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Brytningsmekanismer ved TBM-boring i hardt fjell

Amund Bruland

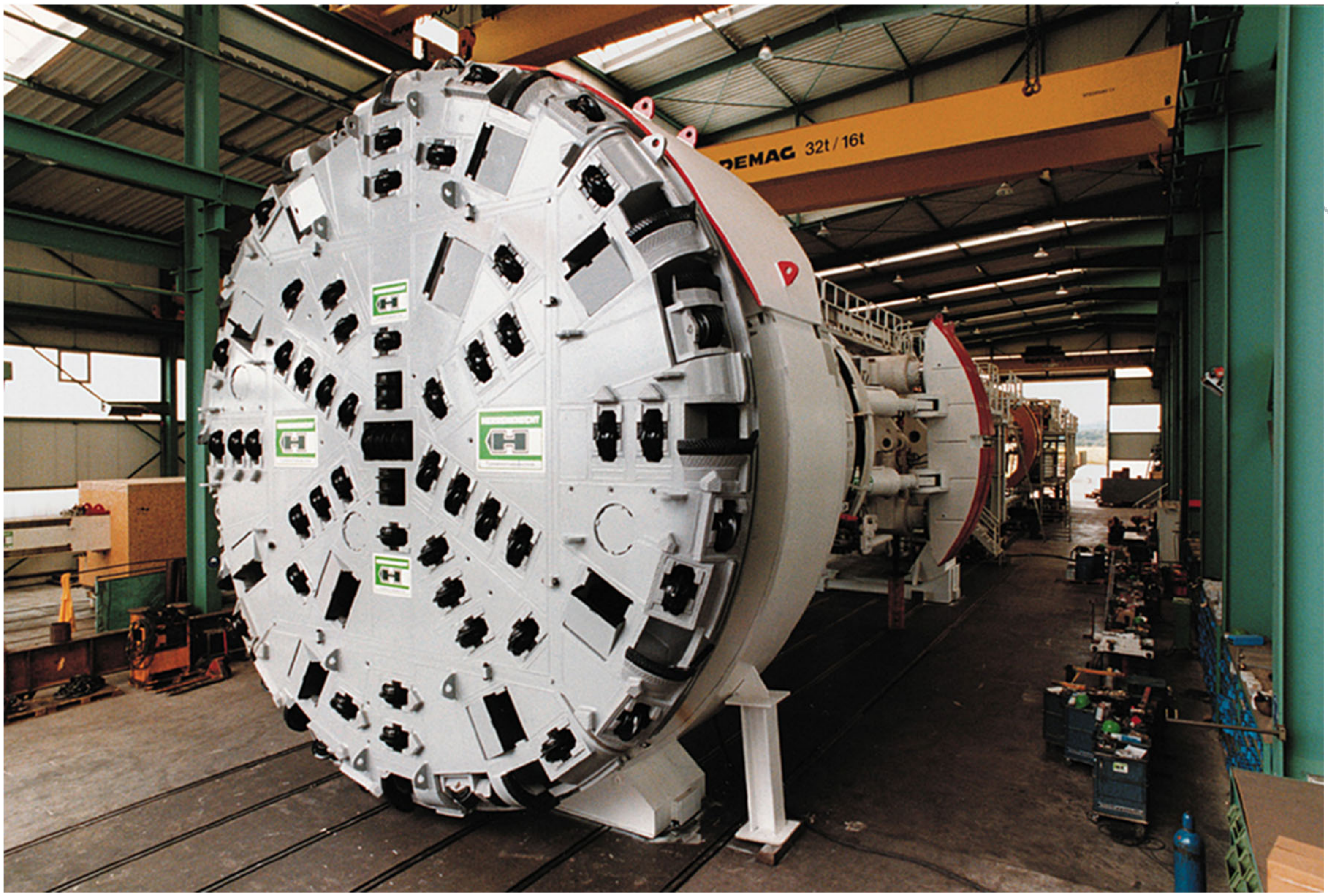
NGB-kurs

Bergteknikk for TBM-boring i hardt fjell

Innhold

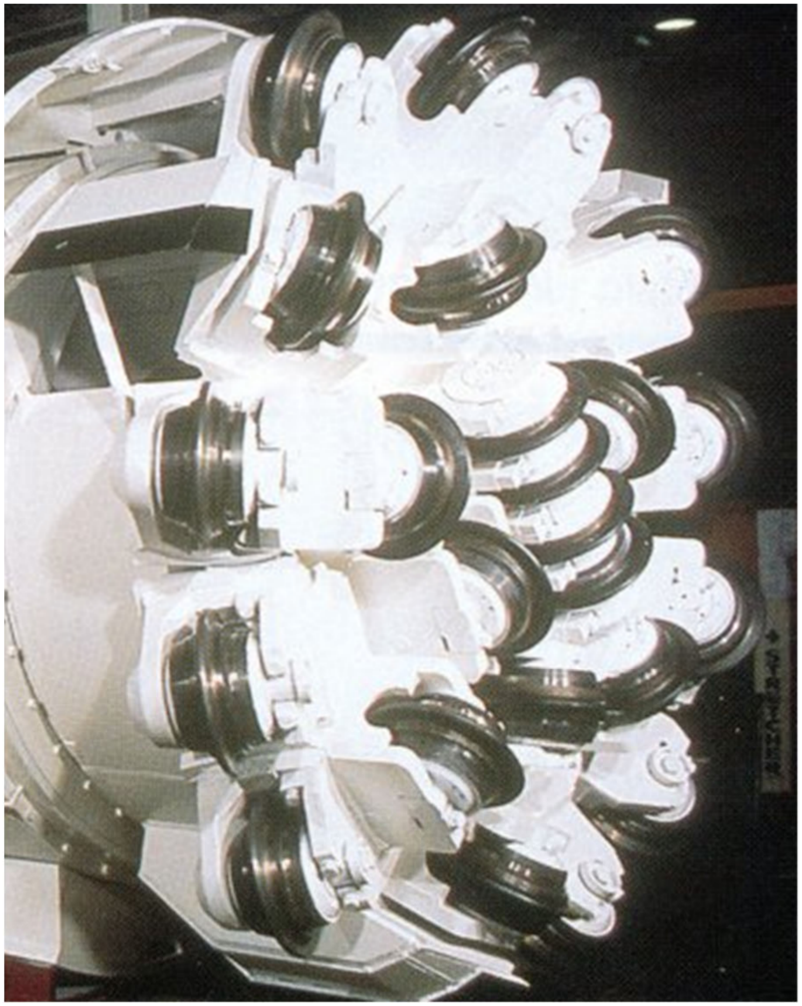
1. TBM og kuttere
2. Brytning av berg under en kutter
3. Design og bruk av TBM

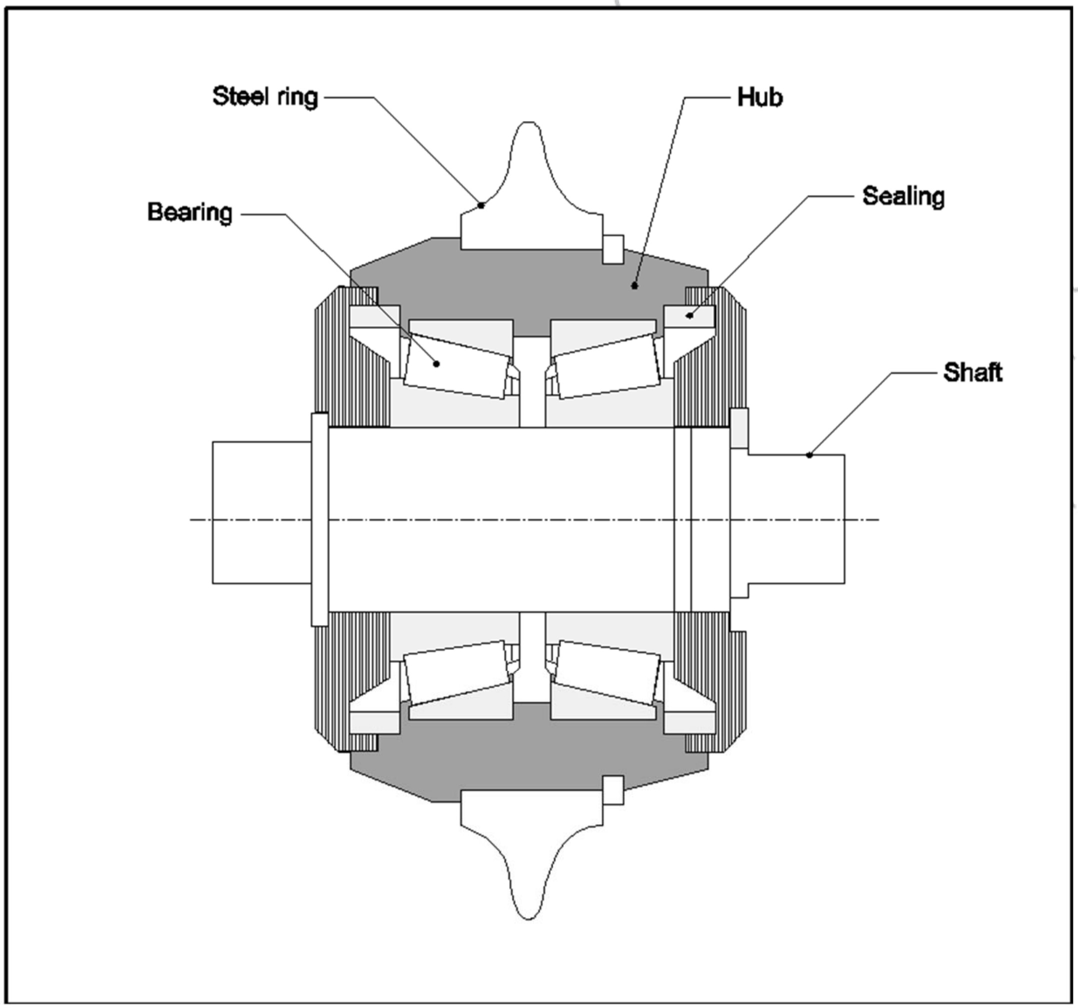
TBMs for Hard Rock (gripper TBM)



