the tunnel is non-uniform. Consequently, shear stresses are mobilized at the zone interfaces. These shear stresses reduce rock deformations and pressures inside the weak zones [6], and thus also the TBM thrust that is needed in order to overcome friction [5]. Therefore, the shorter the weak zone, the more pronounced this so-called "wall-effect" will be.



Uluabat Tunnel: Variability of the width of the fault zones

The diagram shows the necessary thrust force as a function of the thickness of the weak zone. In the present case, the required thrust force would exceed the installed thrust (which means that the TBM would get stuck) in fault zones longer than about 8 m.

The sensitivity of the computational results is remarkable. As a consequence of relatively small variations in the thickness of the encountered fault zones, engineers might experience the ground as problematic or not. This agrees with the experiences from Uluabat construction, where an extremely variable behaviour (in terms of the ability to keep the TBM advancing) was observed.

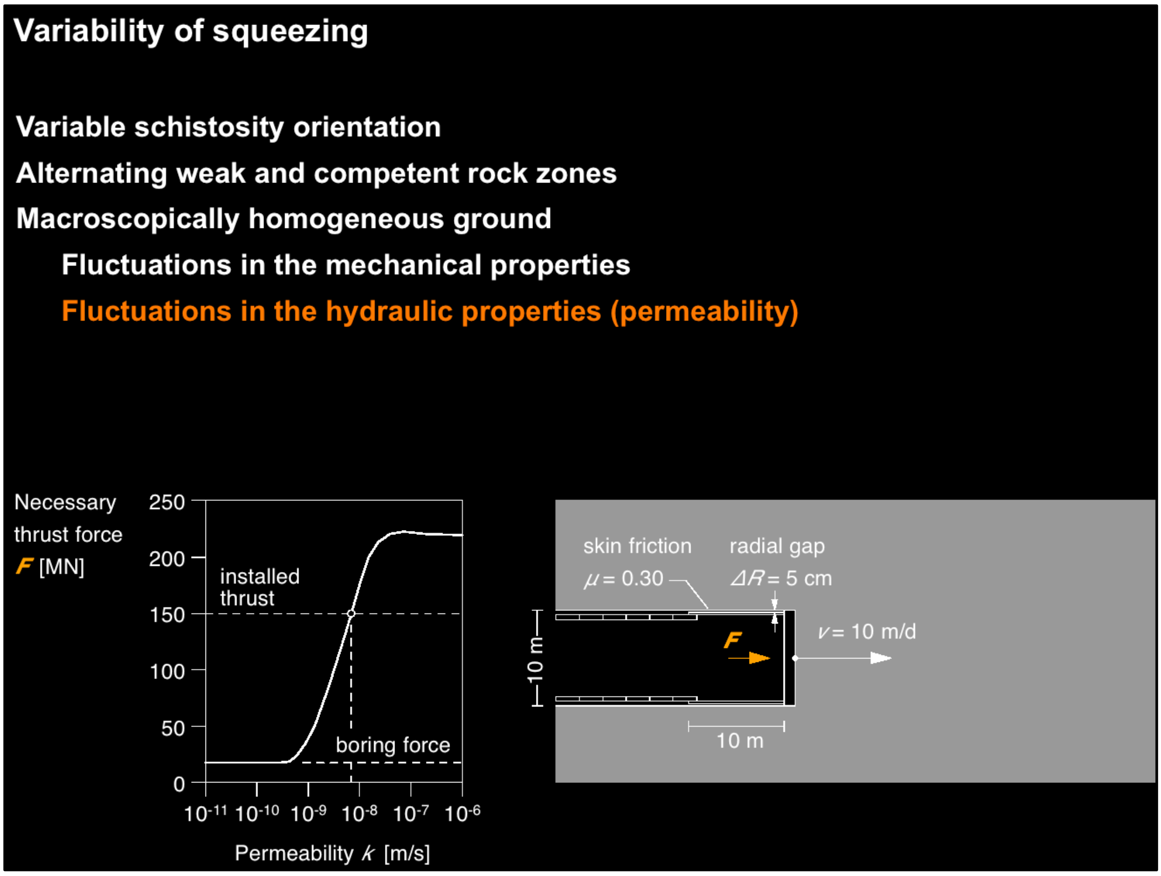


Variability of squeezing

- Variable schistosity orientation
- Alternating weak and competent rock zones
- Macroscopically homogeneous ground
    - Fluctuations in the mechanical properties
    - Fluctuations in the hydraulic properties (permeability)

Finally, it should be noted that intensity of squeezing may vary not only due to the variability of mechanical or geometrical parameters of the ground but also due to variability of the hydraulic conditions [7].

During excavation in low-permeability water-bearing ground, excess pore pressures develop around the advancing face. They dissipate more or less quickly, depending on the permeability of ground. The permeability affects, therefore, the rate of the consolidation and of the deformations of the ground around the shield and thus the rate of shield loading as well as the thrust that is required in order to overcome skin friction.



Variability of squeezing

Variable schistosity orientation

Alternating weak and competent rock zones

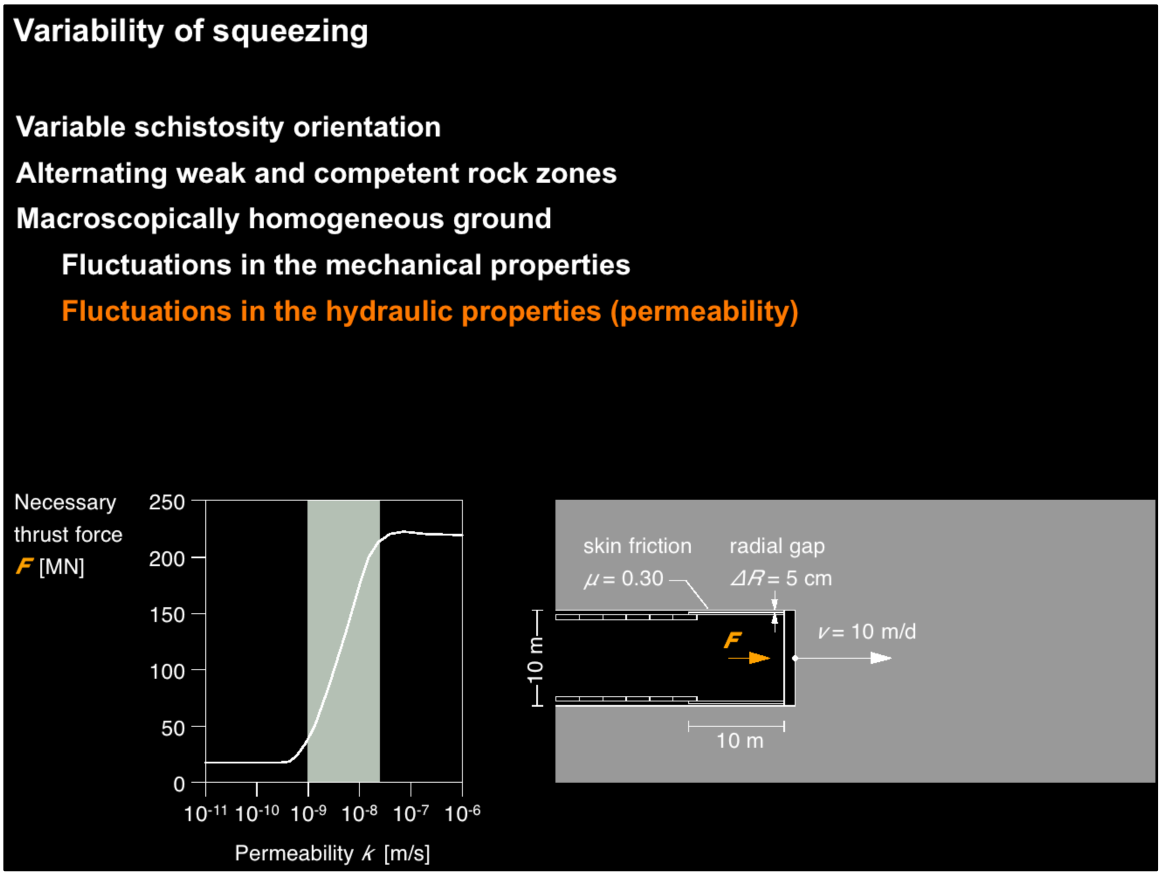
Macroscopically homogeneous ground

- **Fluctuations in the mechanical properties**
- **Fluctuations in the hydraulic properties (permeability)**

Consider, for example, a TBM advancing by 10 m/d. The diagram shows the necessary thrust force as a function of the permeability [8].

For a very low permeability ground, the deformations develop slowly and the ground does not establish contact to the advancing shield. A thrust force is required only for the boring process.

With increasing permeability, rock closes the gap around shield faster, thus exerting a pressure and increasing frictional resistance and thrust demand.



Variability of squeezing

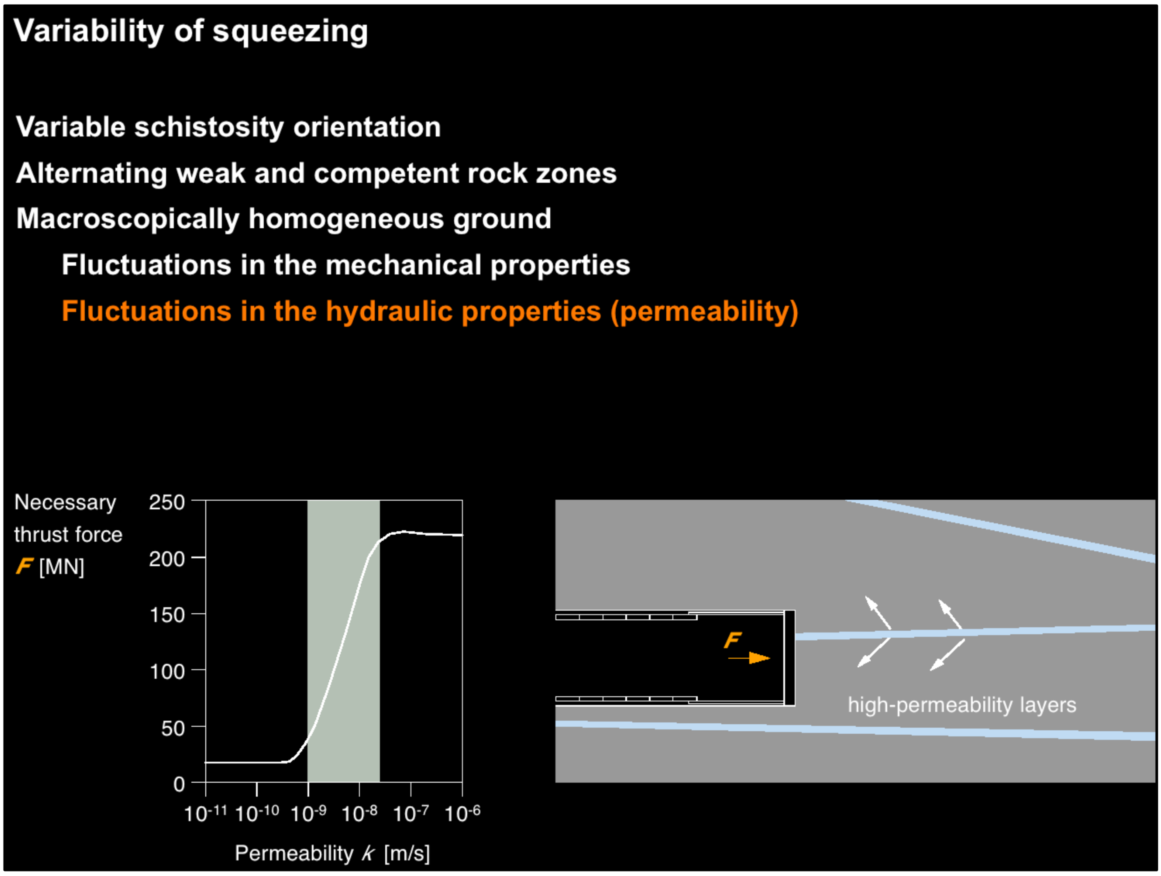
Variable schistosity orientation

Alternating weak and competent rock zones

Macroscopically homogeneous ground

- **Fluctuations in the mechanical properties**
- **Fluctuations in the hydraulic properties (permeability)**

It is remarkable, that relatively small changes in the permeability result in extremely variable behaviour – the TBM may get stuck or not.



Variability of squeezing

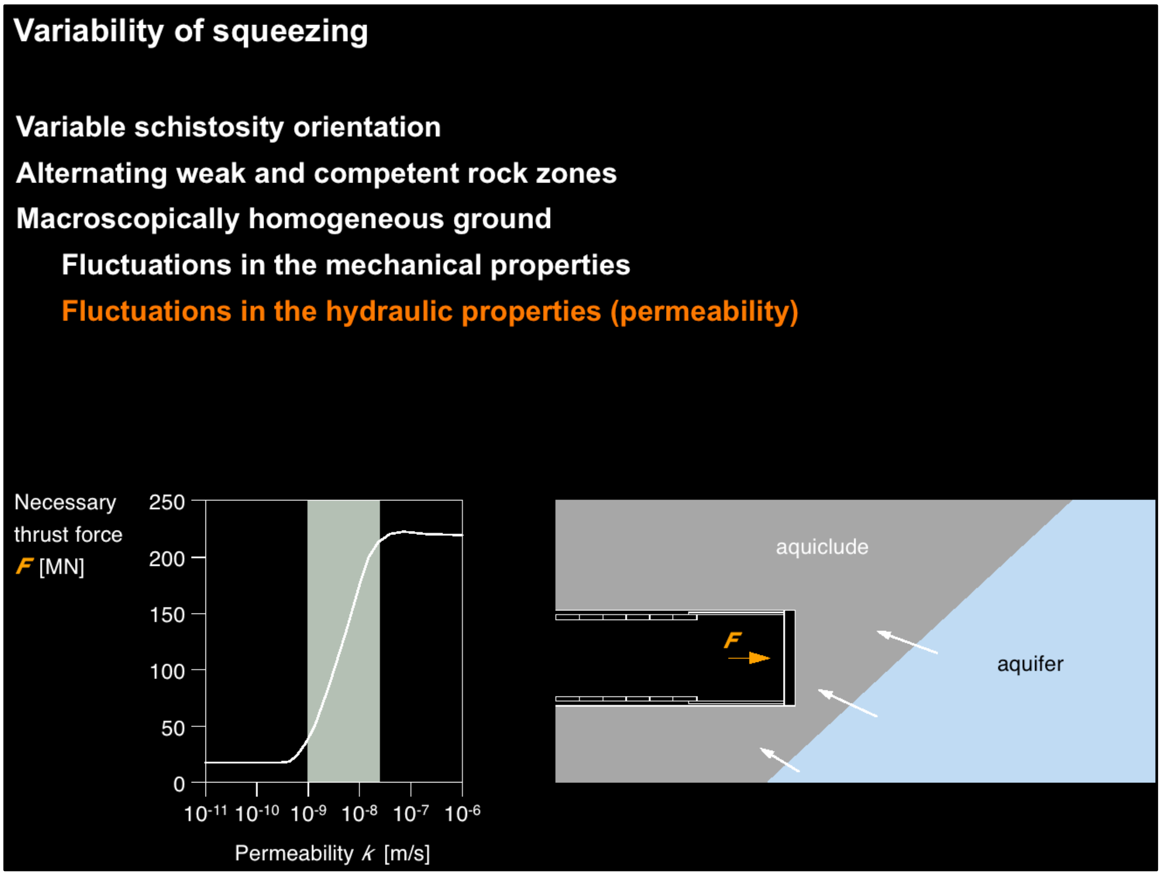
Variable schistosity orientation

Alternating weak and competent rock zones

Macroscopically homogeneous ground

- **Fluctuations in the mechanical properties**
- **Fluctuations in the hydraulic properties (permeability)**

Overall ground permeability may increase as a consequence, for example, of erratically distributed water bearing layers. The latter shorten drainage paths, thus accelerating excess pore pressure dissipation and intensity of squeezing deformations as well.