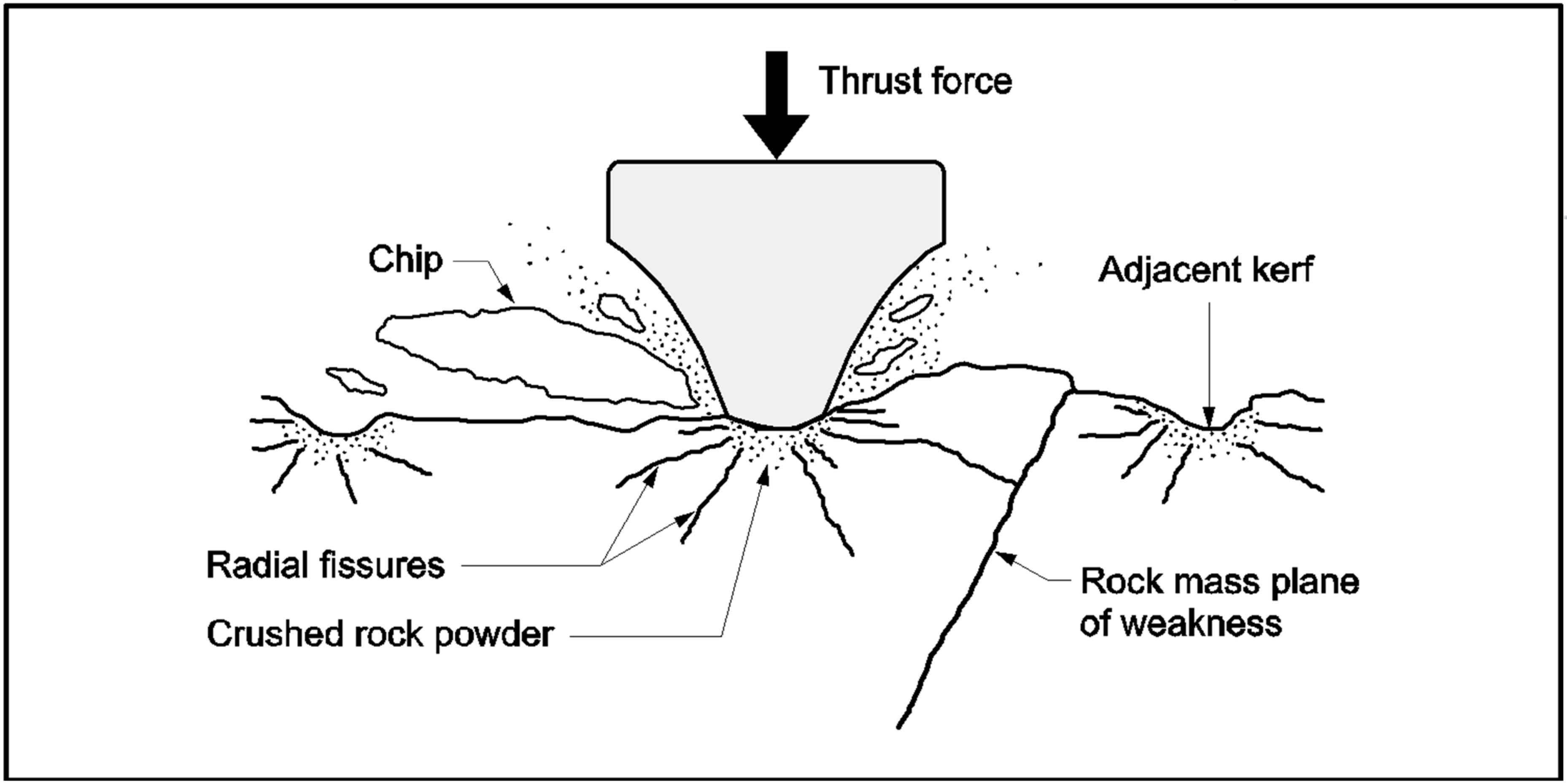
TBMs for Hard Rock (gripper TBMs)

TBM disk-kutter

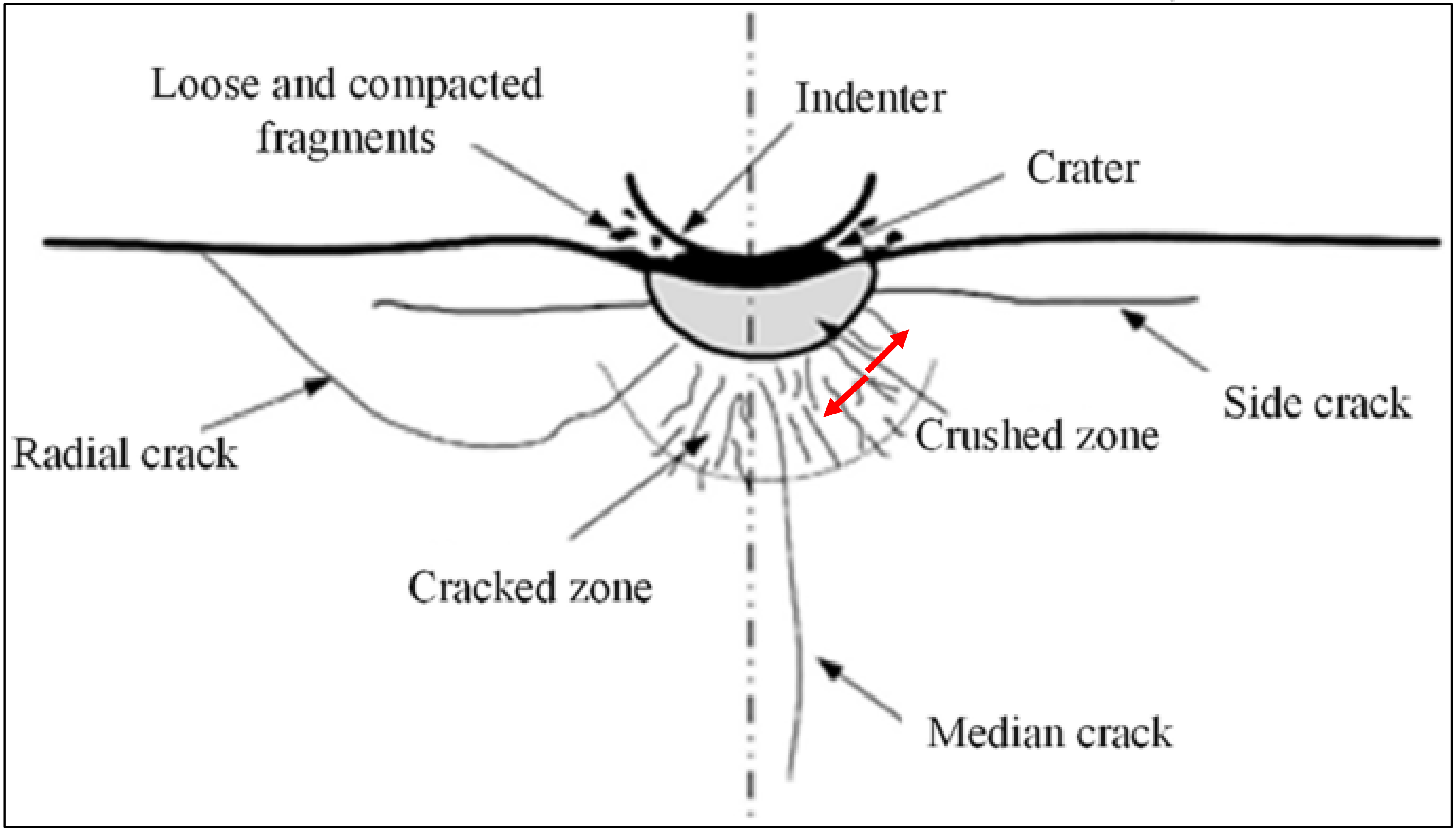




Brytning under kuttereggen (chipping, kaksbrytning)

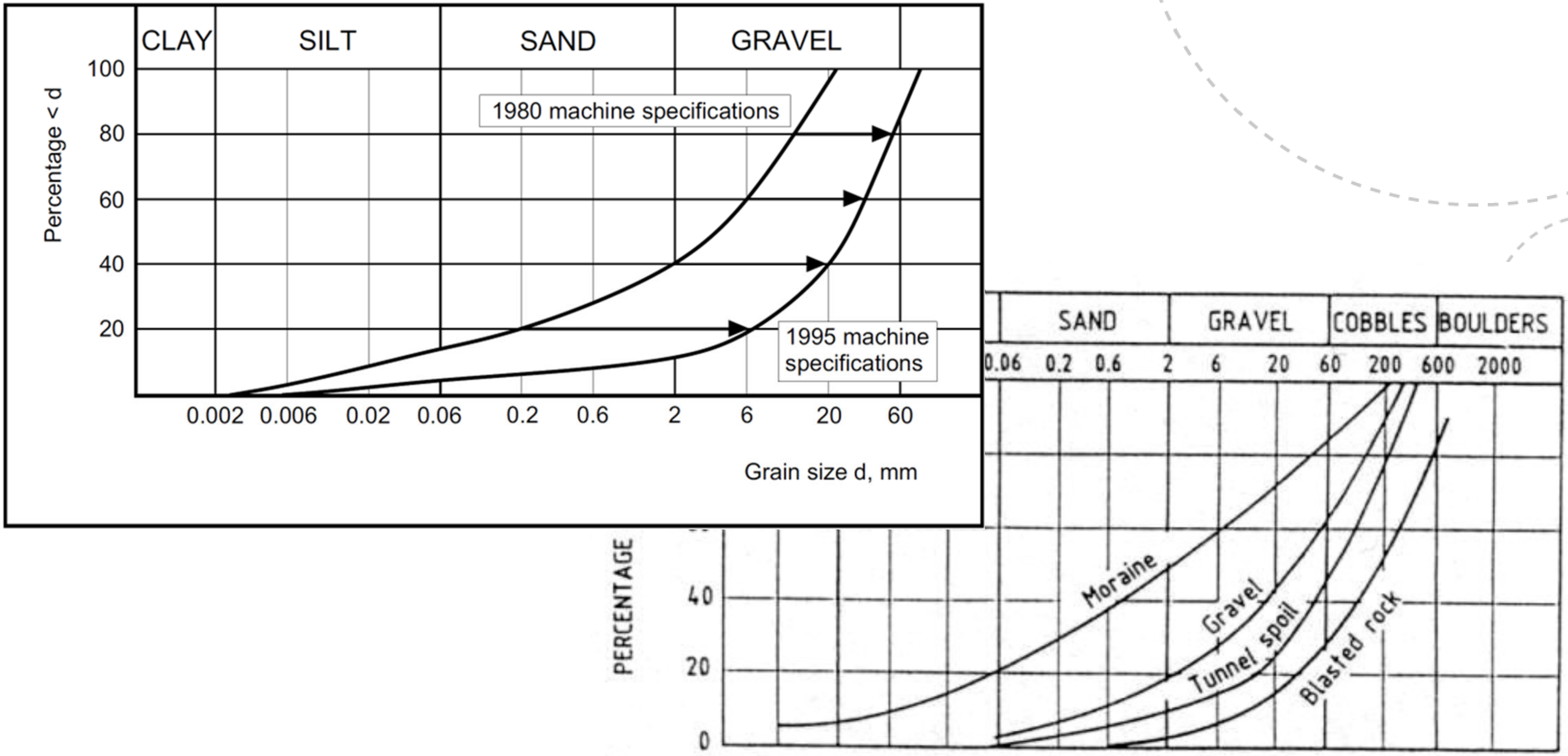


Spenninger under kutteren (inkl. Poisson's ratio)