Variability of squeezing

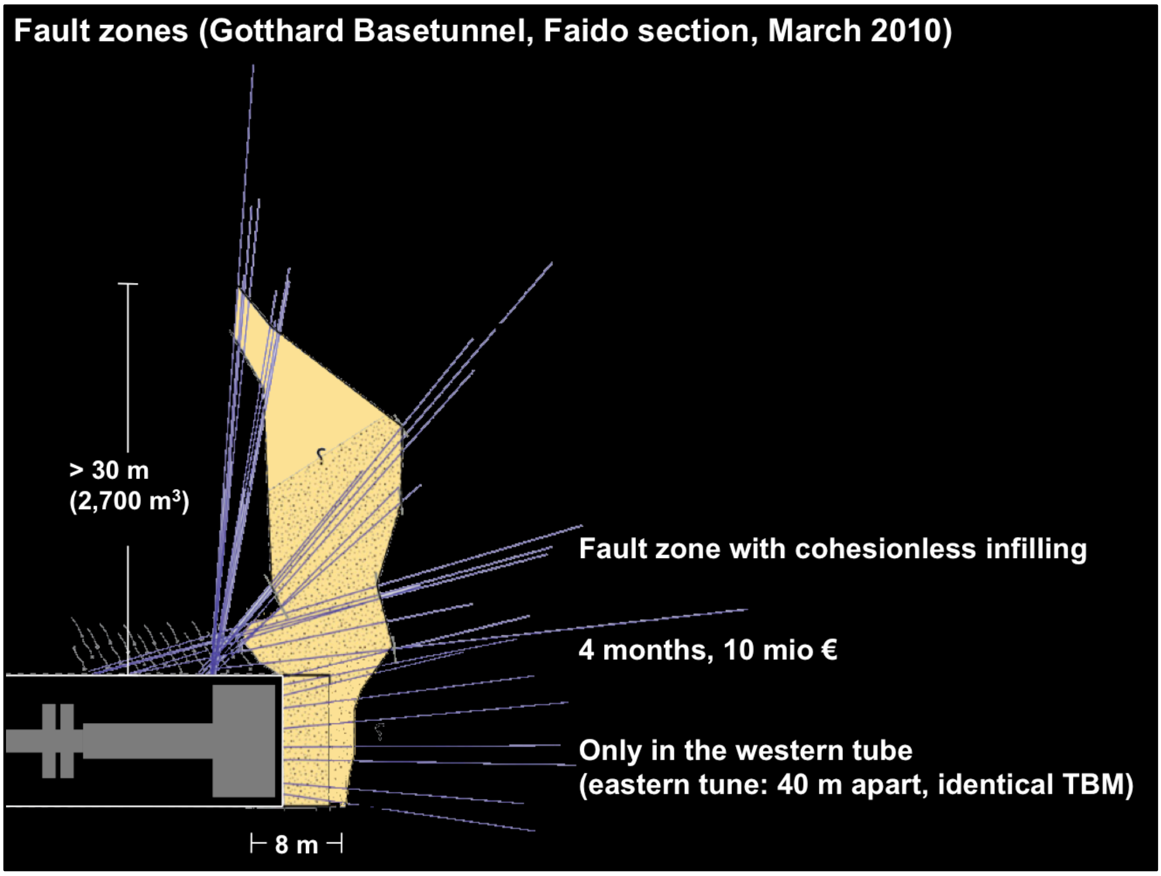
Variable schistosity orientation

Alternating weak and competent rock zones

Macroscopically homogeneous ground

- **Fluctuations in the mechanical properties**
- **Fluctuations in the hydraulic properties (permeability)**

The same is true in the vicinity of aquifers – drained boundaries accelerate consolidation too.



Fault zones (Gotthard Basetunnel, Faido section, March 2010)

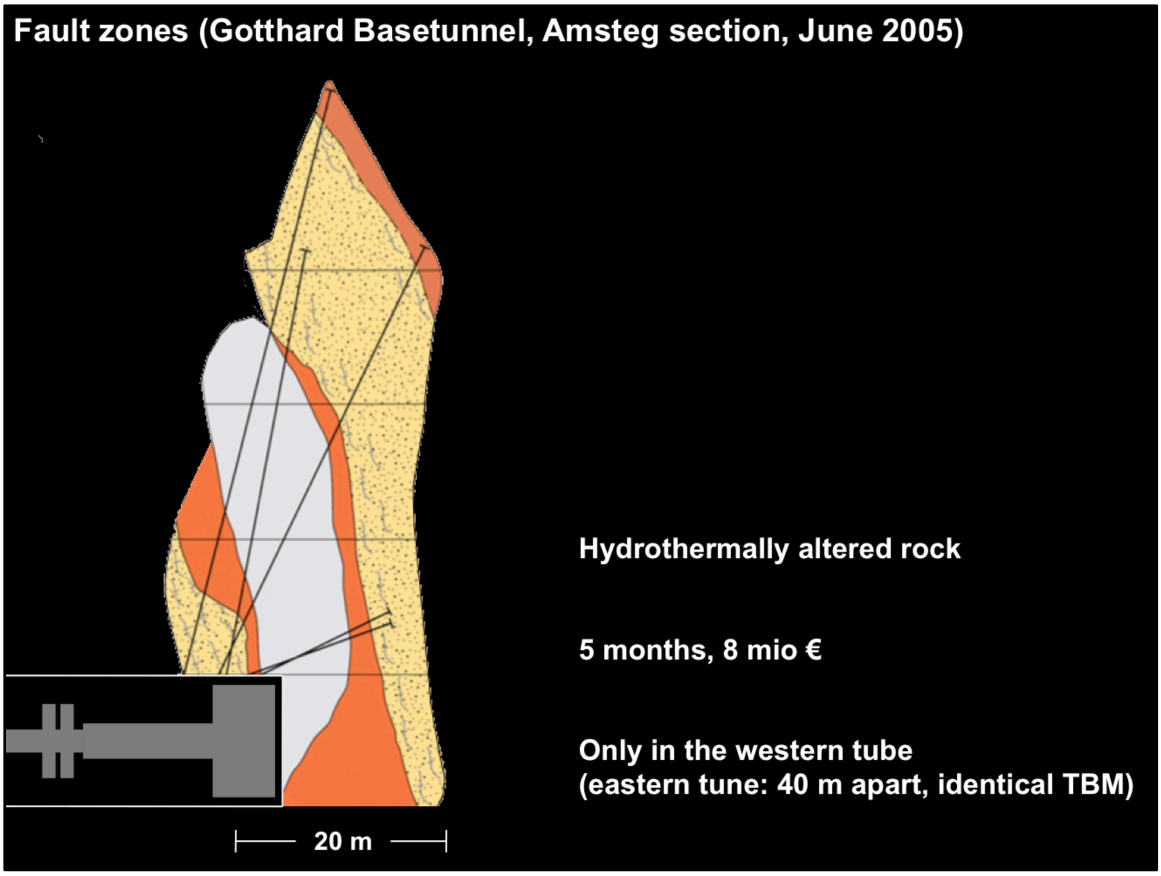
Fault zone with cohesionless infilling

4 months, 10 mio €

Only in the western tube
(eastern tune: 40 m apart, identical TBM)

Complex hydraulic conditions occur frequently in geologically complex formations, particularly in fault zones. Geological complexity is often associated with tectonic processes and, more specifically, with the substantial heterogeneity induced by faulting or shearing.
Fault zones often present also serious construction problems.

For example, one fault encountered during construction of the Western tube of the Gotthard Basetunnel in the Faido section took 138 working days to overcome [9]. It is characteristic of the variability of the ground that the Eastern TBM drive did not encounter any difficulties although the two tubes were spaced only 40 m apart.



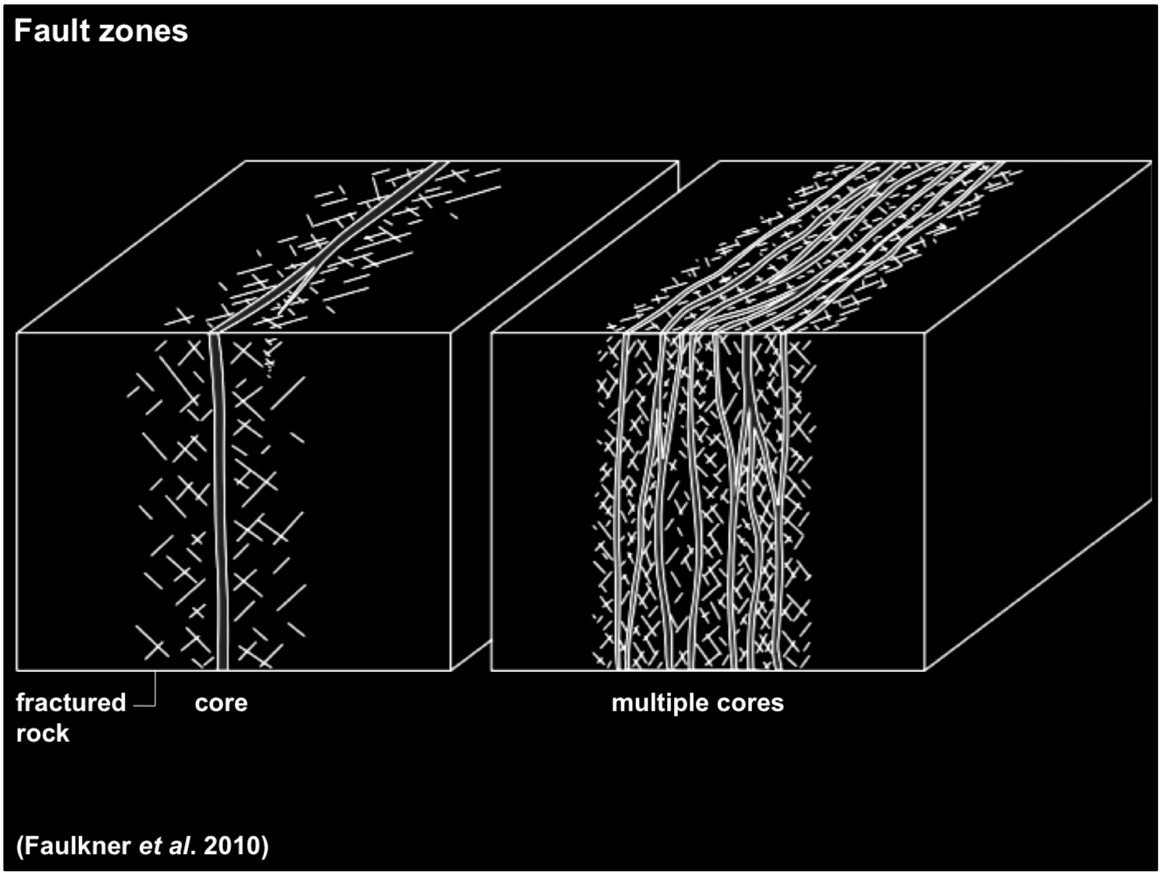
Fault zones (Gotthard Basetunnel, Amsteg section, June 2005)

Hydrothermally altered rock

5 months, 8 mio €

Only in the western tube
(eastern tune: 40 m apart, identical TBM)

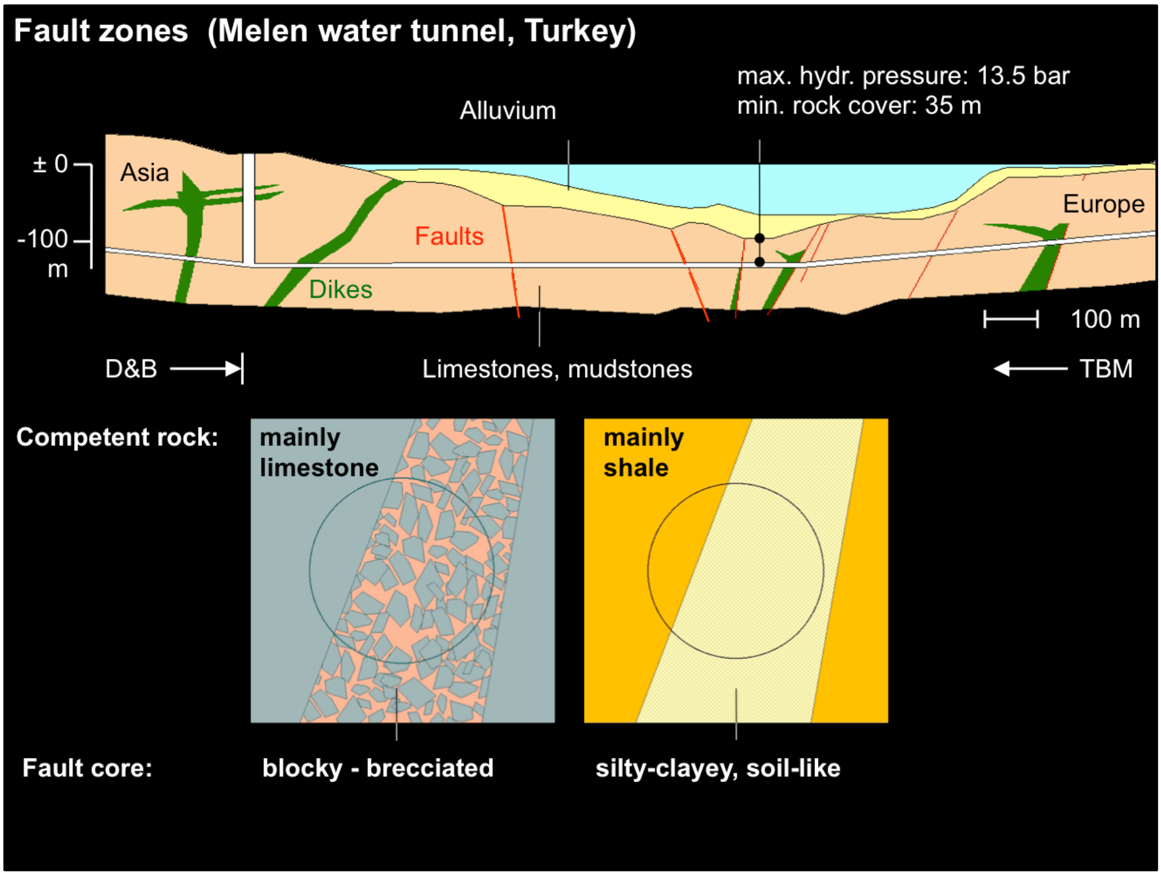
A similar experience was made in the Amsteg lot, where unstable face conditions in hydrothermally altered rock caused a delay of 5 months (again, in the Western tube only) [9].



Fault zones

(Faulkner *et al*. 2010)

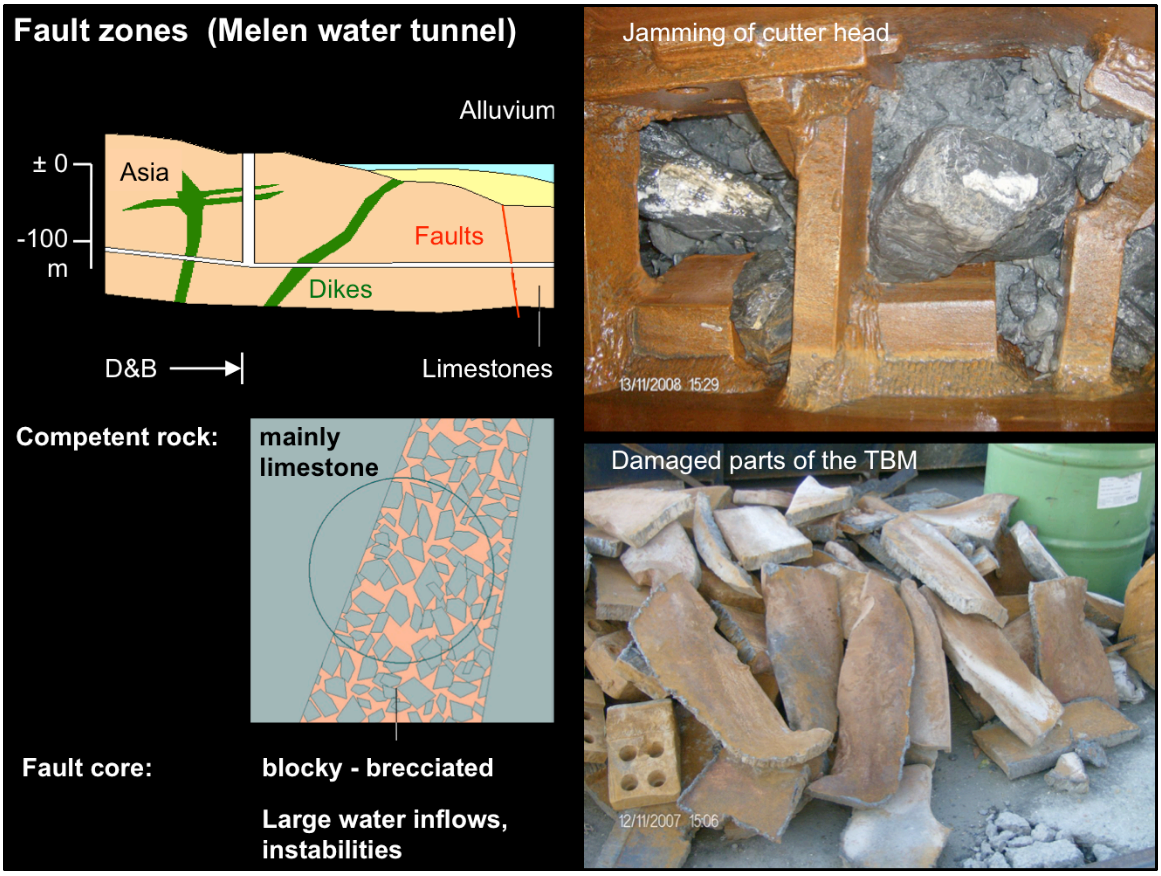
Fault zones occur alone or in a group, with a single or a branching fault core and with more or less competent rock in-between [10]. The condition and the behaviour of the ground in the faults depend essentially on the dominant lithology of the competent host rock.



Fault zones (Melen water tunnel, Turkey)

Consider, for example, the case of Melen tunnel – a tunnel serving Istanbul's drinking water supply. It is the first bored tunnel underneath Bosphorus (and also the first bored tunnel in the world connecting two continents).

The major part of the tunnel, including the subsea section, was constructed using a shielded TBM. The bedrock in the project area consists of mudstones and limestones. Fault zones in limestones appear blocky and brecciated, while in predominately shaly rocks the fault material is fine-grained and resembles soft ground.



Fault zones (Melen water tunnel)

Competent rock: **mainly limestone**

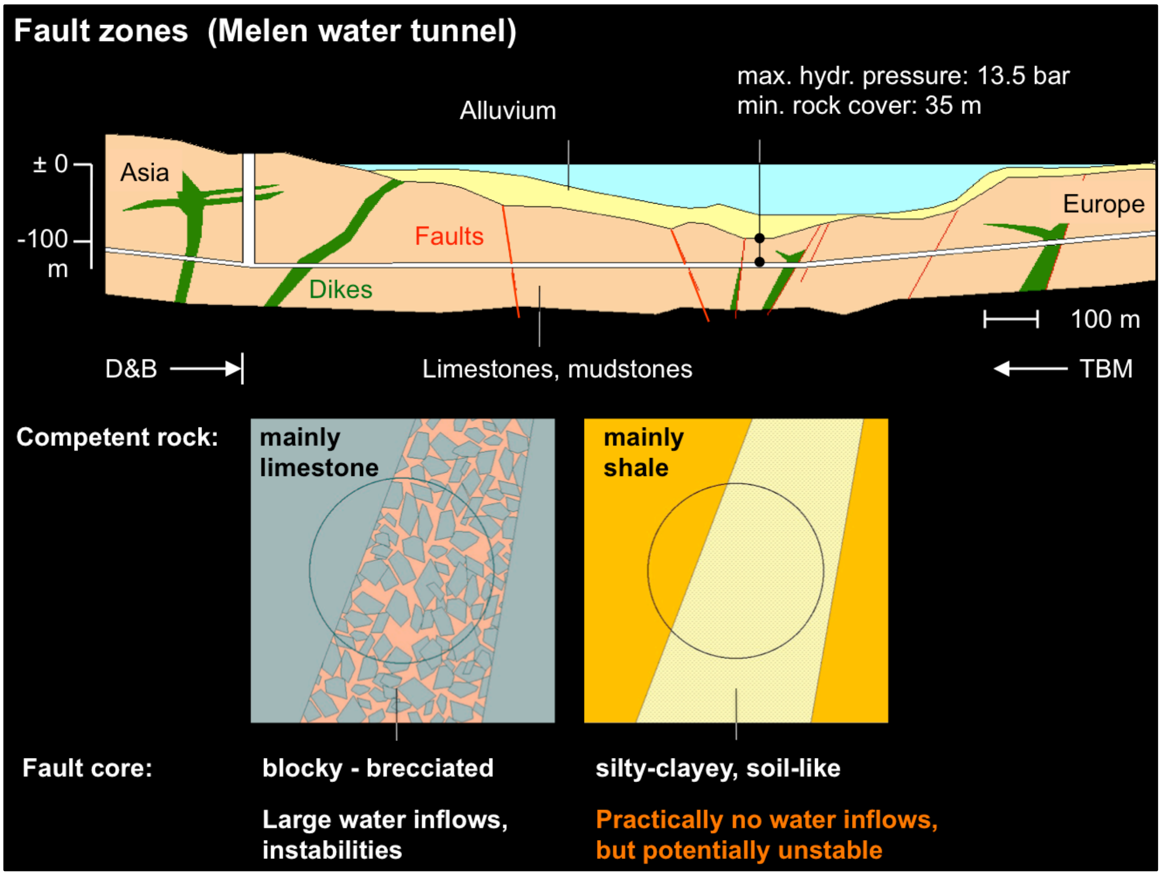
Fault core: **blocky - brecciated**

Large water inflows, instabilities

Jamming of cutter head

Damaged parts of the TBM

Problems in blocky fault zones include rock instabilities in front of the TBM and high water inflows. The instabilities may block or damage the cutter head. The water inflows may cause difficulties in mucking-out, in the installation of the segmental lining or in the annulus grouting.



Fault zones (Melen water tunnel)

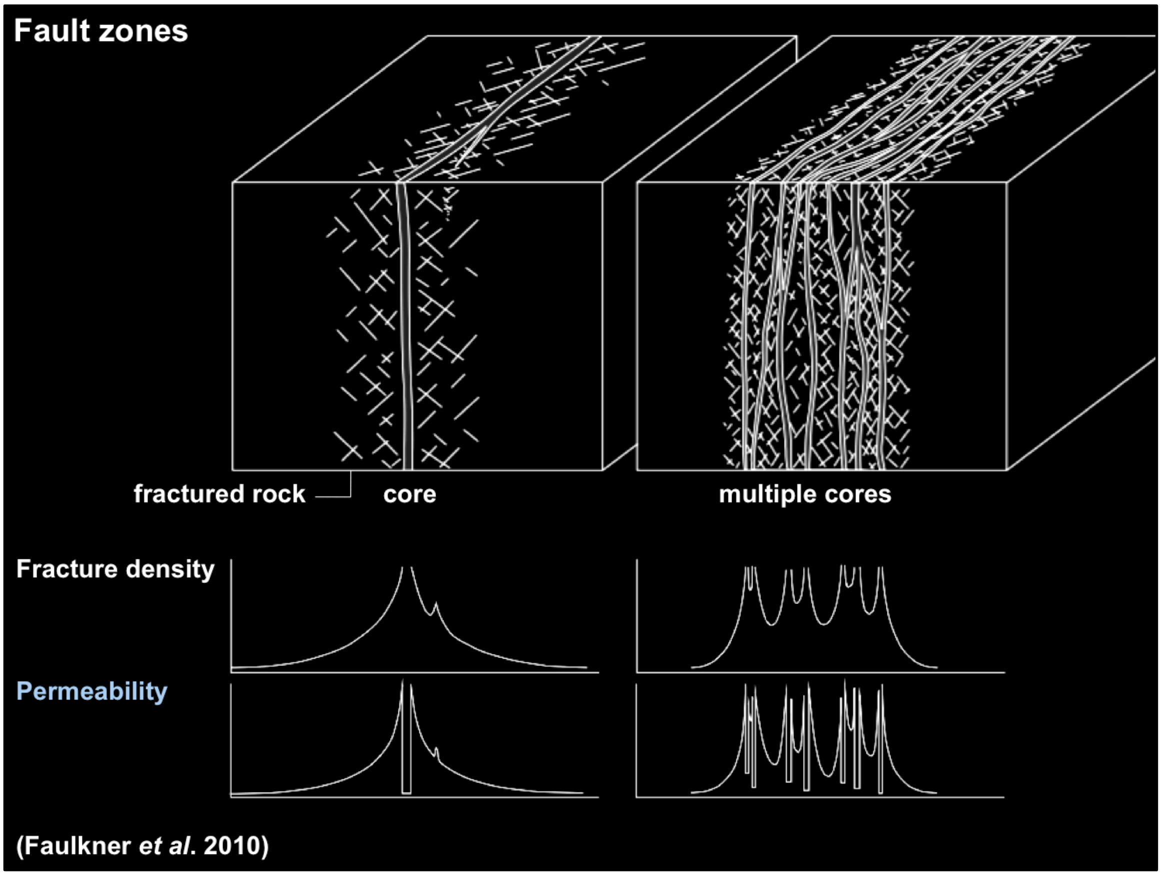
Competent rock:

Fault core: **blocky - brecciated** / **silty-clayey, soil-like**

Large water inflows, instabilities

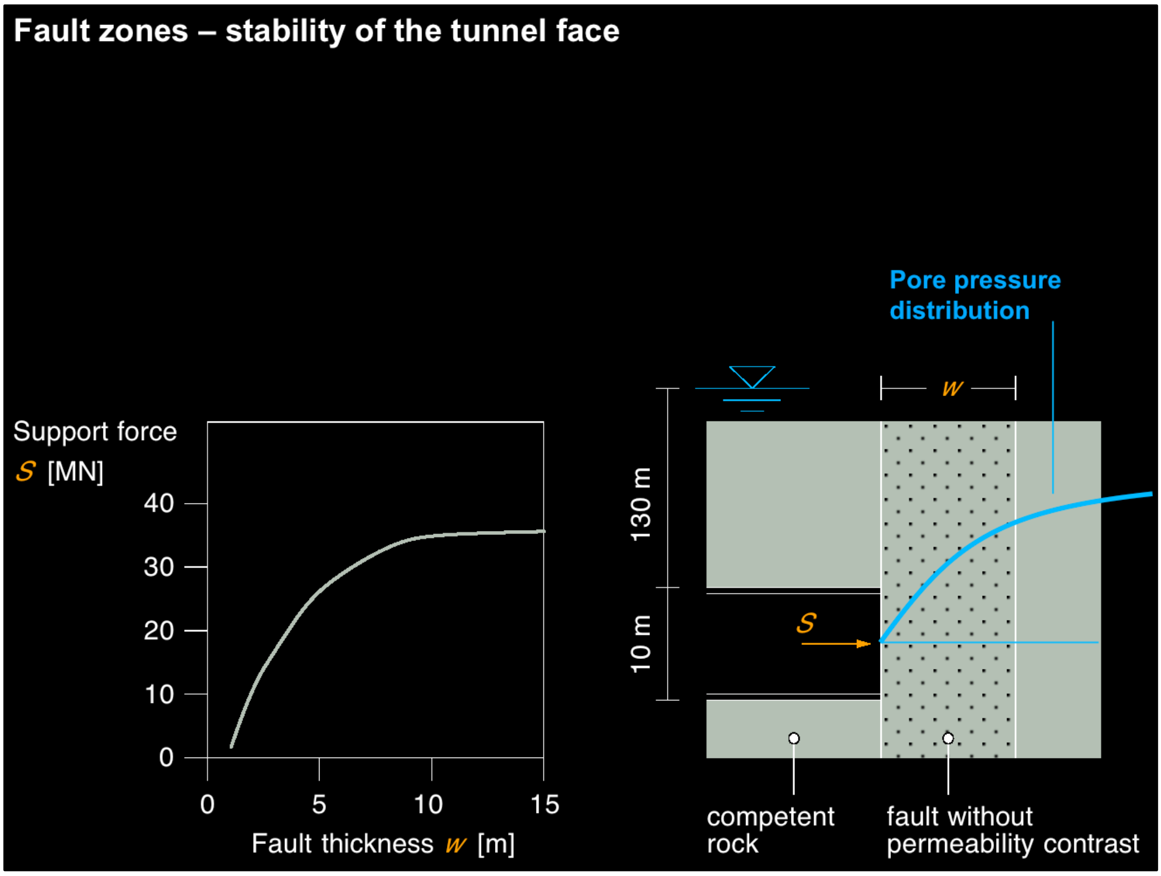
Practically no water inflows, but potentially unstable

Also in the fine-grained faults, a face instability represents the main potential hazard (due to the high hydrostatic pressure and the low strength of the material). Normally, the quantity of water inflow (as observed in boreholes drilled ahead of the TBM) represents a reliable indicator of such problems. However, in faults consisting of fine-grained, low-permeability material, the water inflows are very limited and may give a false sense of security.