Siktekurve

Siktekurve



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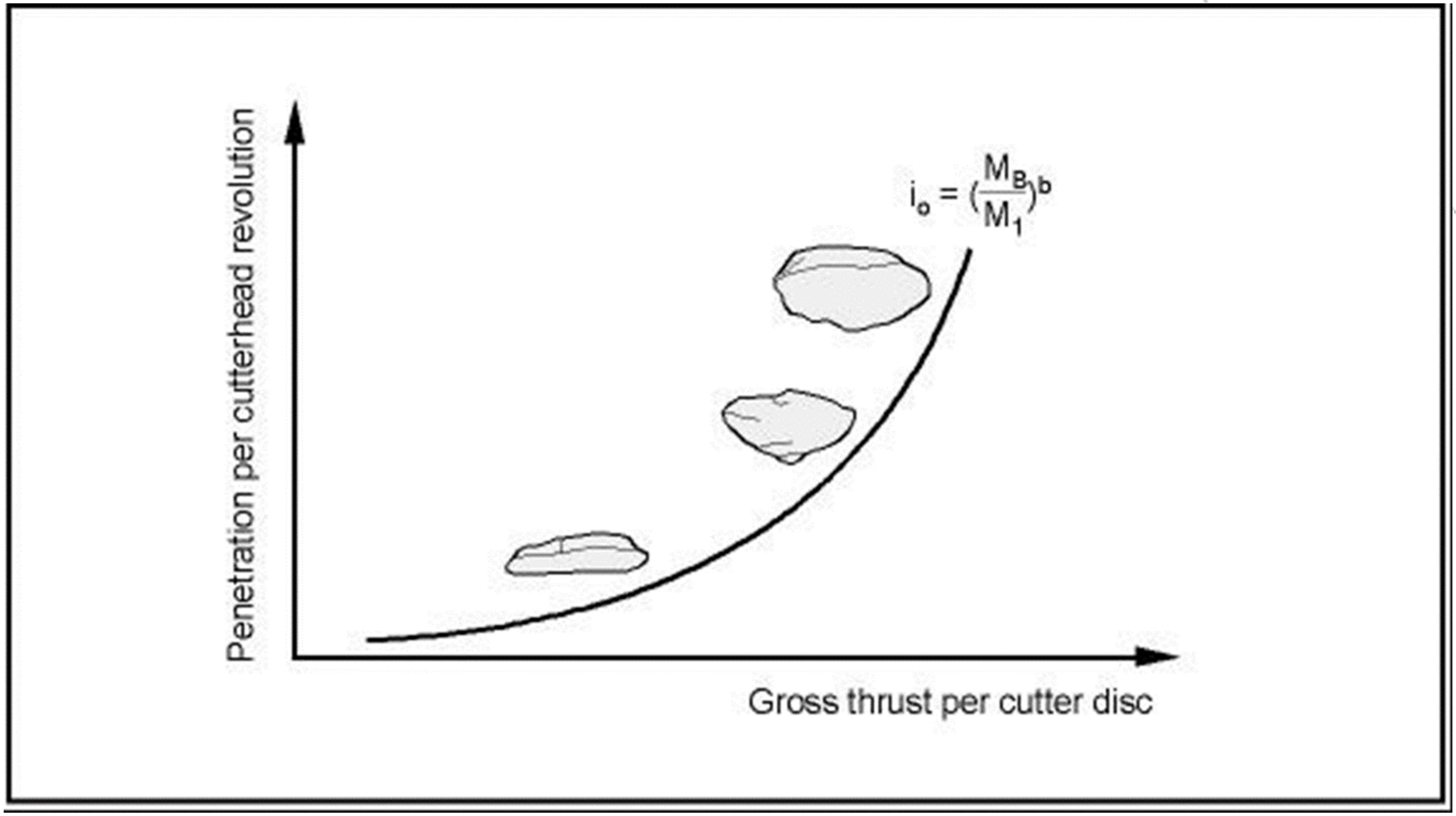
Inntrengningskurve – effektiv brytning



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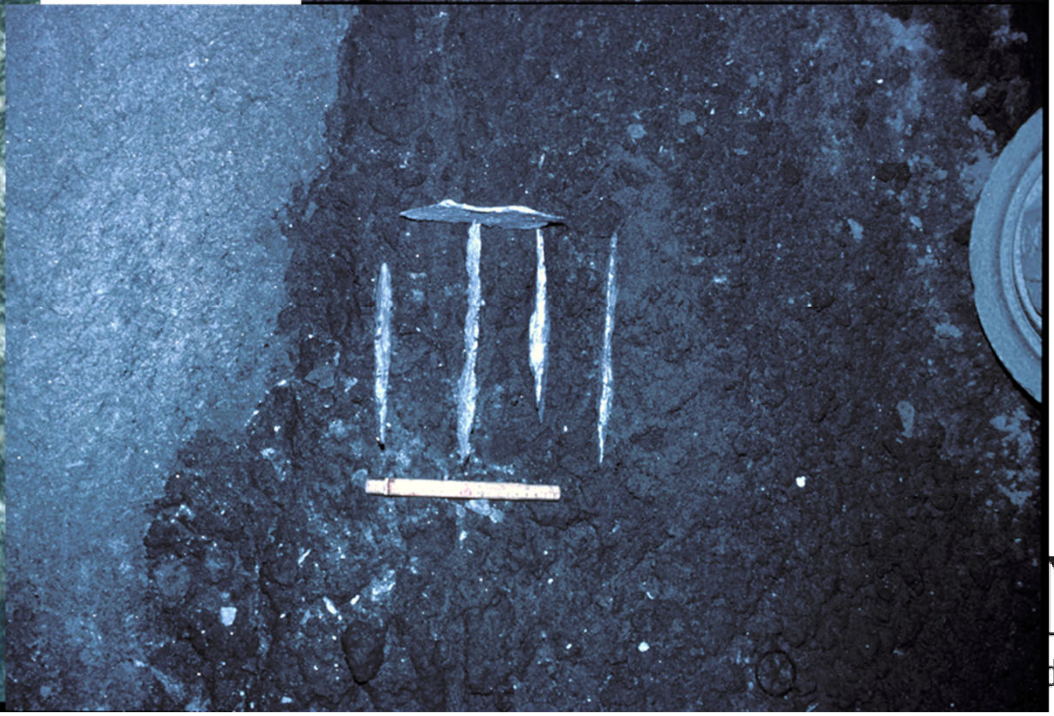
Effektiv kaksbrytning?

"Costly experience due to high cutter wear and low penetration rate"



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Inndriftsparametre (mm/omdreining)

Rock Mass Parameters	Machine Parameters
• Fracturing; frequency and orientation • Drilling Rate Index, DRI • Porosity	• Cutter thrust • Cutterhead rpm • Cutter spacing • Cutter size and shape • ~~Installed cutterhead power~~

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Tomromsareal i stuff → kraftdynamikk

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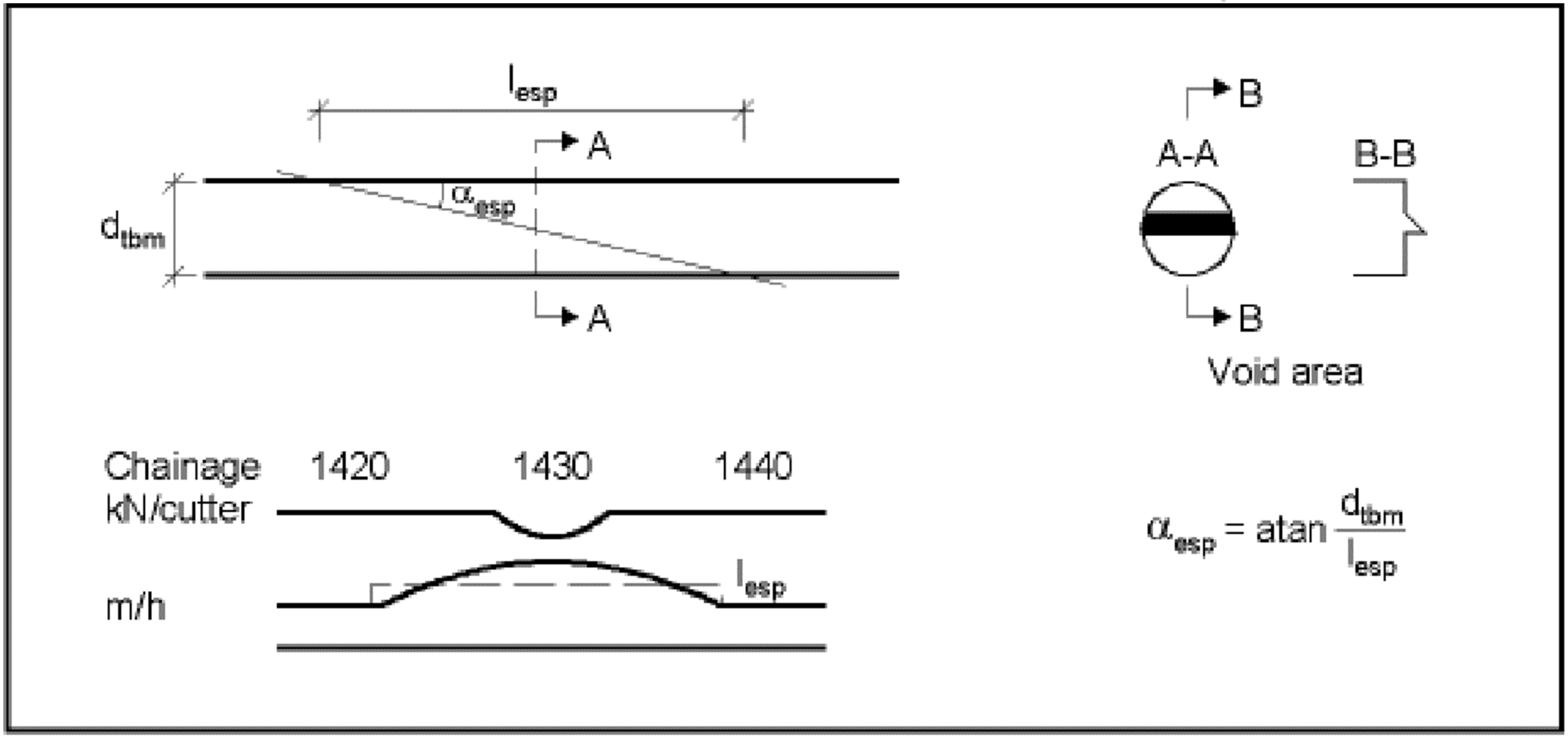
Boring gjennom en svakhetsflate



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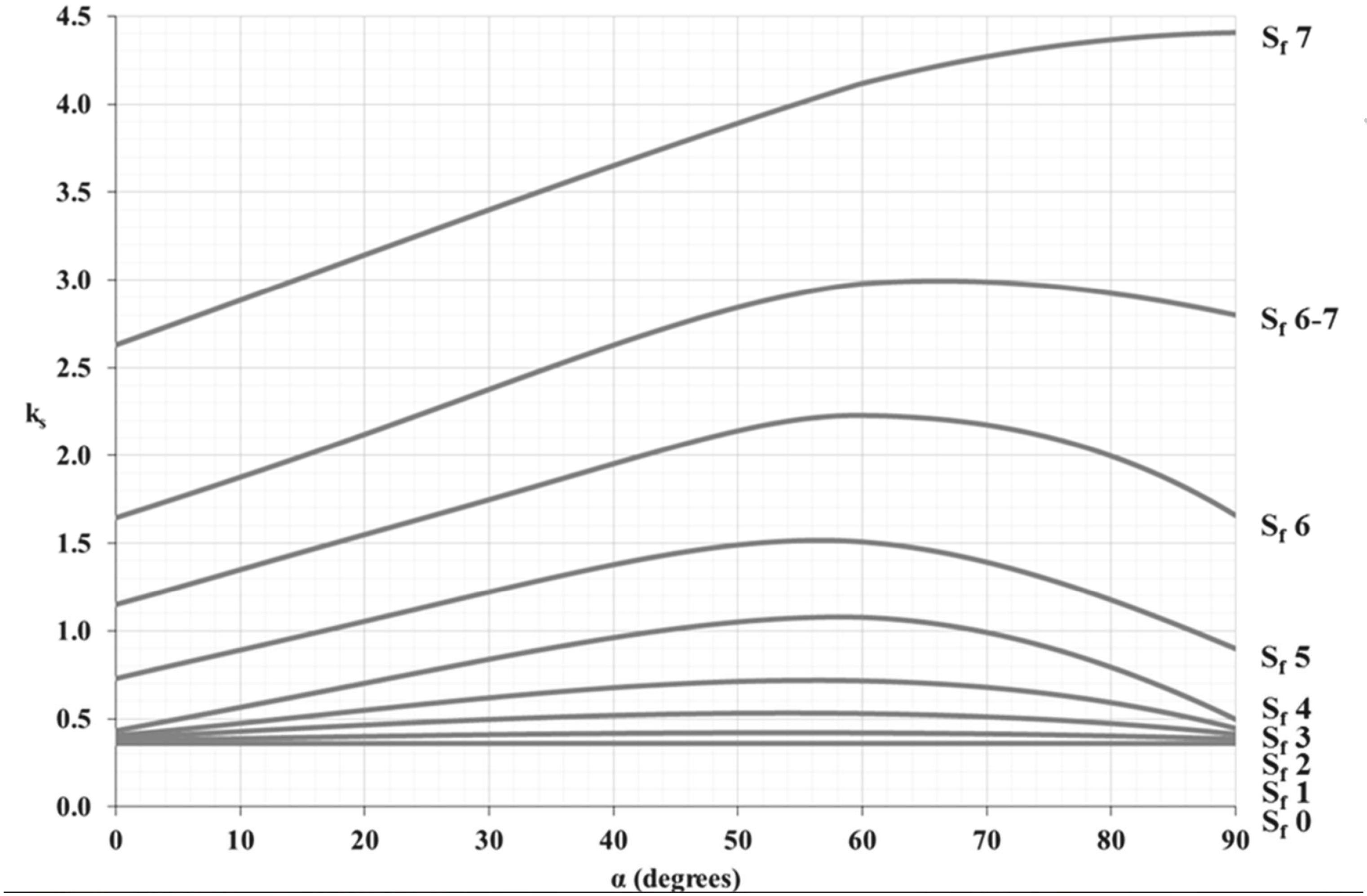
Effekten av systematisk oppsprukket bergmasse



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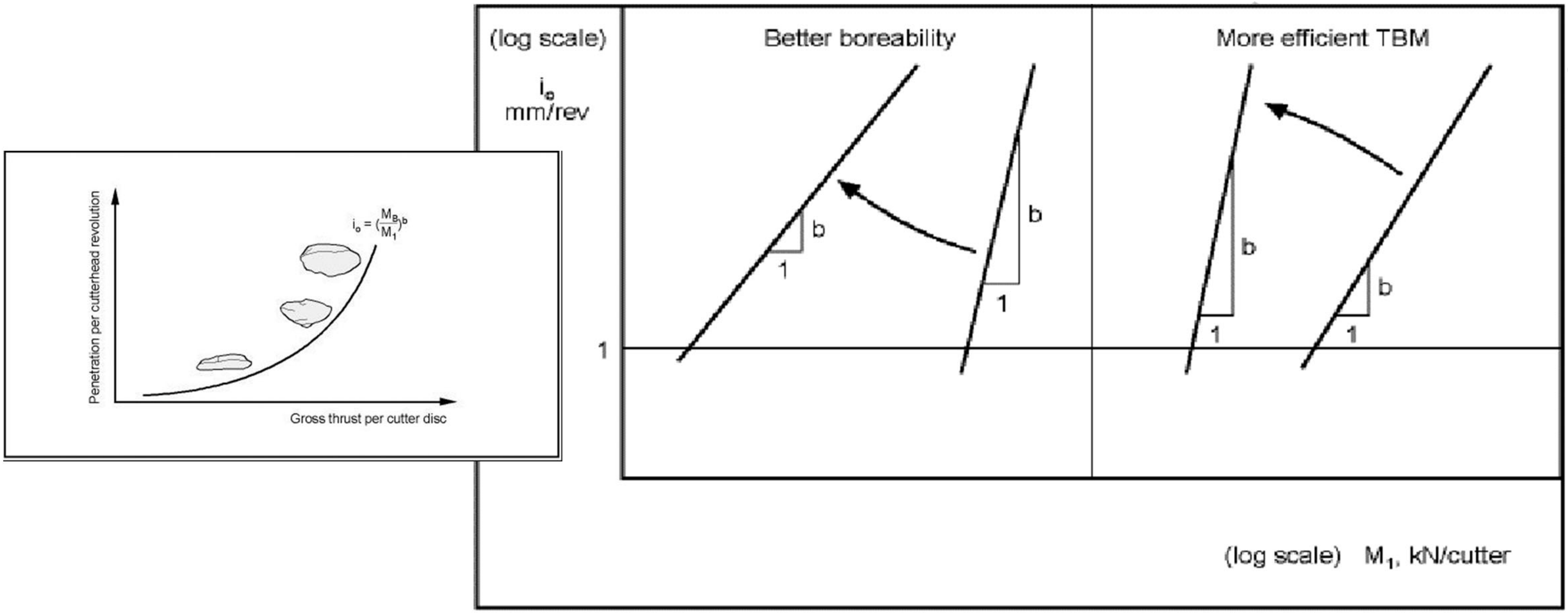
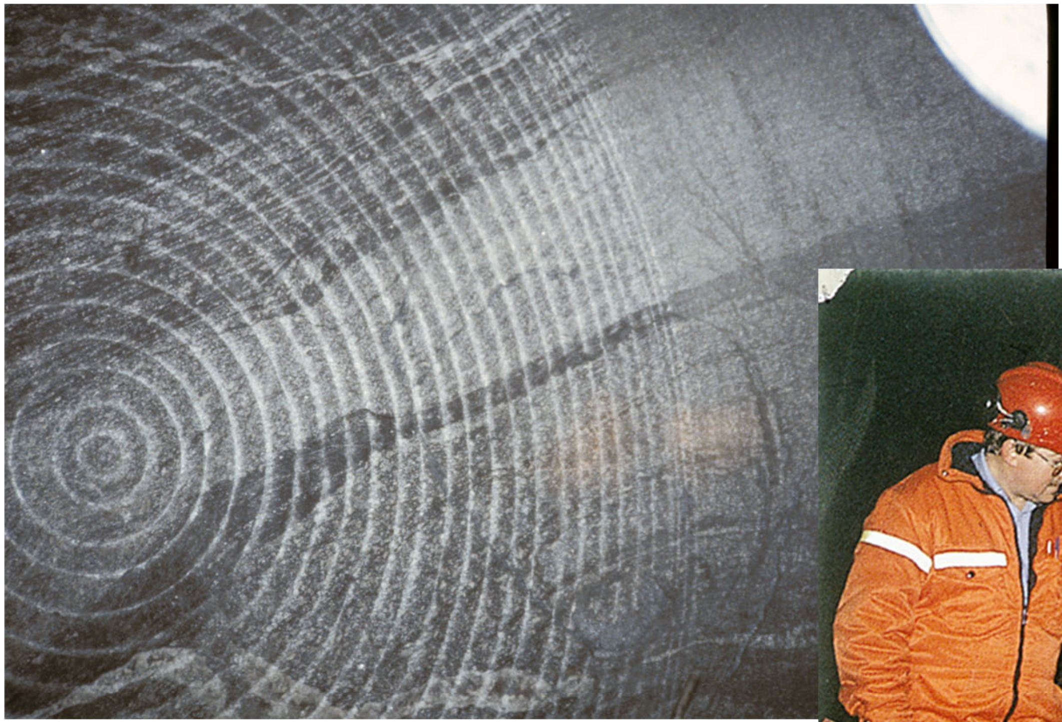
Hvordan øke ytelsen for TBMen?



Bergmassekvalitet ved kontraktskriving?



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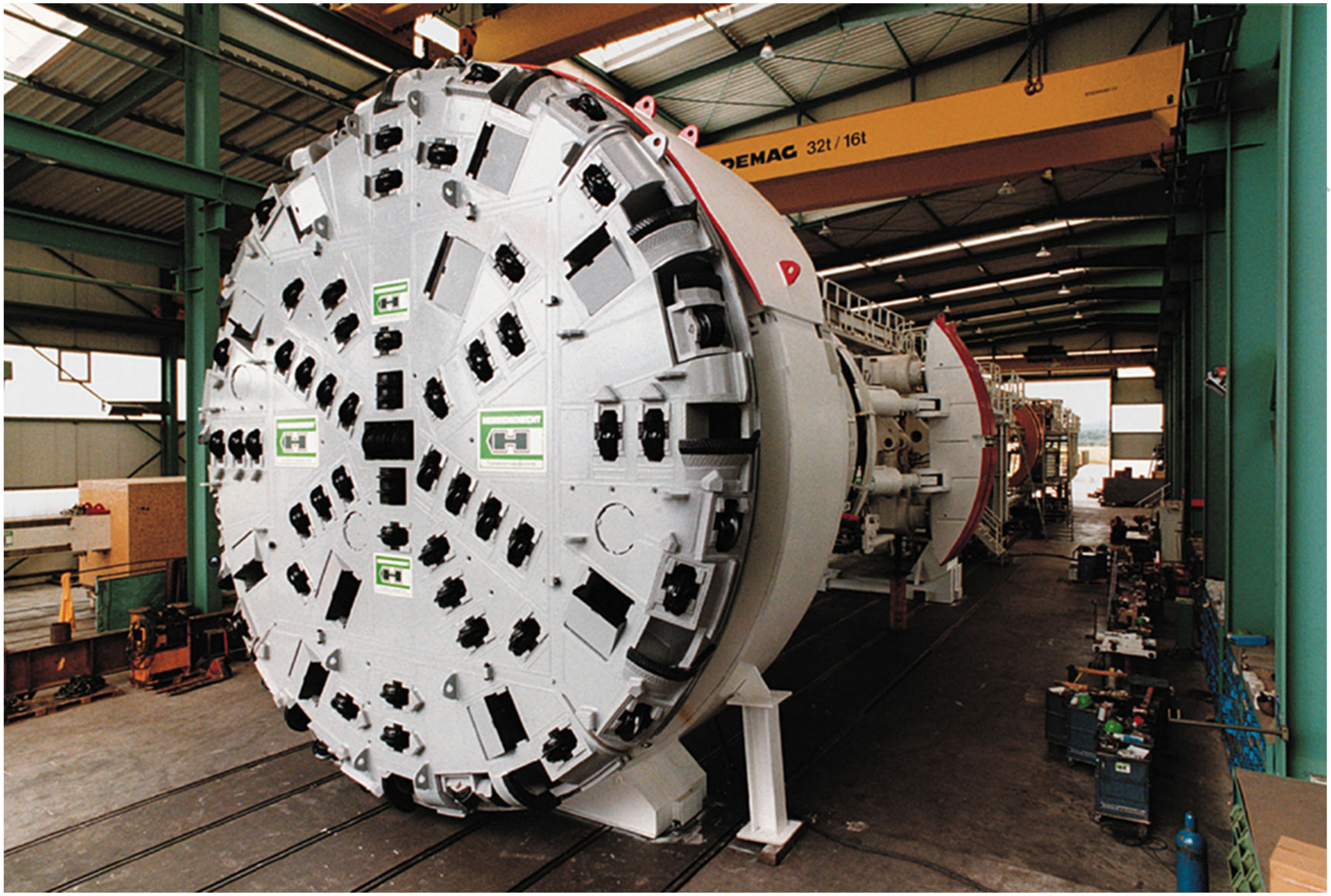
TBM-design ved kontraktskriving?



Takk for oppmerksomheten!