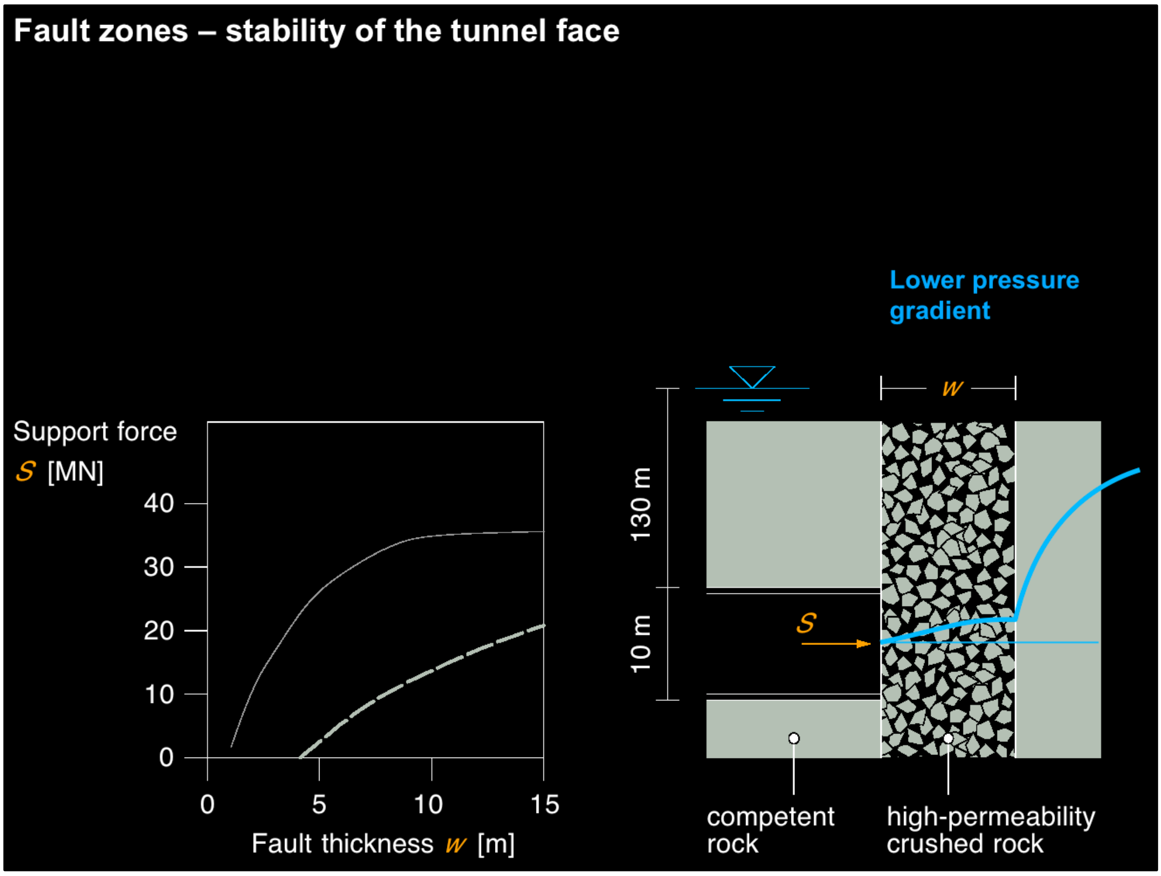
(Faulkner *et al*. 2010)

One remarkable feature of complex fault zones is the anomaly of pore pressure distribution, which is due to an extreme permeability heterogeneity. Fault zones often include simultaneously both aquifers and aquicludes, exhibiting permeability contrasts of several orders of magnitude [10]. The fault core (if fully developed and consisting of gouge) typically has a low permeability, while the adjacent rocks normally (depending on the connectivity of the joints) exhibit a higher permeability than the competent host rock.



Fault zones – stability of the tunnel face

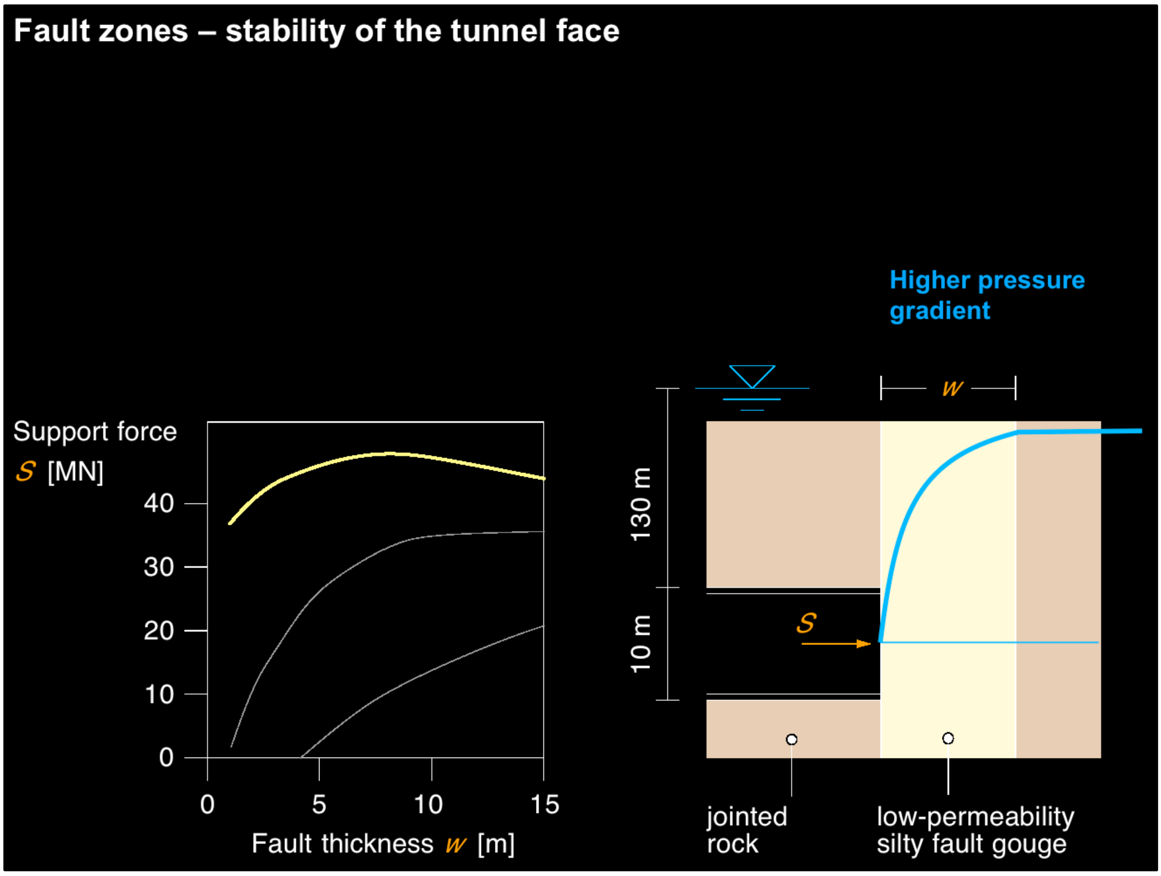
The heterogeneity with respect to permeability affects face stability conditions. Consider first a fault without permeability contrast to the adjacent competent rock. The diagram shows the necessary face support force as a function of the fault thickness [11,12]. Narrow zones are more favourable due to the wall-effect mentioned before.



Fault zones – stability of the tunnel face

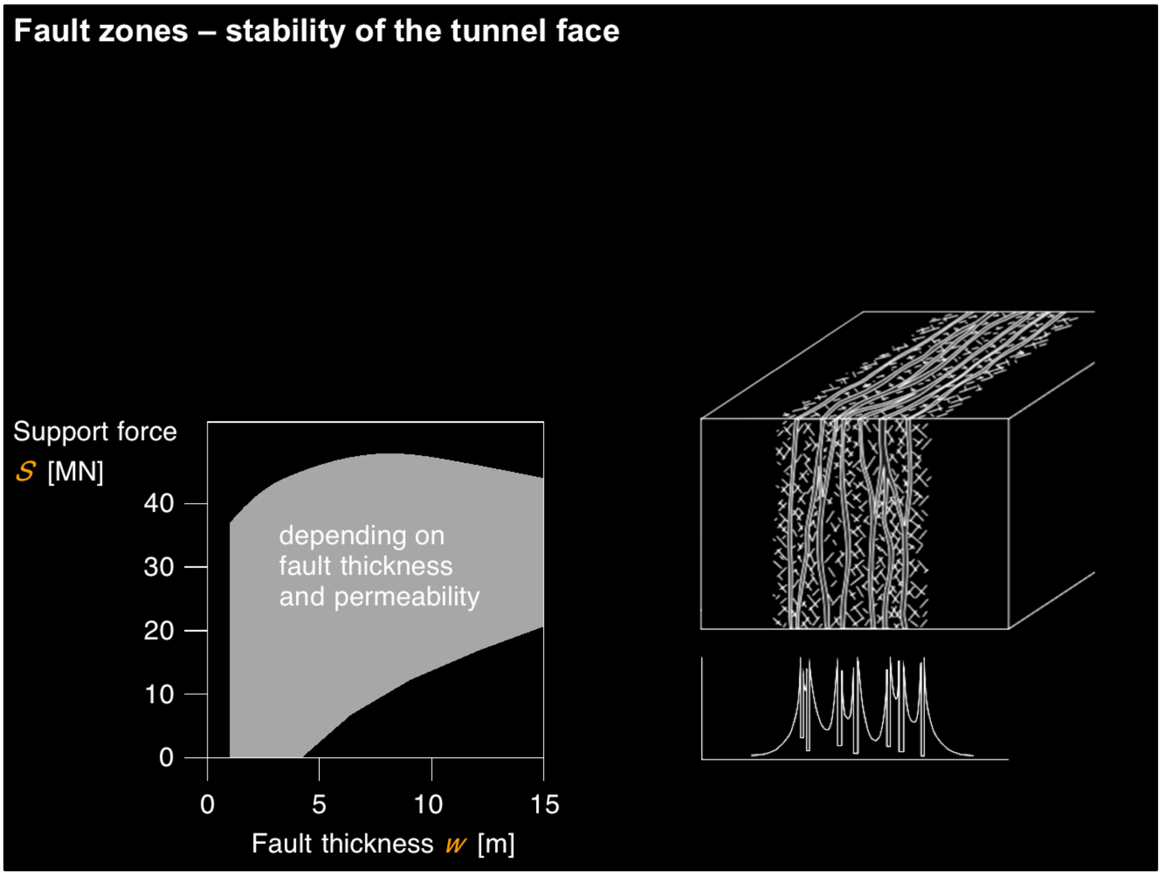
Lower pressure gradient

For comparison, we see here the necessary support pressure for the case of a coarse-grained fault, much more permeable than the adjacent competent rock. In this case, pore pressure gradients develop mainly within the competent rock (on account of its lower permeability), and this is why the necessary face support pressure is lower than in the case of uniform ground permeability.



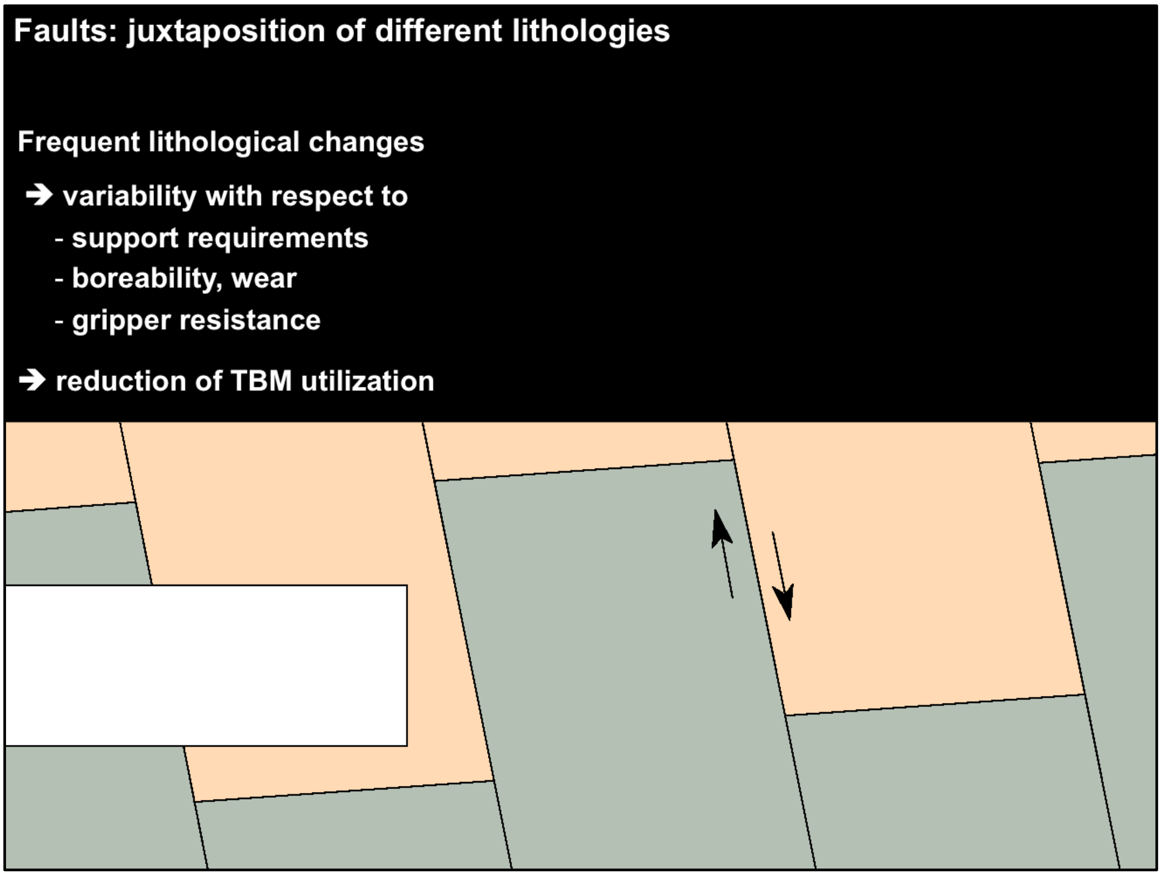
Fault zones – stability of the tunnel face

However, if the fault core exhibits a lower permeability than the adjacent rock (for example, a silty fault gouge bounded by fractured rock), then the pore pressure gradient within the core will be high (particularly if the fault is narrow), which is unfavourable with respect to face stability and necessitates a higher face support pressure.



Fault zones – stability of the tunnel face

Fault thickness and permeability are thus, in addition to the shear strength of the material, important for face stability. All of these parameters may be highly variable in faults and cause extremely variable face stability conditions during construction.



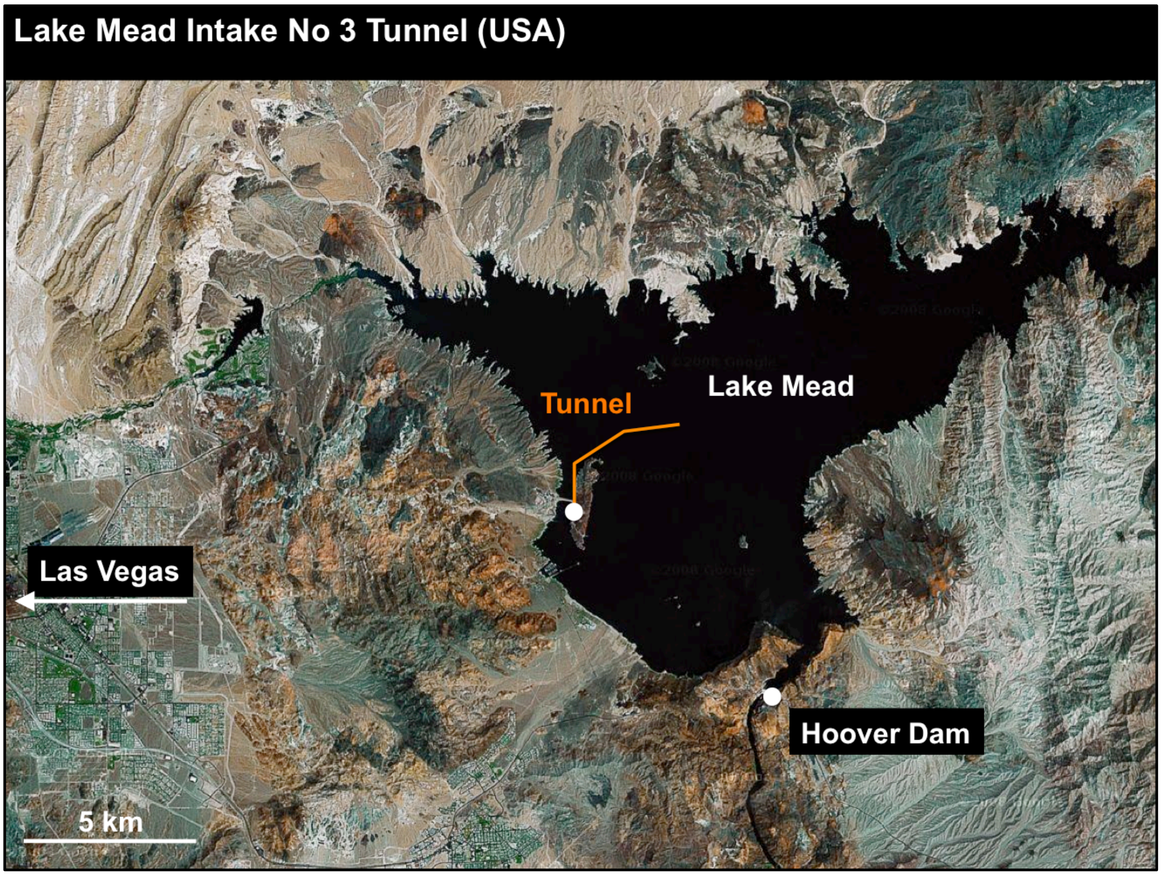
Faults: juxtaposition of different lithologies

Frequent lithological changes

➔ variability with respect to
  - **support requirements**
  - **boreability, wear**
  - **gripper resistance**

➔ reduction of TBM utilization

Finally, it should be noted that often faults are not problematic *per se* and may remain completely unnoticed during construction.
Depending on their spacing, however, they may cause frequent lithological changes, which in-turn may result to engineering complexity (characterized by a lower TBM utilization due to variability with respect to support requirements, boreability and wear, gripper resistance etc.).

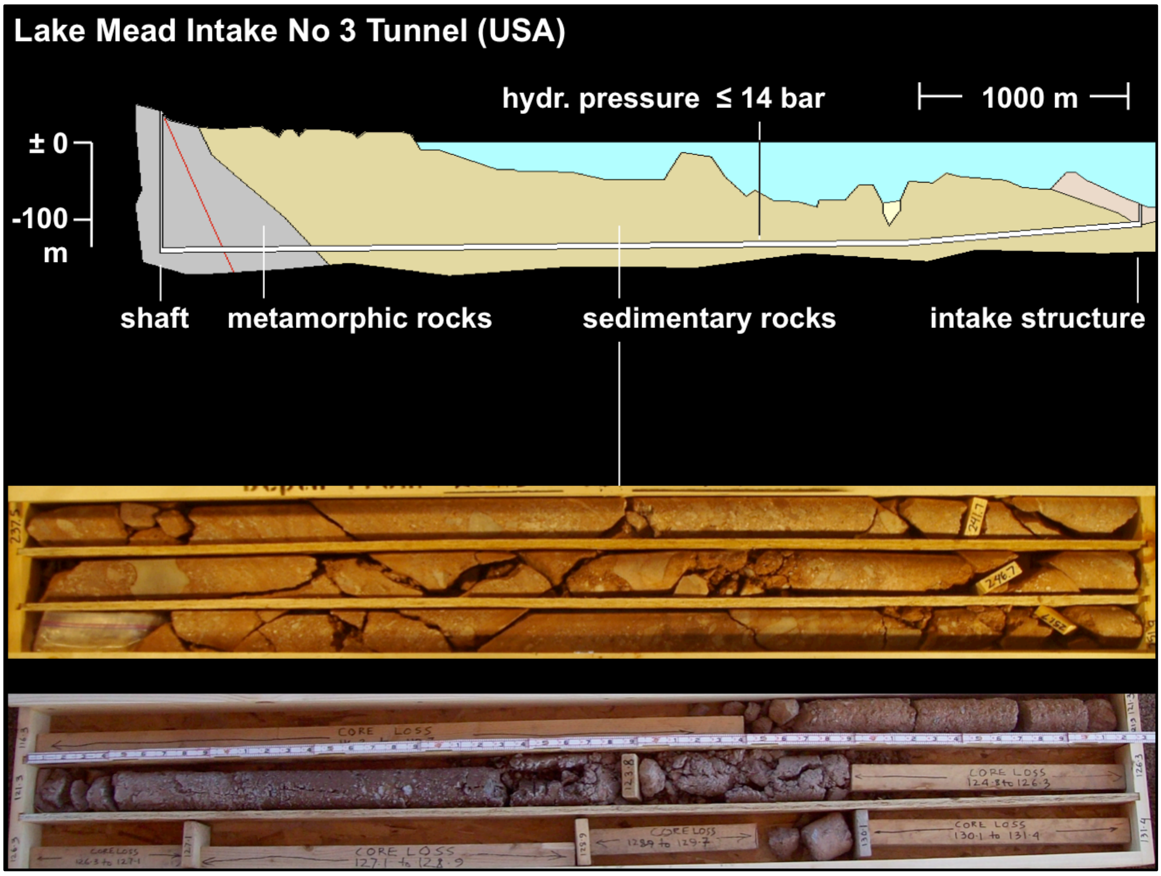


Lake Mead Intake No 3 Tunnel (USA)

The last part of this talk is about a recent construction project – the Lake Mead Intake No 3 tunnel. Lake Mead, behind the Hoover Dam, supplies about 90% of Las Vegas valley's water.

Over recent years, drought has caused the lake level to drop by more than 30 meters.

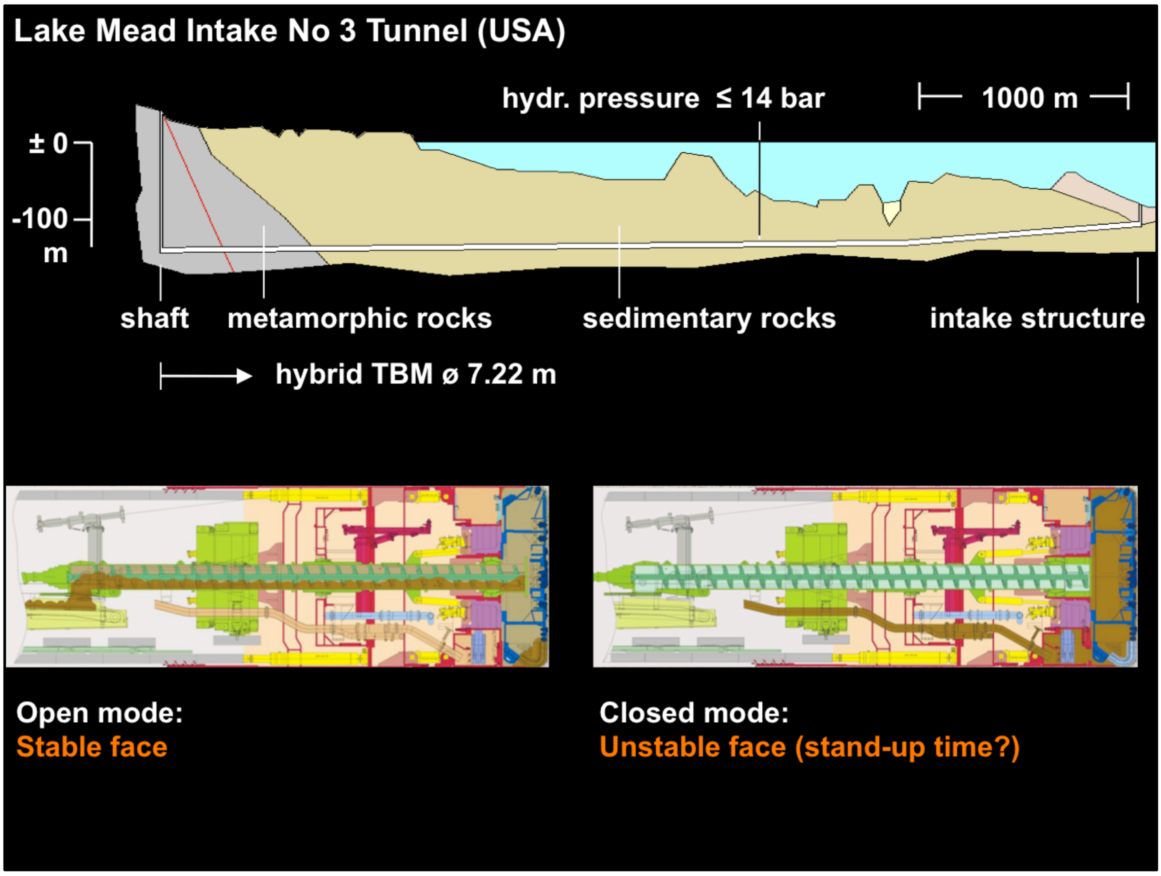
Here, a view from Hoover dam towards the lake.



Lake Mead Intake No 3 Tunnel (USA)

In order to maintain water supplies, a third intake was constructed, deep enough to function at the lowest lake levels [13].

The tunnel crosses metamorphic rocks and tertiary sedimentary rocks, at a maximum depth of about 140 m beneath the current lake level.

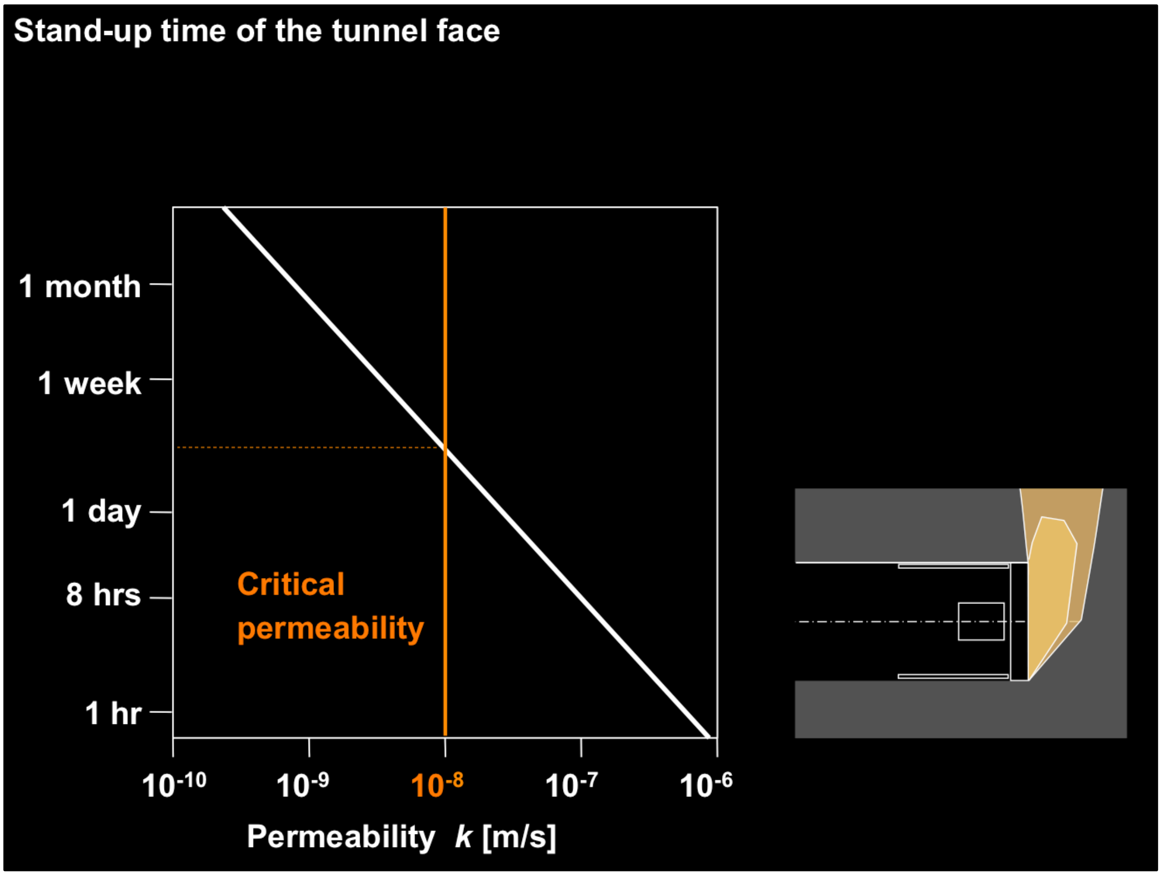


Lake Mead Intake No 3 Tunnel (USA)

Open mode:
Stable face

Closed mode:
Unstable face (stand-up time?)

It was constructed using a TBM, which was designed for boring either in open or in closed mode (with a pressurized bentonite slurry), the latter under water pressures of more than 14 bar [14].



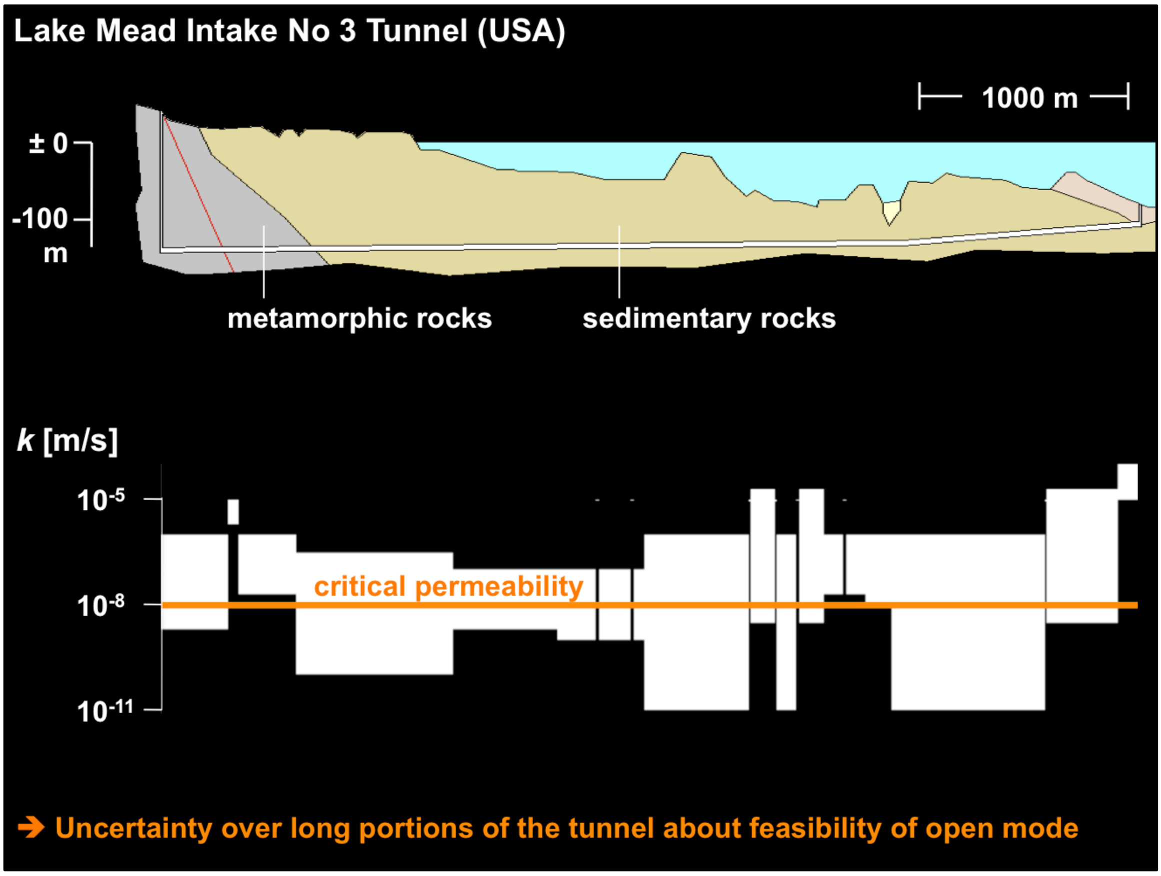
Stand-up time of the tunnel face

The main difficulty with assessing the behaviour of the prevailing low-permeability rocks is that their response to tunnel excavation is time-dependent: an unsupported tunnel face is initially stable but fails after a period of time.