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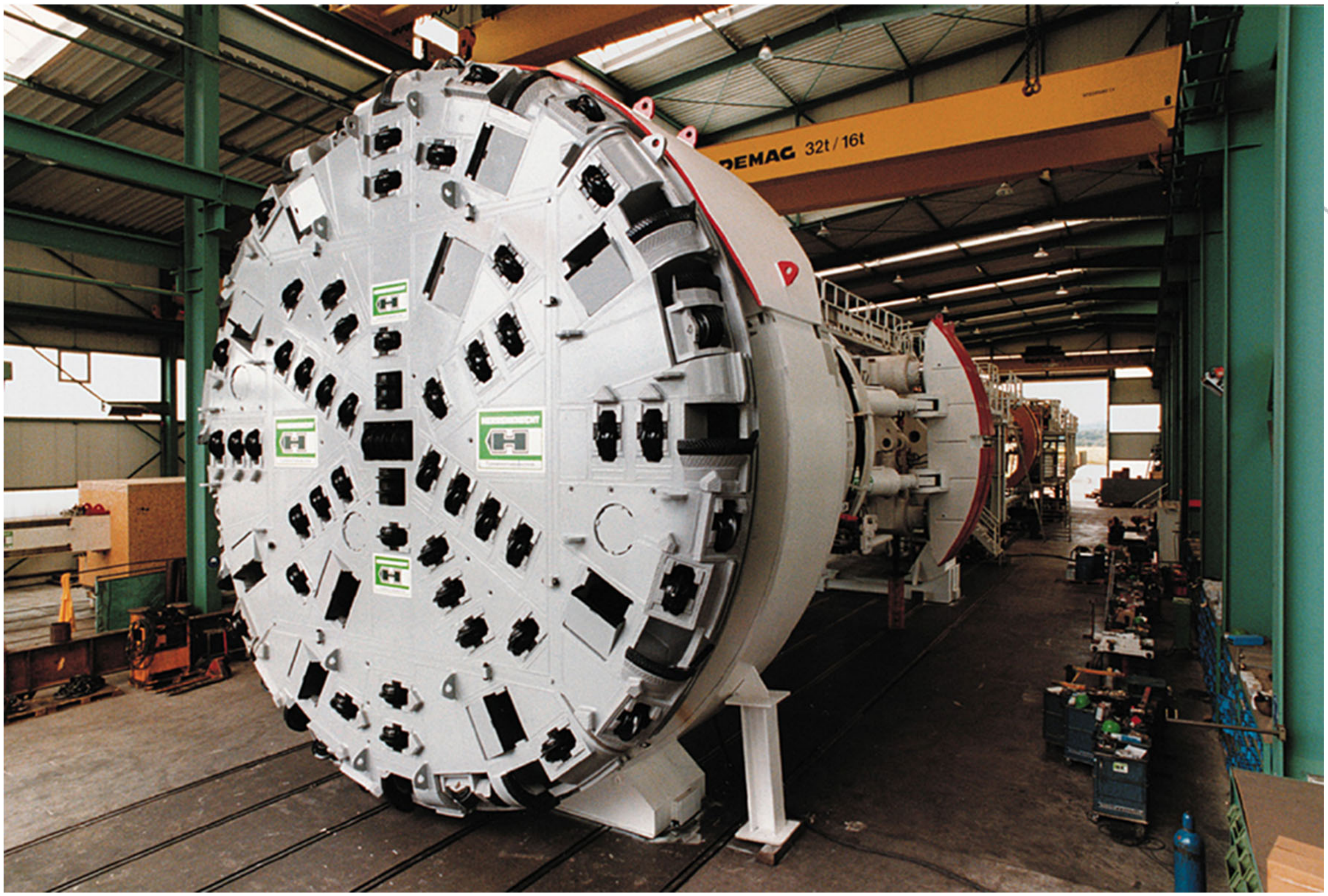
Kutterslitasje - kutterringlevetid

Amund Bruland

NGB-kurs

Bergteknikk for TBM-boring i hardt fjell

Borhodedesign påvirker kutterlevetid



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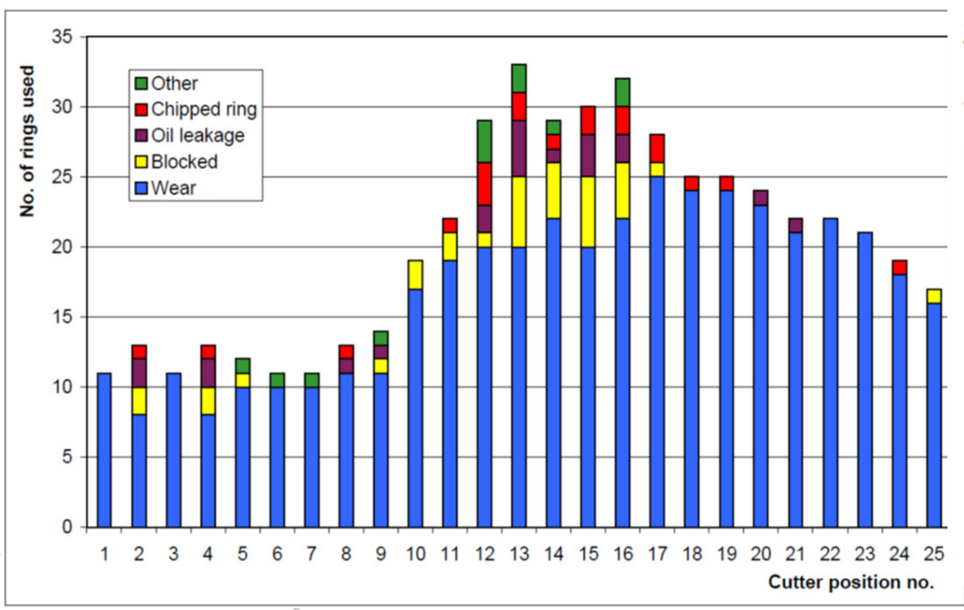
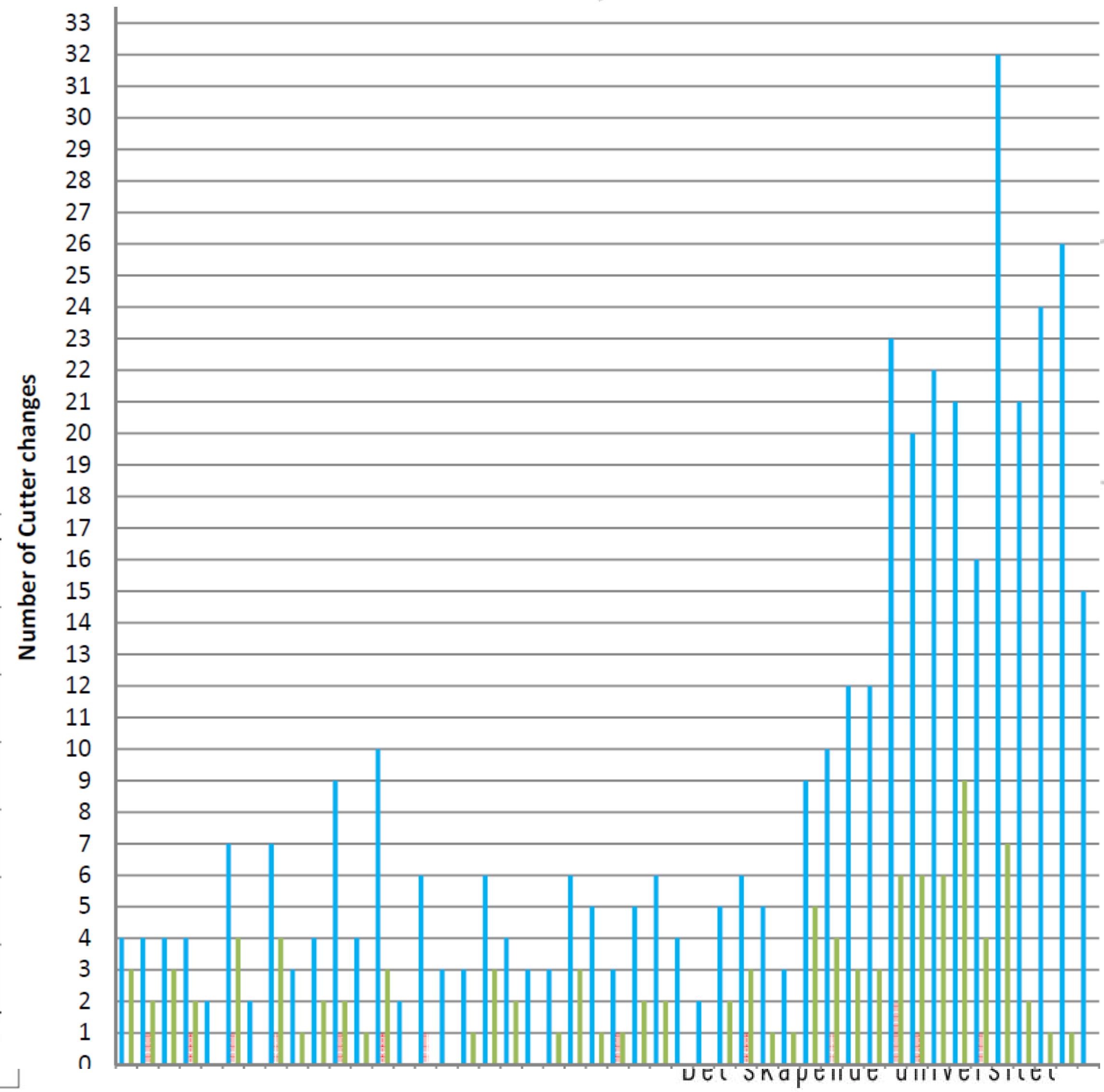
Cutter Layout Pattern