The central question was thus: for how long the face will remain stable? The decisive parameter in this respect is the permeability of the ground. The stand-up time of the tunnel face can be estimated by numerical calculations that take account of the time-dependent processes in the ground ahead of the tunnel face [15, 16]. The diagram shows typical results.

For permeability values less than 10^{-8} m/s, the stand-up time would amount to a few days. For higher permeability values, the stand-up time would drop to maximum few hours only.

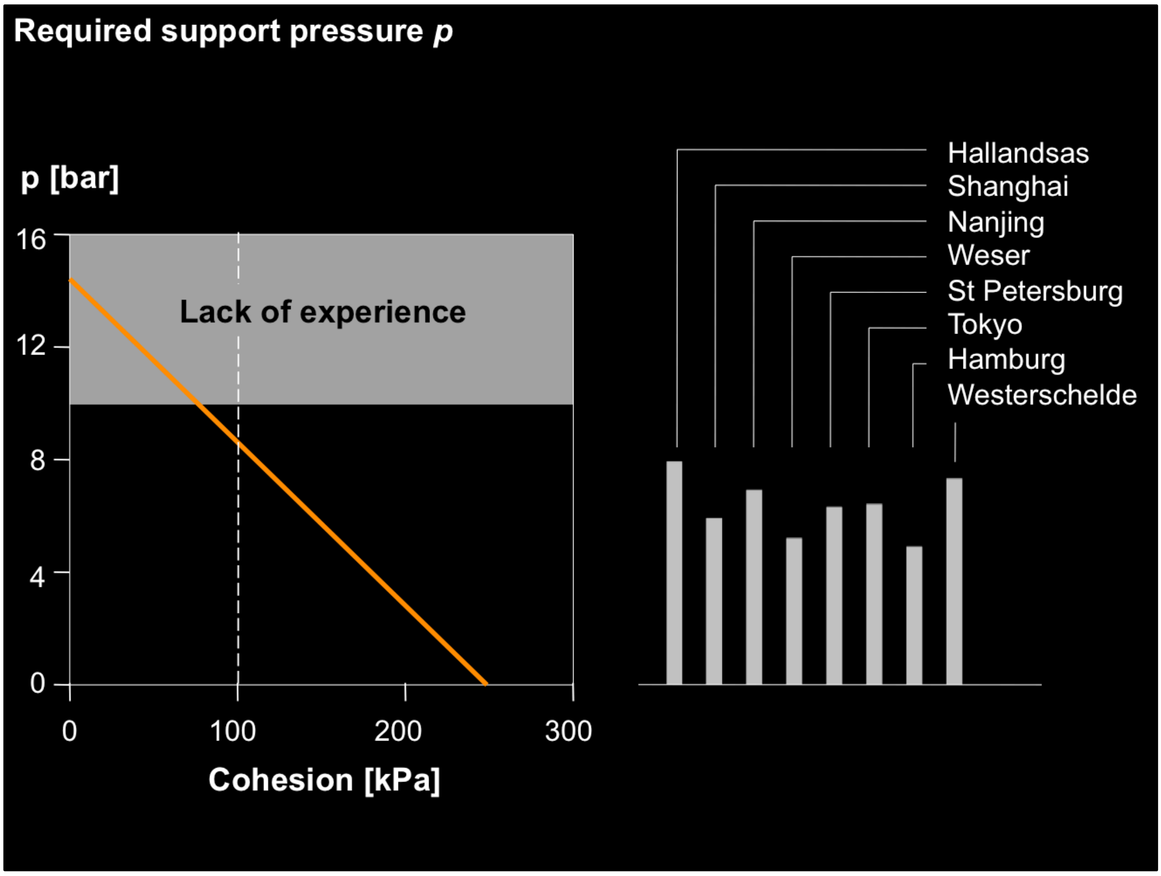
The difference between a few hours and a few days is very significant from the construction point of view: A stand-up time in the order of days would allow open mode TBM operation and maintenance under atmospheric conditions. A stand-up time of a few hours might allow TBM advance in open mode or at low slurry pressure, but would very probably necessitate hyperbaric interventions for maintenance.



Lake Mead Intake No 3 Tunnel (USA)

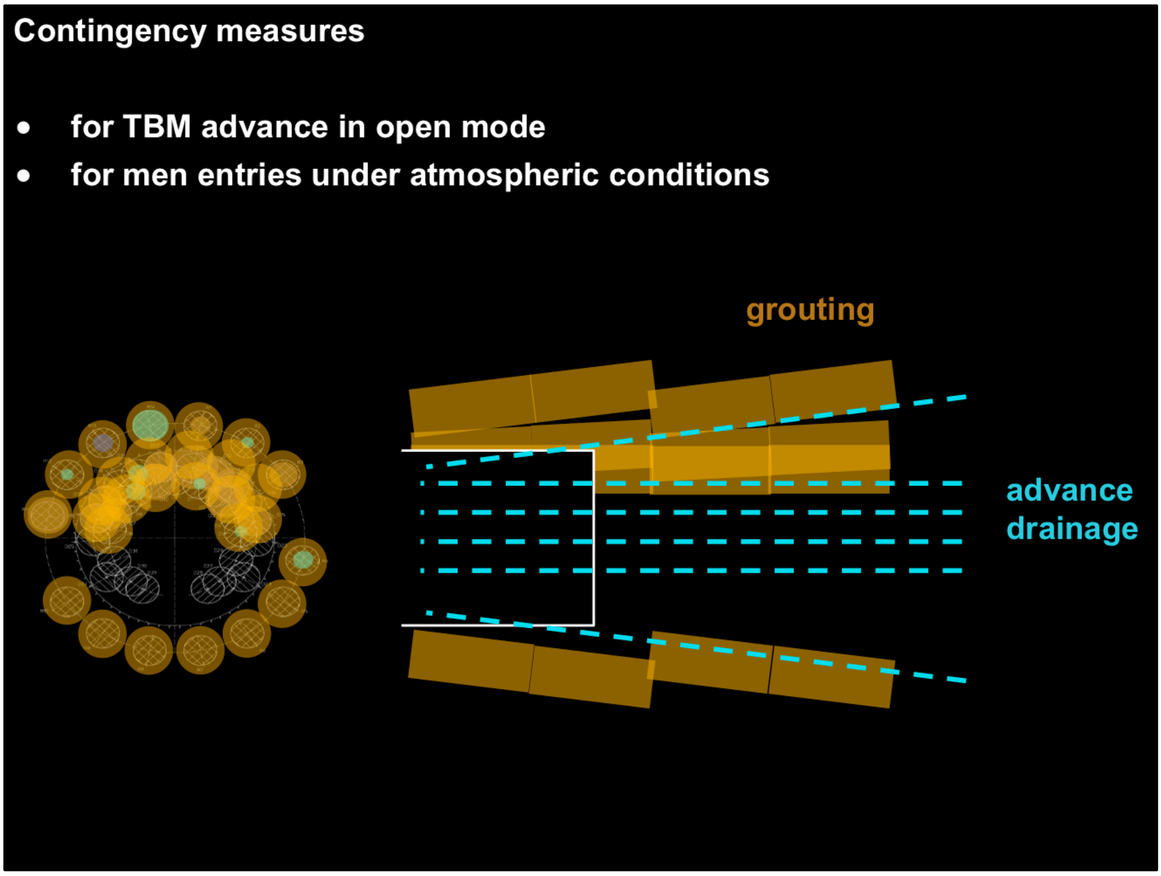
➔ Uncertainty over long portions of the tunnel about feasibility of open mode

This diagram shows the expected range of permeability along the tunnel. Considering that the critical permeability is about 10^{-8} m/s, the diagram indicates that the stand-up time in the present could be anything between a few hours and several days. This variability introduces an element of uncertainty concerning the feasibility of open mode operation. A permeability higher than the critical one in combination with a low shear strength would necessitate support of the face.



The diagram shows the necessary support pressure as a function of the cohesion of the ground (computation after [12]).

At cohesion values less than about 100 kPa, the necessary slurry pressure amounts to more than 10 bar. Experiences with such high pressures did not exist before Lake Mead. (The columns at the right hand side show the pressures applied in a number of older, well known projects [17].)