Bergmassen påvirker kutterlevetid

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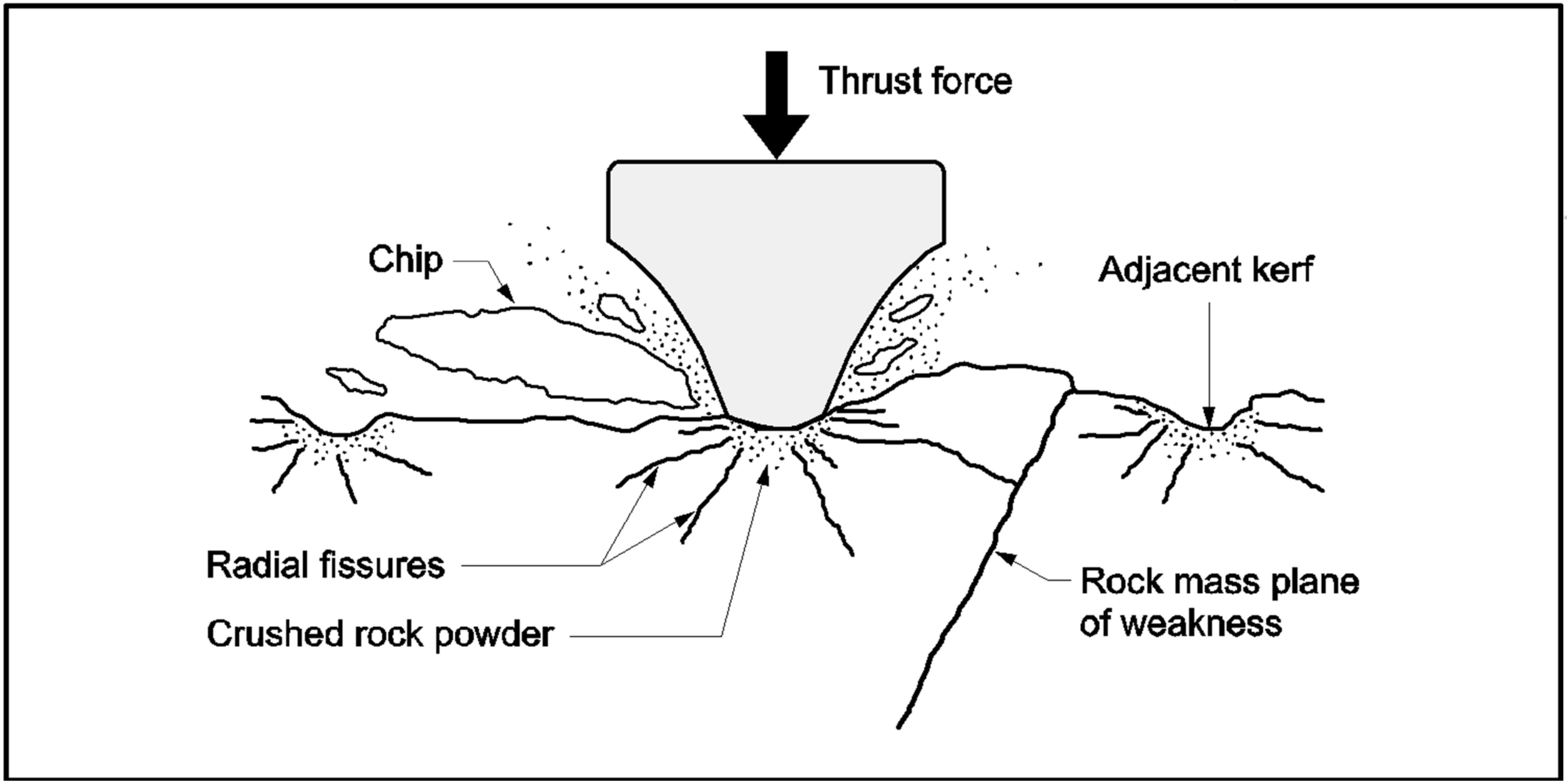
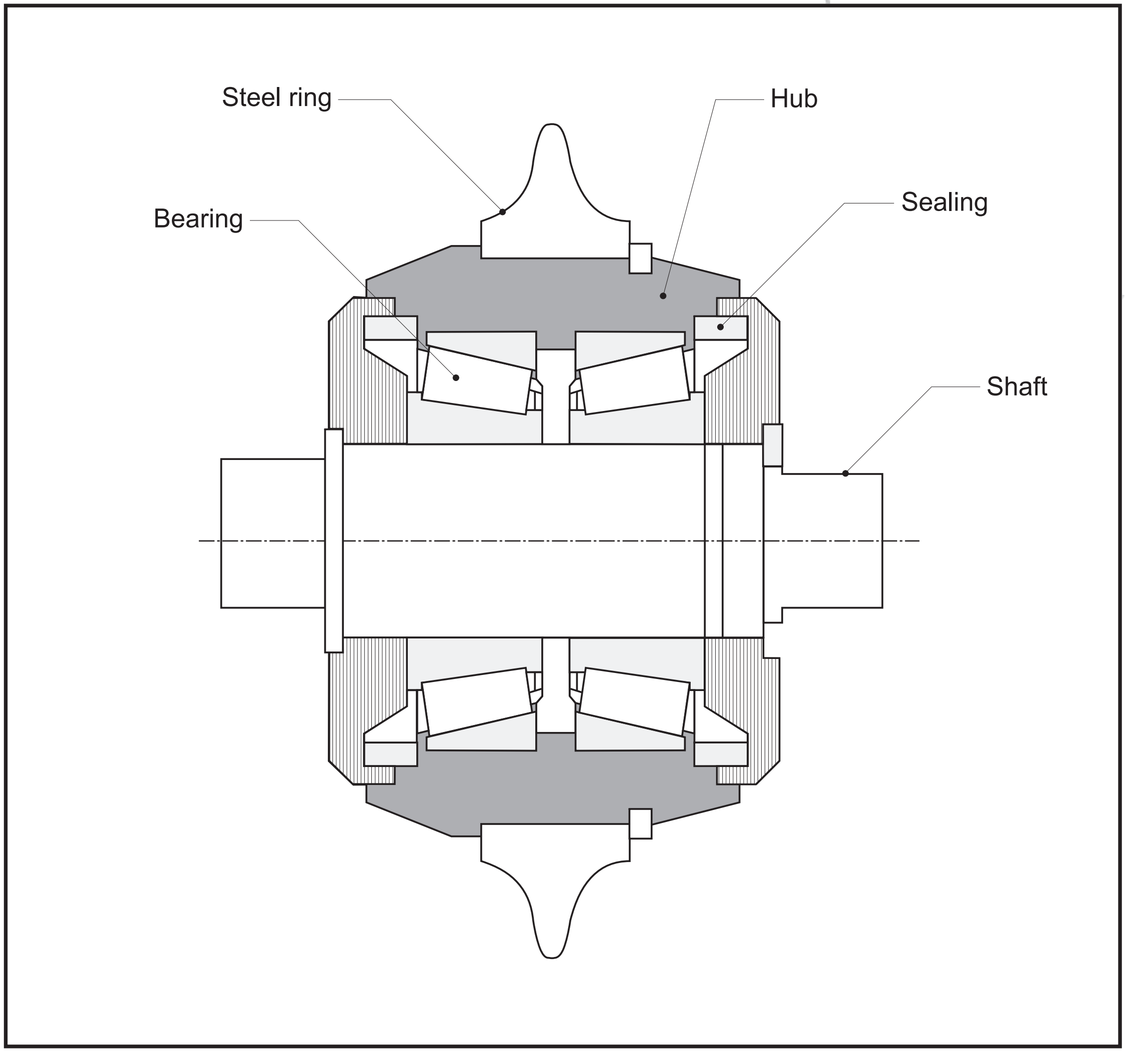
Slitasje av kutterringen under boring



Kutterslitasje

- Ring
- Lager
- Hub
- Aksling



Kutterringslitasje ved høy matekraft

Kutterringslitasje (destruktiv) ved dårlig ringkvalitet

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Hvordan måle kutterringlevetid?

- Meter tunnel boret pr. utslitt kutterring
- Kubikkmeter utboret volum pr. utslitt kutterring
- Timer pr. kutterring er ikke et godt mål, bør bare brukes for å gå over fra
  - laboratorietester som måler slitasje over tid
  - kutterbyttelogger ved tilbakeregning av levetid

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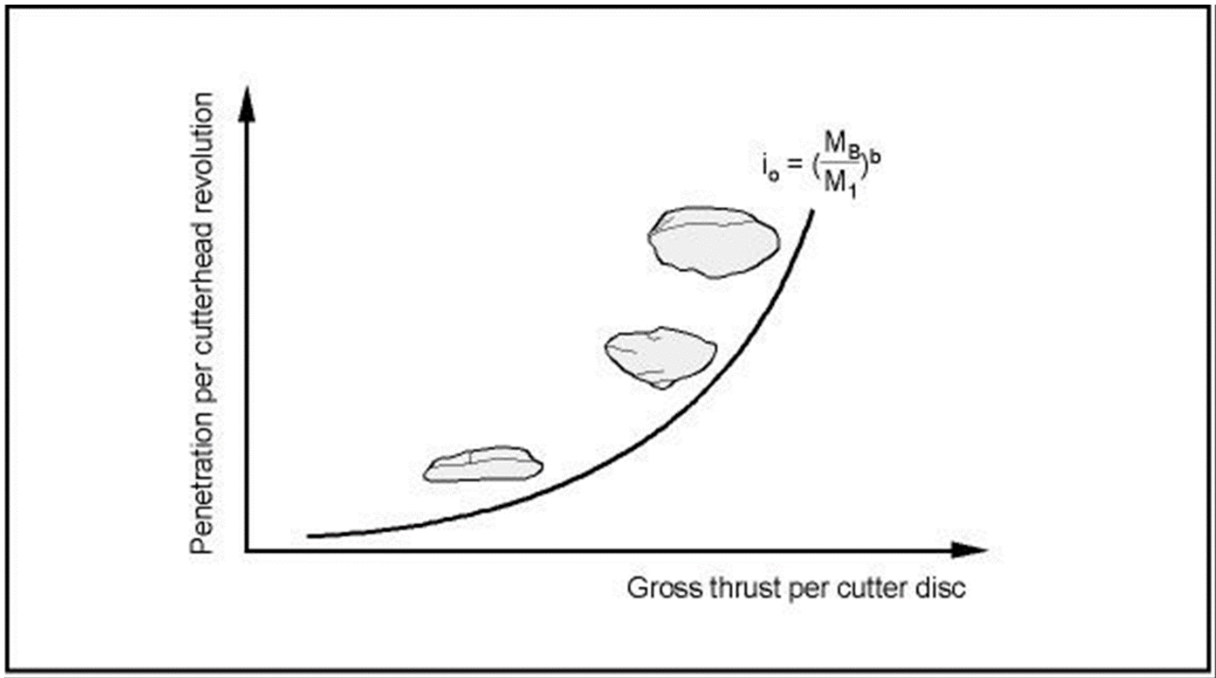
Inntrengningskurven er overproporsjonal

- Bruke så høy matekraft som mulig uten for mye destruktiv slitasje



Tomromsareal i stuff → kraftdynamikk → borhodet må tåle høye vibrasjoner

Levetidsparametre etter NTNUs modell

Rock Mass Parameters	Machine Parameters
• Cutter Life Index, CLI • Content of abrasive minerals	• Cutter diameter • Cutter type and quality • Cutterhead diameter and shape • Cutterhead rpm • Number of cutters on the cutterhead

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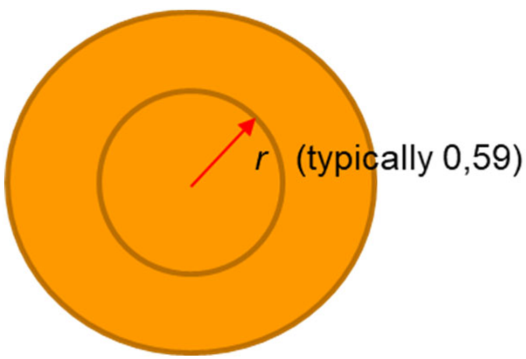
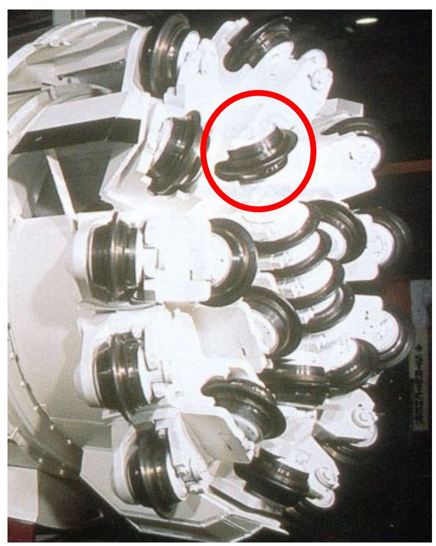
Levetidsparametre etter NTNUs modell

- Kutterringlevetid estimeres i boretimer pr. kutterring, for en midlere kutterposisjon.
- En individuell kutterring i midlere posisjon kan ha en levetid på f.eks. 200 h.
- For en TBM med 50 kuttere, vil den totale slitasjen (og dermed kutterbytte) være en kutterring pr. 4 boretimer.





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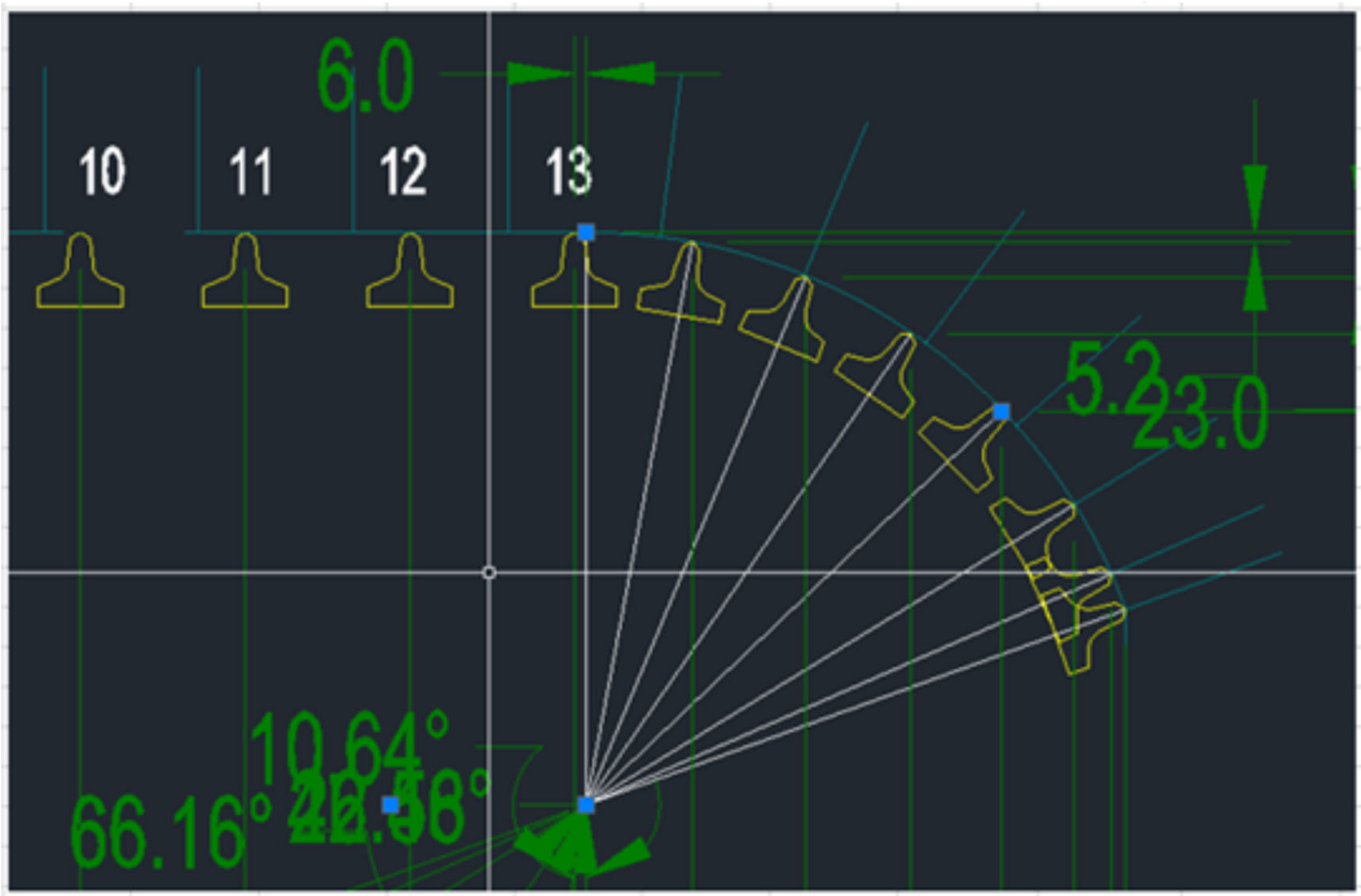
Borhodeprofil



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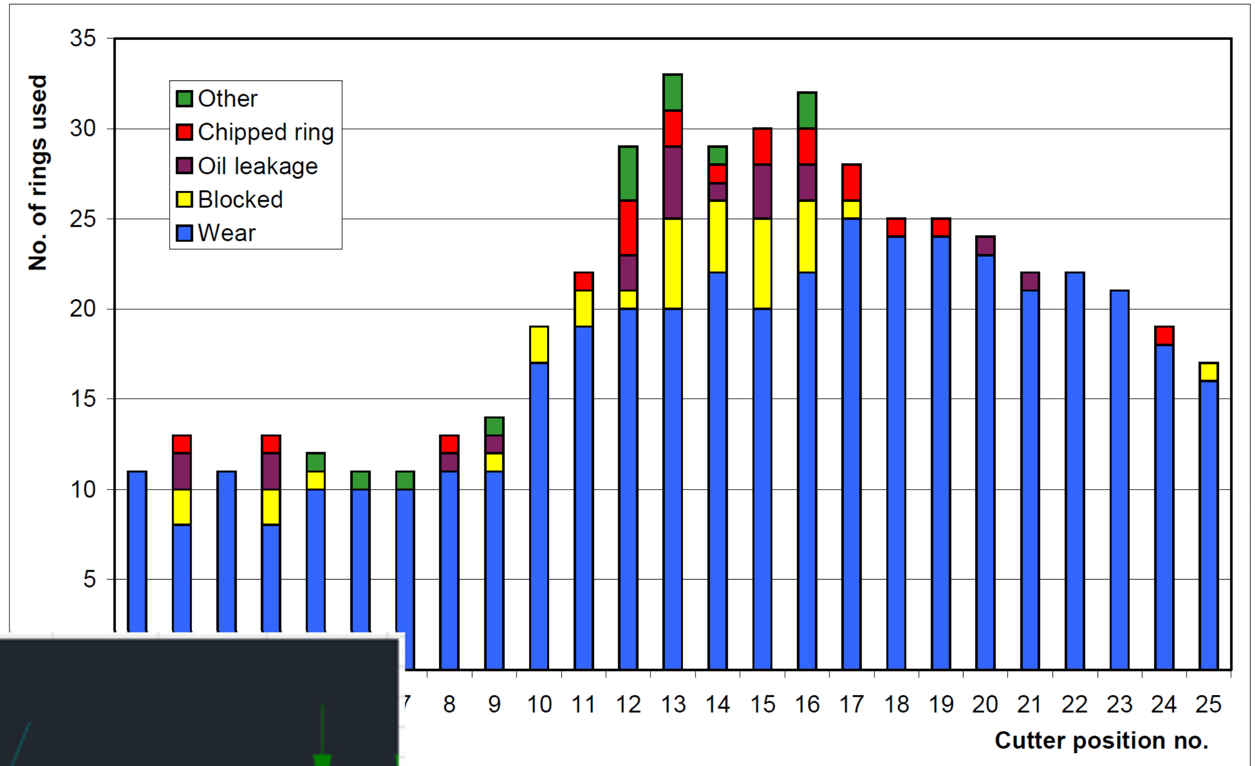
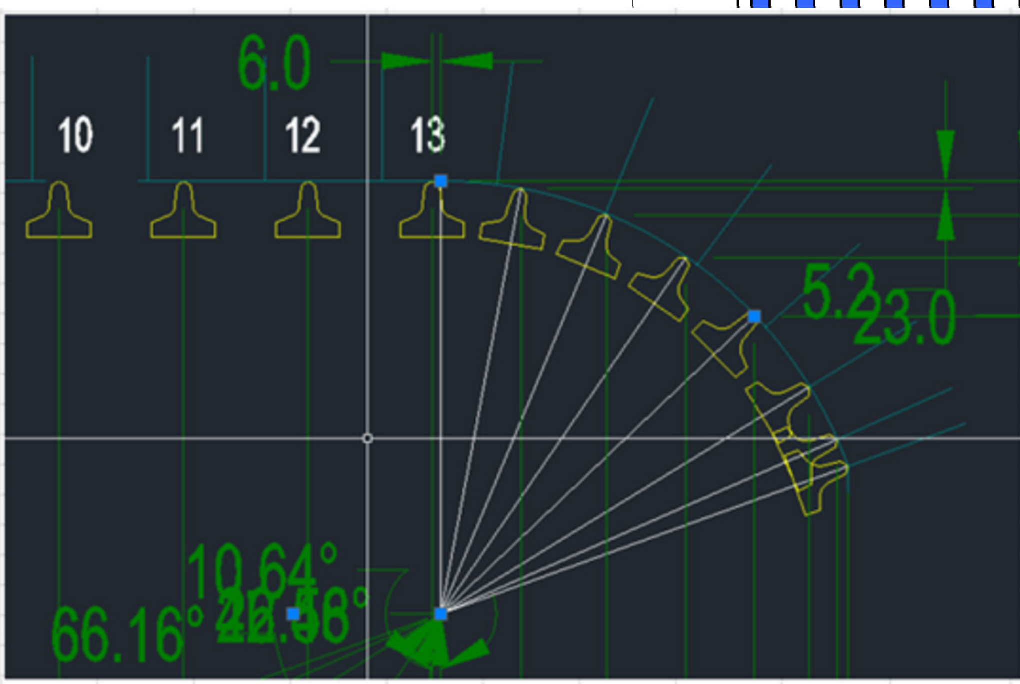
Borhodeprofil





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Noen andre levetidsparametre

- TBM-diameter: Senter- og periferikuttere har lavere levetid enn strossekutterne. For store TBM-diametere, utgjør strossekutterne en større andel av totalt antall kuttere på borhodet.
- Borhodets omdreiningstall: Levetiden er tilnærmet proporsjonal med rullet distanse for en kutterring.
- Antall kuttere på borhodet: Dess flere kutter, dess mer stål slites pr. tid.

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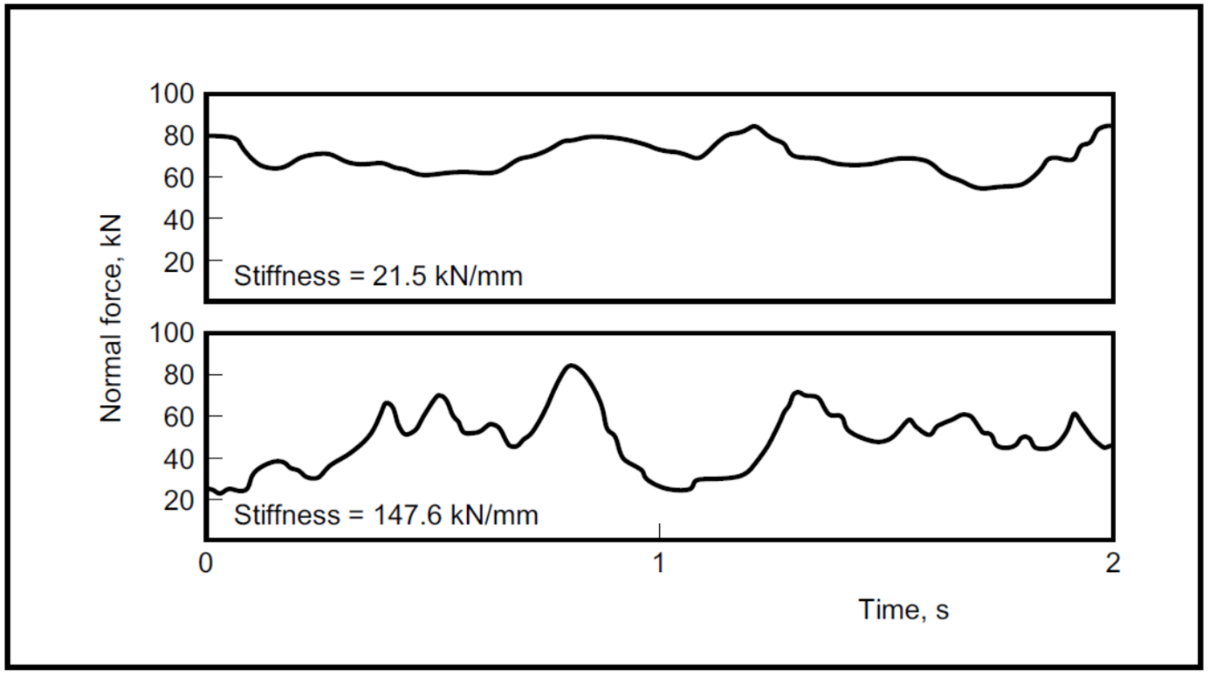
Noen andre levetidsparametre

- TBM-stivhet (hydraulisk og strukturell) (LCM-testing)
  - begge systemer har samme mm/omdreining



Noen andre levetidsparametre

- Kapasitet og diameter hovedlager

- Midlere last og topplast på kutterne øker med
økende posisjonsradius
(pga. økt rullehastighet)
- 50 % av brytningen er utenfor 0,7·radius
- Større hovedlager vil redusere fleksing av borhode i periferi
- Større hovedlager vil også gi mulighet for flere kuttere på borhodet.