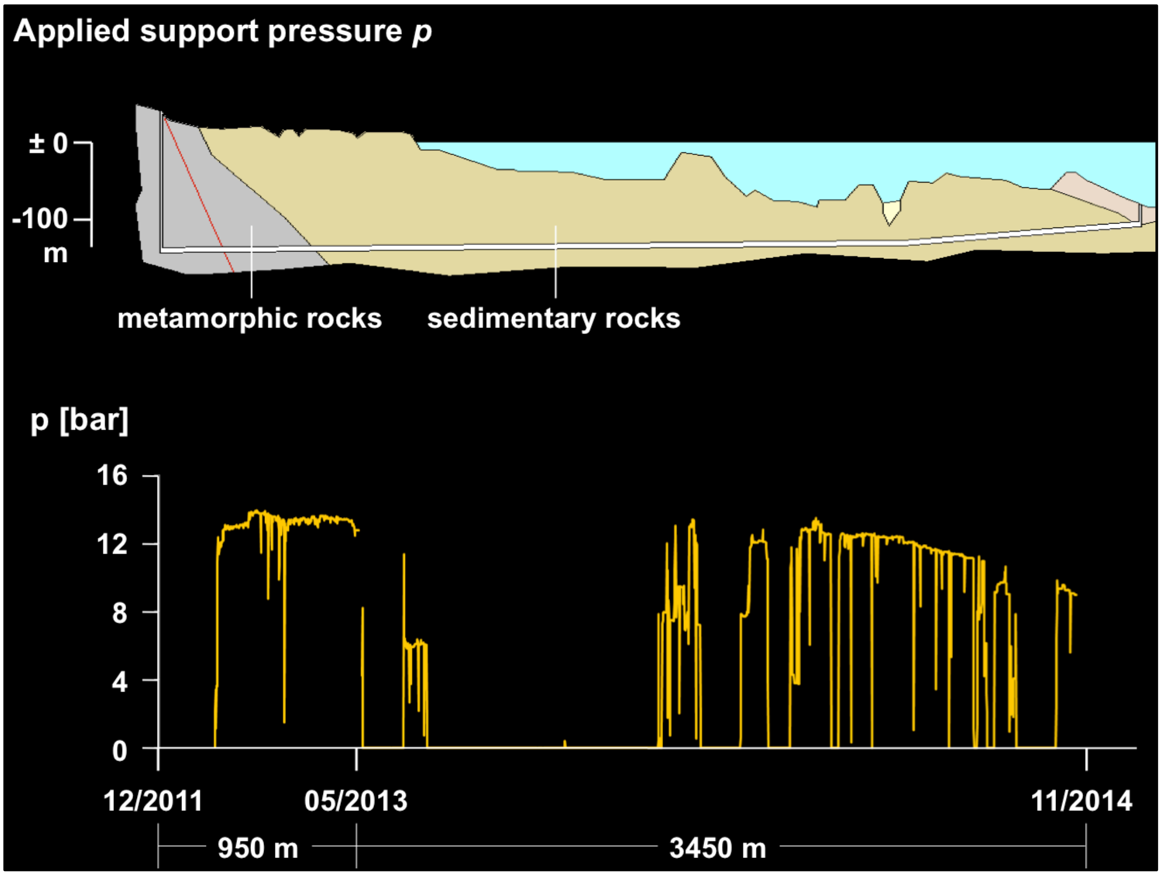
Contingency measures

- for TBM advance in open mode
- for men entries under atmospheric conditions

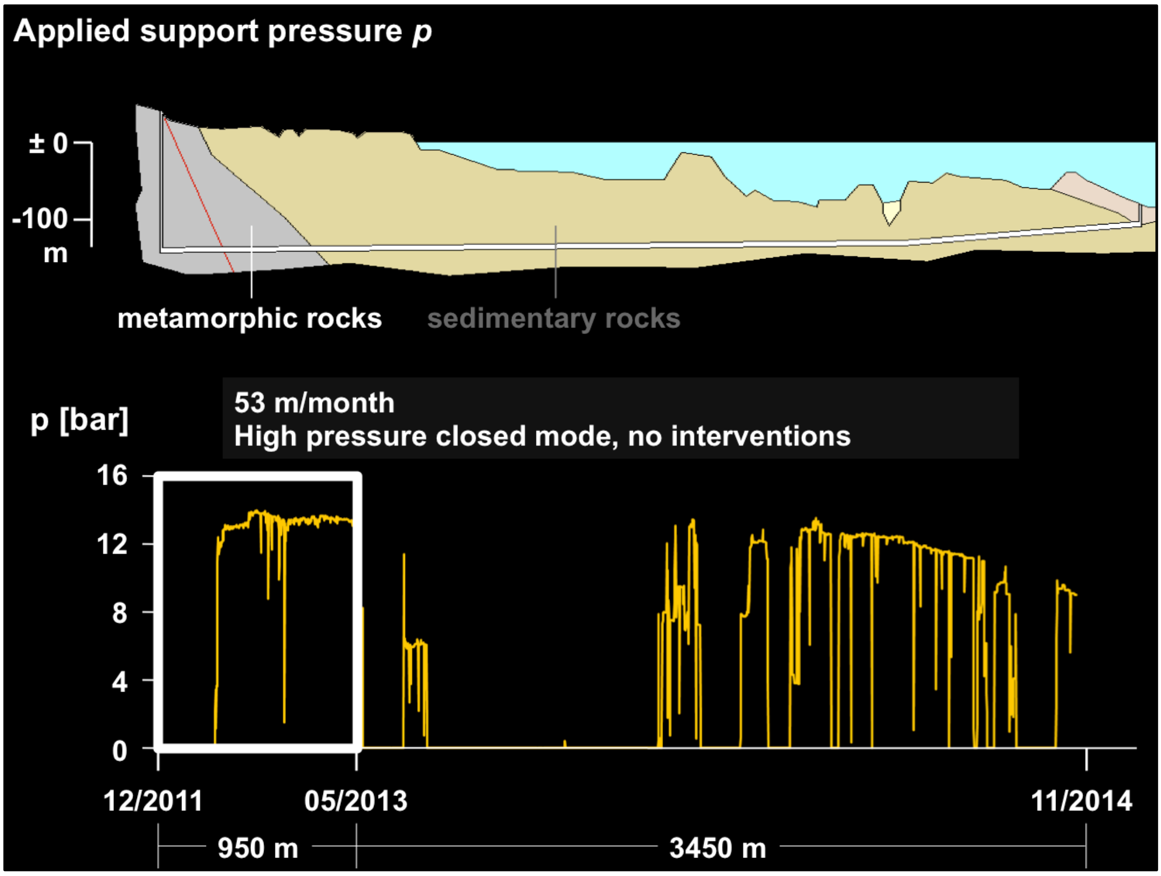
grouting

advance drainage

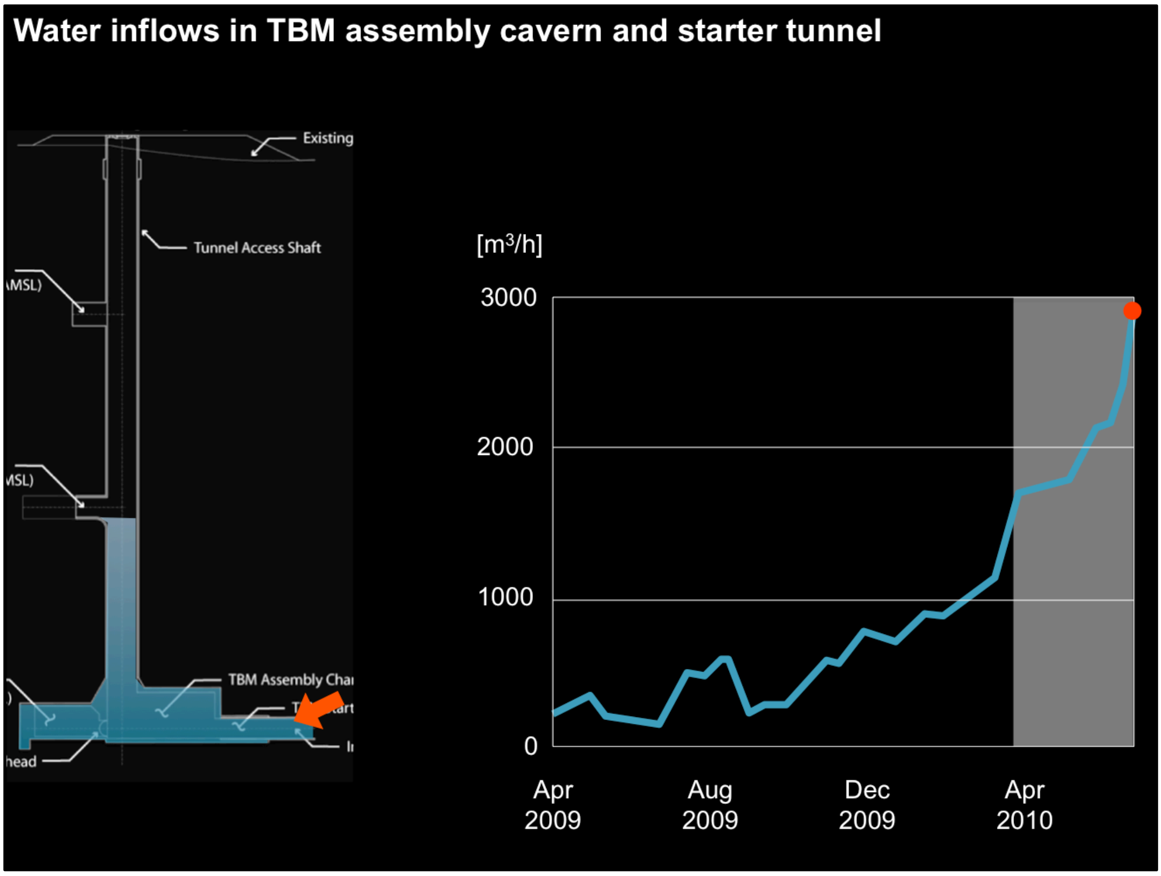
The inherent technological risk of such high-pressure closed-mode TBM operation and the lack of experience with hyperbaric interventions at 14 bar made it necessary to develop fall-back strategies, involving open mode operation in combination with advance grouting and/or drainage [18].



TBM excavation started in December 2011. This diagram shows the applied face support pressure along the alignment.



In the first part of the alignment through the metamorphic rocks, the overall advance rate of the TBM was extremely low due to construction difficulties caused by the combination of high water pressure, extremely high rock permeability and the presence of an unexpected fault zone.



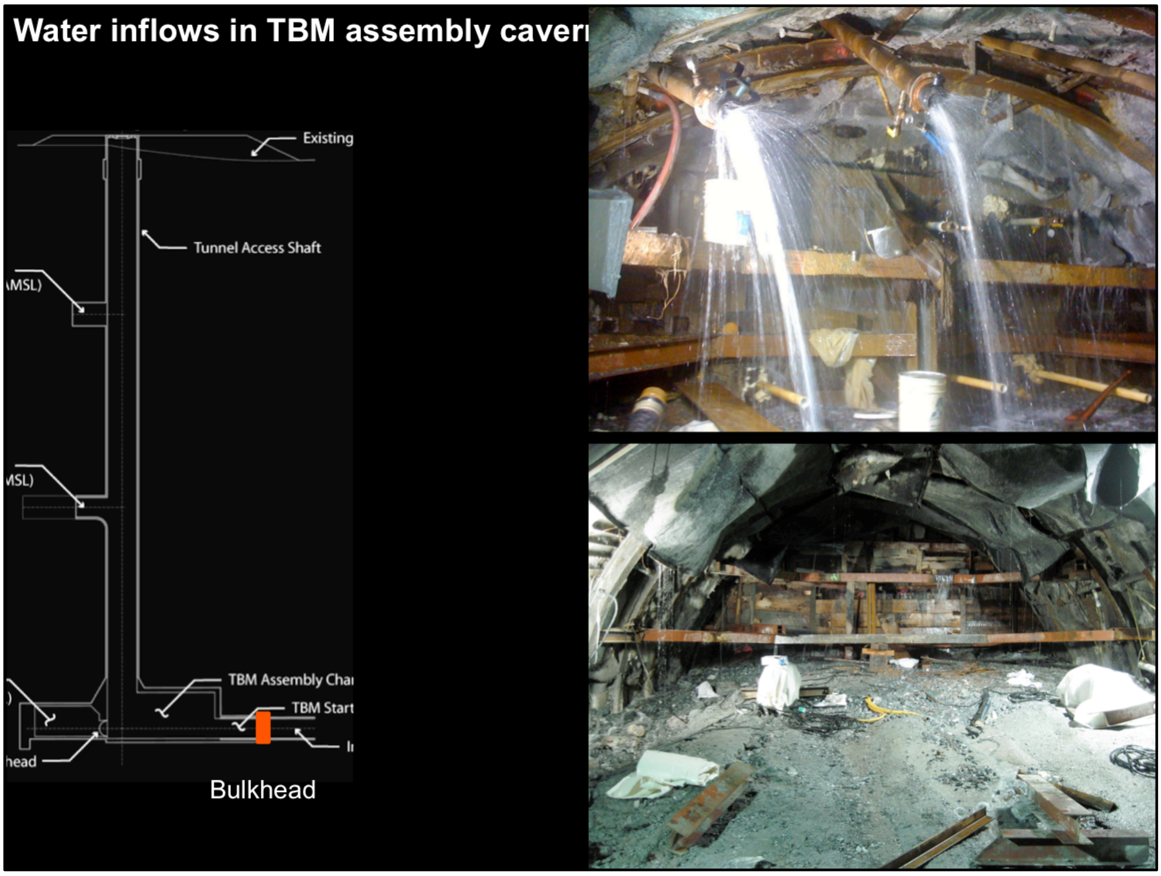
Water inflows in TBM assembly cavern and starter tunnel

Problems started already during the construction of TBM assembly cavern and starter tunnel as the mentioned fault progressively entered the tunnel cross-section. Initially (when the fault occupied only a small part of the tunnel cross-section) only moderate water inflows and slow ravelling at the face were observed.

The quantity of water inflow increased progressively [19, 20] and finally a major instability occurred causing flooding of the tunnel and of the shaft, …

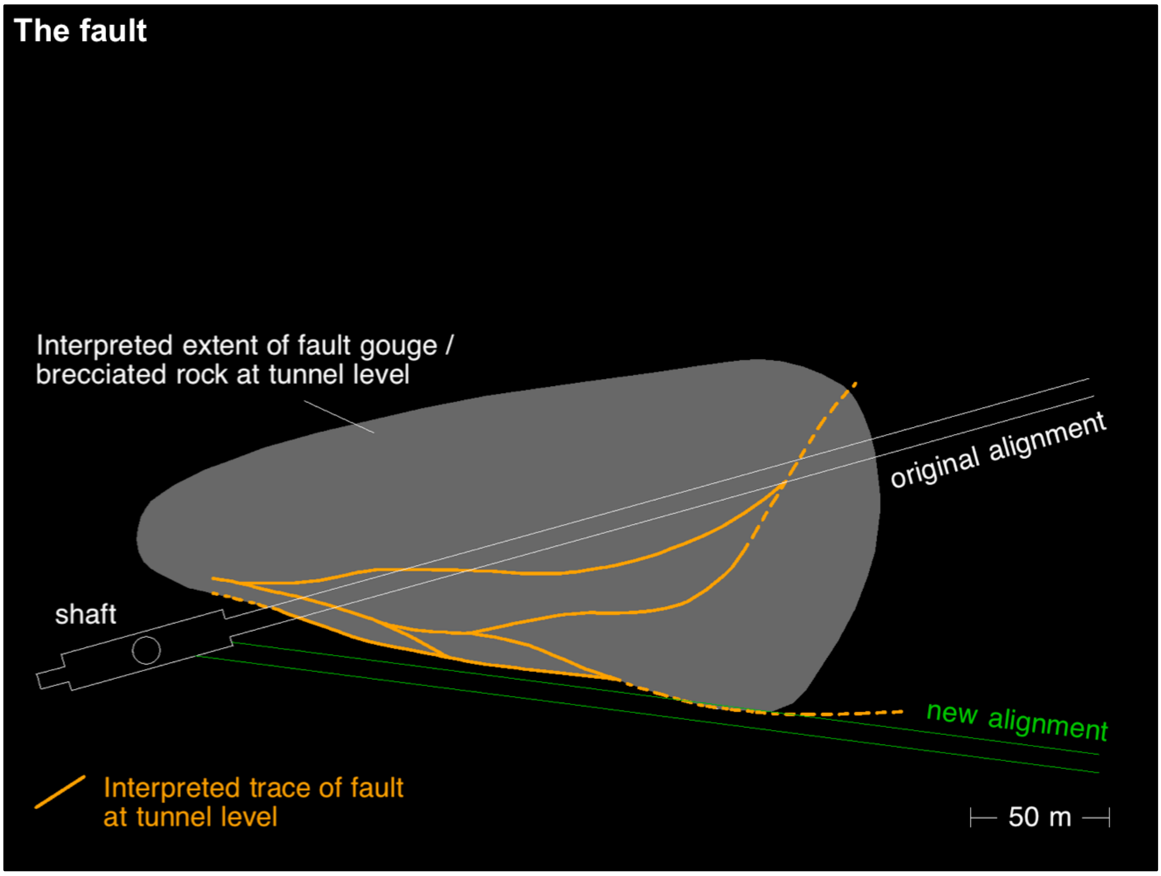
Water inflows in TBM assembly cavern

… accompanied by a big quantity of mud inrush into the tunnel.



Water inflows in TBM assembly caver

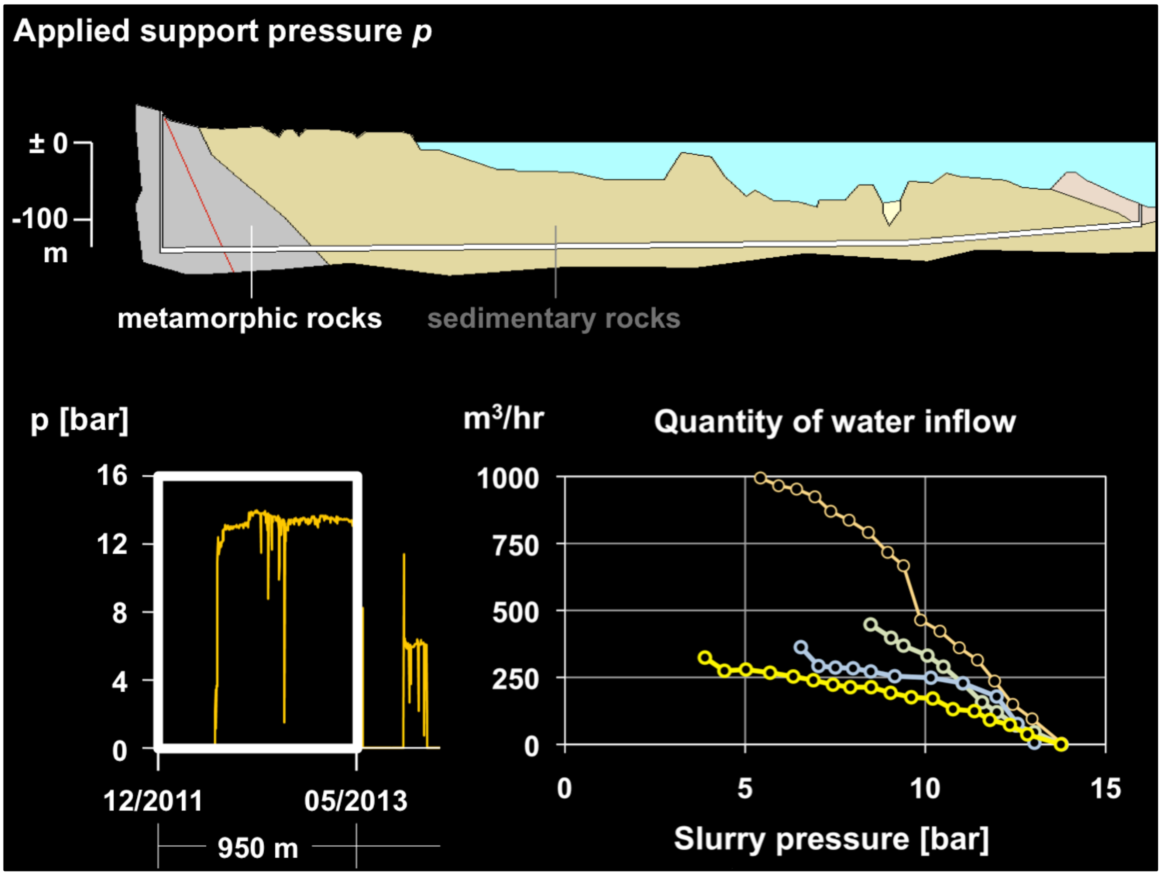
The photograph shows the water inflows through a bulkhead that was constructed later during the rehabilitation works.



The fault

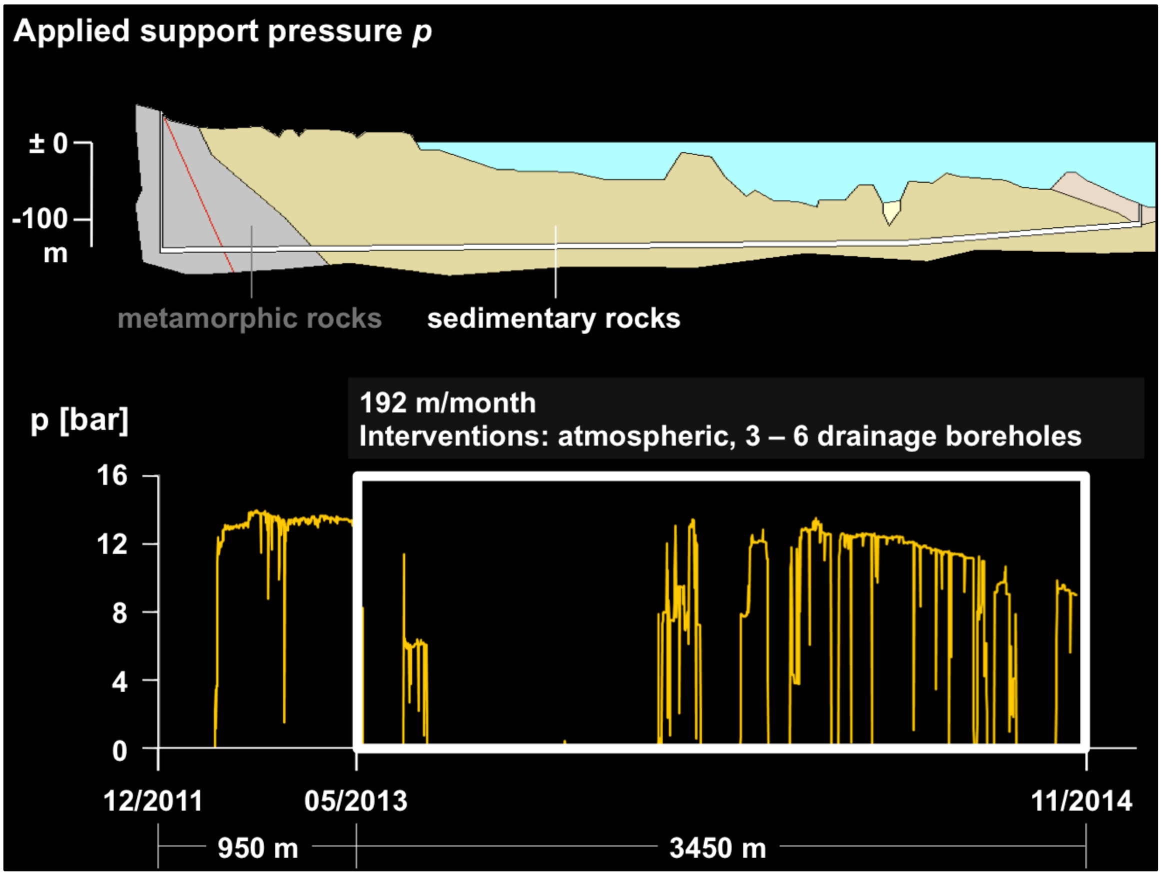
The fault, consisting of almost cohesionless material, was oriented sub-parallel to the tunnel and would affect construction works for a big portion of the alignment. Therefore, the tunnel was realigned by rotating its axis eastwards by 23° [20]. A bigger rotation of the axis was impossible due to the constraints imposed by the TBM assembly.

However, conditions worsened again soon (as the TBM encountered branches of the above-mentioned fault) and made it necessary to operate the slurry shield in closed mode at 14 bar for several hundred metres. This is a remarkable achievement. It has never been done before anywhere in the world.



A very big problem was the virtual impossibility of accessing the excavation chamber for maintenance under atmospheric pressure. Attempts to lower the slurry pressure from the in situ hydrostatic pressure (14 bar) to atmospheric pressure were often interrupted, because the water inflows reached hundreds of cubic metres per hour even at relatively high slurry pressures [21].

This photograph gives an impression of the water inflows in an exceptional case, where it was still possible to reduce the pressure in the chamber to atmospheric.
A series of pre-excavation grouting campaigns succeeded in reducing water inflow to an extent, which allowed maintenance work to be carried-out at least on the slurry lines. This was indispensable for continuing excavation.
Work could be performed at the cutterhead only later, after reaching competent rock.

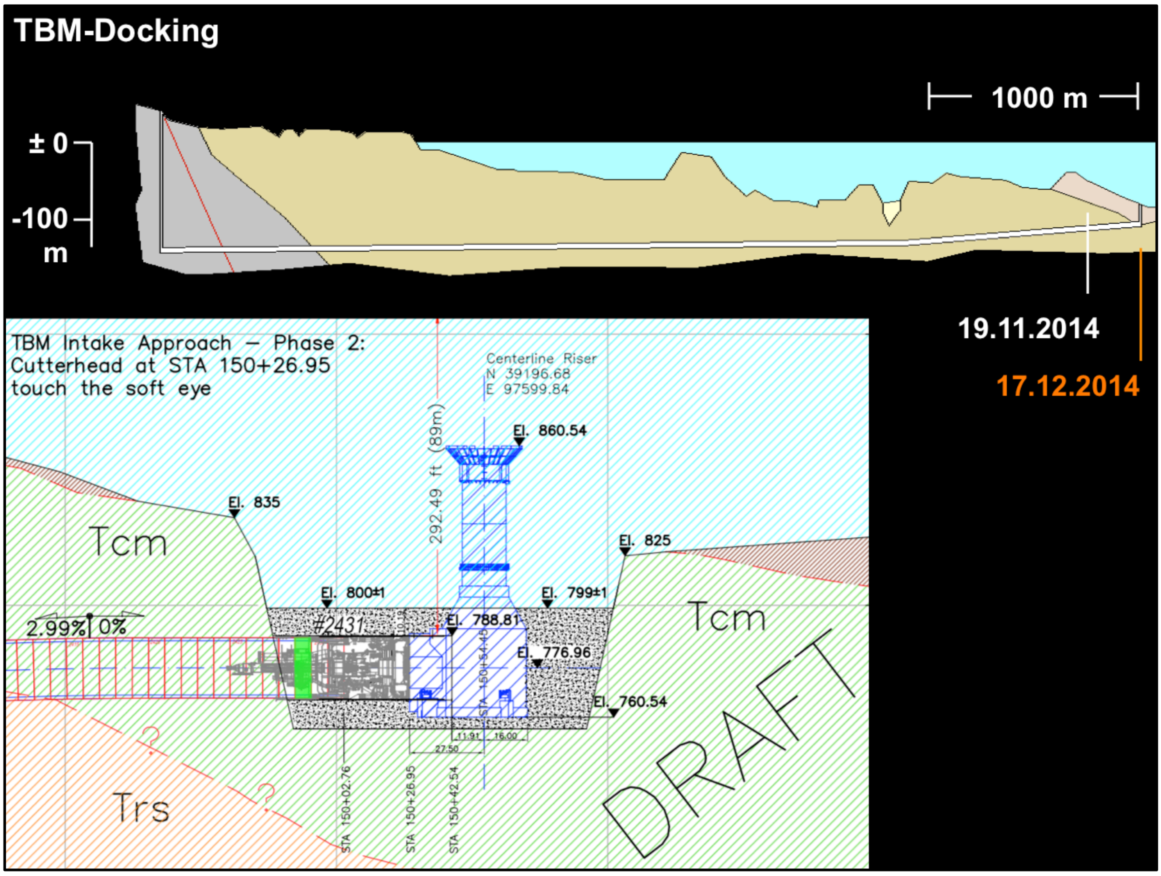


Applied support pressure *p*

192 m/month
Interventions: atmospheric, 3 – 6 drainage boreholes

Considerably higher production rates (on average 190 m monthly) were achieved in the second part of the alignment through the sedimentary rocks. Advance drainage proved to be a very effective stabilization measure. The interventions in the working chamber were carried-out under atmospheric pressure, always in combination with three to six drainage boreholes through the cutterhead.
However, the quantities of water inflows were high and caused mucking-out problems (the excavated material was too fluid-like). Therefore, TBM advance was often carried-out closed mode under a high pressure.

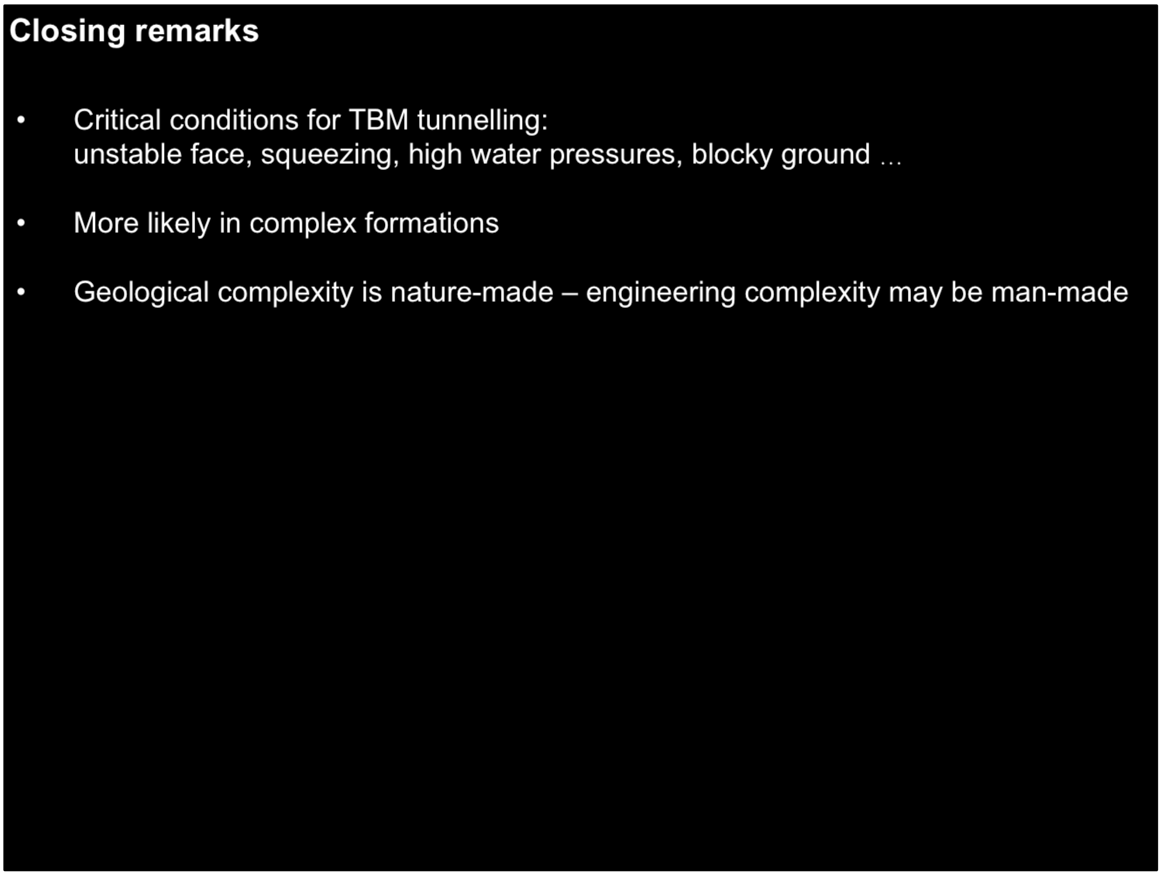
TBM-Docking



19.11.2014

17.12.2014

Construction was finished 2 years ago, with the successful docking-in of the TBM into the intake structure.



Closing remarks

- Critical conditions for TBM tunnelling:
  unstable face, squeezing, high water pressures, blocky ground …
- More likely in complex formations
- Geological complexity is nature-made – engineering complexity may be man-made

Critical conditions for TBM tunnelling include an unstable face, squeezing ground, rocks with short stand-up time, high water pressures, karst cavities, blocky ground or a mixed face.

TBMs respond sensitively to deviations from ideal operational conditions. Such deviations are more likely to occur in complex formations as they often involve highly variable ground including weak rocks.

Geological complexity reduces the reliability of predictions as to lithological or structural characteristics, and the parameters or behaviour of the ground along the alignment. Depending on the construction method, this may (but will not necessarily) result in related uncertainties with respect to the construction process.

References

[1] Morgenstern, N. R., Cruden, D. 1977. Description and classification of geotechnical complexities. Proc. Int. Symp. on the Geotechhnics of Structurally Complex Formations, Capri, Vol. 2, 195 - 203

[2] Mezger, F., Anagnostou, G., Ziegler, H. 2013. The excavation-induced convergences in the Sedrun section of the Gotthard Base Tunnel. Tunnelling and Underground Space Technology, 38, 447 - 463

[3] Cantieni, L., Anagnostou, G. 2007. On the variability of squeezing in tunneling. Proc. 11th Congress of the International Society for Rock Mechanics, 983 - 986, Lisbon

[4] Bilgin, N., Algan, M. 2012. The performance of a TBM in a squeezing ground at Uluabat, Turkey. Tunnelling and Underground Space Technology, 32, 58 - 65

[5] Ramoni, M., Anagnostou, G., 2011. The interaction between shield, ground and tunnel support in TBM tunnelling through squeezing ground. Rock Mechanics and Rock Engineering, 44, 37 - 61

[6] Kovári, K., Anagnostou, G. 1995. The ground response curve in tunnelling through short fault zones. Proc. 8th Congress of the Int. Soc. for Rock Mech., Tokyo

[7] Anagnostou, G., Kovári, K. 2005. Tunnelling through geological fault zones. Int. Symp. on Design, Construction and Operation of Long Tunnels, Taipei, Taiwan

[8] Ramoni, M., Anagnostou, G., 2011a. The effect of consolidation on TBM shield loading in water-bearing squeezing ground. Rock Mechanics and Rock Engineering, 44, 63 - 83

[9] Ehrbar, H., Wildbolz, A., Priller, A., Seiler, A. 2013. Grouting in the Gotthard Base Tunnel. Geomechanics and Tunnelling, 6 (3), 2 - 32

[10] Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J., Withjack, M.O. 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. J. of Structural Geology, 32, 1557 – 1575

[11] Zingg, S., Anagnostou, G. 2012. Tunnel face stability in narrow water-bearing fault zones. EUROCK 12, Stockholm

References

[12] Zingg, S. 2016. Static effects and aspects of feasibility and design of drainages in tunnelling. ETH Zurich, PhD thesis No. 23729
[13] Feroz, M., Jensen, M., Lindell, J.E. 2007. The Lake Mead intake 3 water tunnel and pumping station, Las Vegas, Nevada, USA. Proc. RETC, 647 - 662
[14] McDonald, J., Burger, W. 2009. Lake Mead Intake Tunnel No. 3. Tunnel, 4, 43 – 48
[15] Schuerch, R., Anagnostou, G. 2013. Analysis of the stand-up time of the tunnel face. Proc. World Tunnel Congress 2013, 709 - 714, Geneva
[16] Schuerch, R. 2016. On the delayed failure of geotechnical structures in low permeability ground. ETH Zurich, PhD thesis No. 23681
[17] Holzhäuser, J., Hunt, S. W., Mayer, C. 2006. Global Experience with Soft Ground and Weak Rock Tunneling under Very High Groundwater Heads. Proc. North American Tunneling, 277 - 289, London
[18] Anagnostou, G., Cantieni, L., Nicola, A., Ramoni, M. (2010): Face Stability Assessment for the Lake Mead Intake No 3 Tunnel. ITA-AITES World Tunnel Congress 2010 “Tunnel Vision Towards 2020”, Vancouver.
[19] Brierley Associates, LLC 2010. Lake Mead Intake #3. Starter Tunnel Recovery Investigations. Geotechnical Interpretation Report. October 2010
[20] Brierley Associates, LLC (2011): Lake Mead Intake #3. Relocated Tunnel Alignment. Geotechnical Interpretive Report (GIR). April 2011
[21] Nickerson, J., Bono, R., Donadoni, N., Nicola, A., Anagnostou, G., Schuerch, R., Zingg, S. 2014. Lake Mead Intake Tunnel No. 3 - A step beyond the limits. Proc. Swiss Tunnel Congress, Lucerne
[22] Croce, A. 1977. Opening address. Proc. Int. Symp. on the Geotechhnics of Structurally Complex Formations, Capri, Vol. 2, 149 - 151