Noen andre levetidsparametre

- Borhodets vekt

- Større ståldimensjoner vil gi mindre fleksing av borhodet
- Mer vekt i borhodet vil gi mindre vibrasjoner og lavere topplaster

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Takk for oppmerksomheten!

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Geologiske forundersøkelser for TBM-boring i hardt berg

Pal.jakobsen@ngi.no

NBG TBM seminar januar 2024

Innhold

- Hvorfor utføre forundersøkelser
- Regelverk, veiledninger, håndbøker og annen formalia
- Forundersøkelser
  - Typer undersøkelser
  - Tetthet av undersøkelser
- Noen prosjekteksempler
- Kost/nytte ved undersøkelser

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Hvorfor undersøkelser

- Gi input til større ting som:
  - Tekniske og økonomiske valg for trasé, byggemetode o.l
  - Alterantivsvurderinger
  - Identifisere risiko, og evt. avbøtende tiltak
  - Avdekke påvirkning på naboer, infrastruktur nært prosjektet
  - Bruk, deponering, avfallshåndtering av masser
  - Estimat på kapasitet, fremdrift og kostnader
  - Internasjonalt: Geotechnical baseline (referanseforhold for anbud)

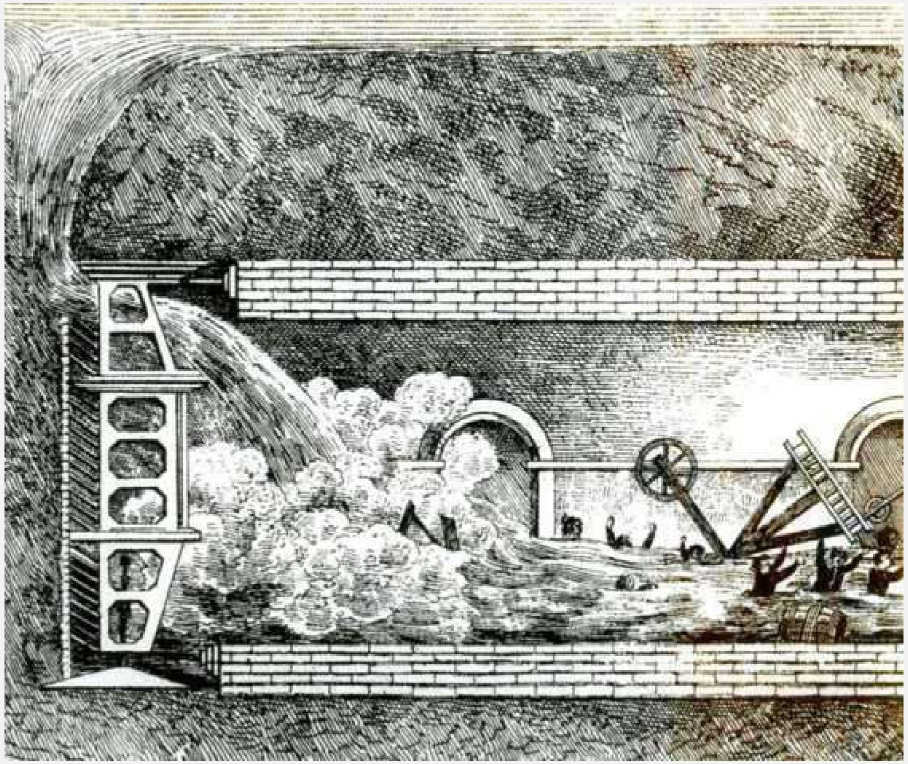
- I tillegg:
  - SVV N500 og BaneNOR TRV stiller krav til undersøkelser for ulike prosjektstadier

Hvorfor undersøkelser: Hvilke masser skal drives tunnel i

Eksempler på forhold som kan være utfordrende med TBM

(photo: tunneltalk.com)

Kollaps av stuff (Thames tunnel 1800 tallet). Ødelagt element som følge av påkjenninger fra jord/berg)



Kollaps over tunnel (Porto metro ca. 2006)

(photo: Babendererde engineers)

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SVV N500 (myntet på boring og sprengning – men brukes som håndbok I Norge)

- Referer til ulike planstadier og omfang av undersøkelser
- Til reguleringsplan nivå skal kostnadsanslag være på ± 20 % som betyr at trase, valg, grunnforhold må være relativt kjent

Krav 2.6—5 **SKAL** Gjeldende fra 31.03.2022

Faktadelen i geologisk rapport for reguleringsplan skal inneholde:

— Oversiktskart med tunneltrasé(er) og profilnummer for hvert tunnelløp.

— Beskrivelse av bergarter, foliasjon, strukturer og andre geologiske observasjoner.

— Analyse av sprekketetthet og sprekkeorientering. Sprekkerose og stereoplott.

— Resultater fra utførte forundersøkelser:

- Grunnboringer (bergkontroll, totalsondering, annen sondering).
- Kjerneboringer.
- Geofysiske undersøkelser.
- Kvalitetsanalyser av steinmaterialer.
- Miljøgeologiske undersøkelser.

— Beskrivelse av spesielle lokale hensyn.

— Oppsummering og konklusjon.

— Referanseliste (geologiske rapporter og annet som denne rapporten bygger på).

Krav 2.6—6 **SKAL** Gjeldende fra 31.03.2022

Tolkningsdelen i geologisk rapport til reguleringsplan skal inneholde:

— Tolkning av de geologiske forholdene langs tunneltraséen: bergartsgrenser, bruddstrukturer og svakhetssoner og lokalisering i tunnelnivå.

— Vurdering av usikkerhet i bergoverdekning og ved påhugg.

— Bergmasseklassifisering med Q-verdier fra feltkartlegging estimert i tunnelnivå og presentert langs traséen med sikringsestimat ihenhold til Tabell 7.5—1.

— Omtale av løsmasser og geotekniske forhold. Konsekvenser for skredfare, setninger og miljø.

— Omtale av hydrogeologiske forhold, eventuelle brønner og vannmagasiner.

— Vurdering av sannsynligheten for å få vann som skaper driveproblemer.

— Anbefaling om maksimal innlekkasje for å unngå skadelig poretrykksenkning.

— Vurdering av omfanget av injeksjonsarbeider.

— Påpekning av eventuelle forhold som kan ha betydning for boring og sprengning (boreavvik, ladevansker o.a.).

— Vurdering av sannsynlighet for å påtreffe høye/lave bergspenninger.

— Påpekning av usikkerheter eller spesielle risikomomenter.

Spesielle eller lokale forhold kan medføre at tolkningsdelen utvides med flere punkt.

Anslagsmodellen (Håndbok R764, SVV)

- Konseptvalgutredring: erfaringer og erfaringskostnader til sammenlignbare prosjekter. Kostnader ± 30 – 50 %
- Kommunedelplan: Kostnader ± 20 – 30 %
- Reguleringsplan: *… skal være ført så langt frem at det omfatter gode mengdeoverslag og en god og grundig beskrivelse av prosjektet. …. Kostnadsoverslaget skal være en del av grunnlaget for vedtak av reguleringpslan.* Nivå på usikkerhet: 10-20 %.

- DVS. alle forundersøkelser bør/skal/må være utført i/før reguleringsplan om man skal følge dette. Undersøkelser under byggeplan og bygging er for validering/justering /dokumentasjon.

Publikasjon 101, SVV. Riktig omgang av undersøkelser.

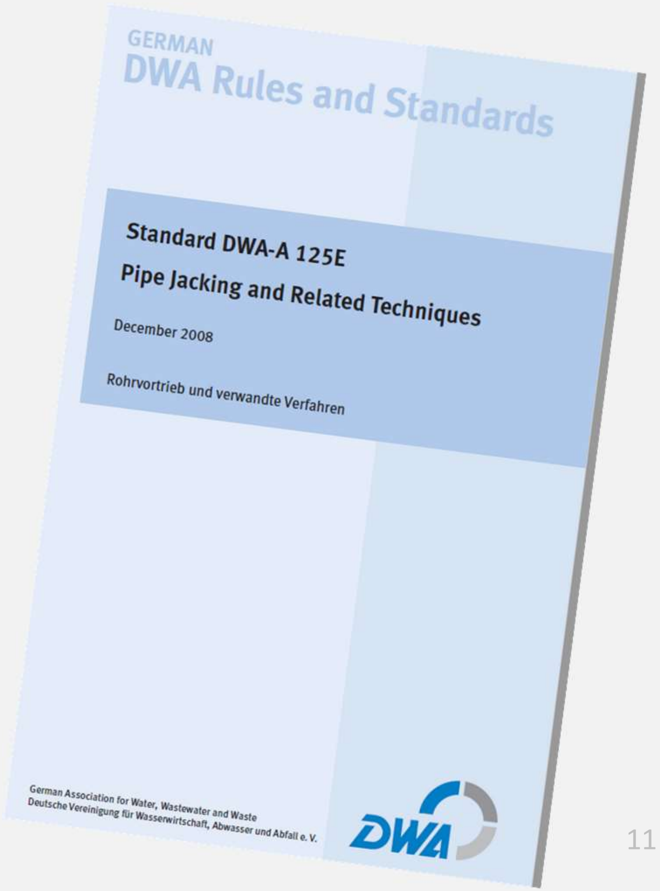
4.4.3 Ingeniørgeologiske rapporter for anbud

Ved inngivelse av anbud på underjordsarbeider ønsker entreprenøren størst mulig kunnskap om følgende forhold:

- Hvilke bergarter påtreffes?
- Opptreden av mulige knusningssoner og kryssende bergartsgrenser
- Borsynk og brytning
- Mulige strekninger med bore- og ladevansker
- Sannsynligheten for å påtreffe vann som skaper driftsproblemer og økte sprengstoffkostnader
- Krav til lekkasje og omfang av injeksjonsarbeider
- Omfang av fjellbolter, sprøytebetong og utstøping.

DWA-125-A (2008): Stiller anbefaler beskrivelse av alle disse parameterne for hver 50. m tunnel!

Soil and rock	
Maximum and minimum groundwater level, hydrograph curves	
Contamination level of soil, soil gas and groundwater	
Disposal advice according to legislation	
Concentration of abrasive minerals and quartz content to determine abrasiveness	
Deformation module	
Aggressive reaction of soil and groundwater	
Swelling behaviour	
Weathering resistance of the rock and/or change when confronted with air or water/supporting fluids	
Sticking potential	
Borehole logs	
Weight per unit volume	
Fault zones, cavities	
Soil	**Rock**
Particle size distribution, particle shape	Weathering level
Water permeability coefficient	Framework of discontinuities and stratum thickness of rock plates, rock fragments (RQD) and areal orientation
Compactness	Hardness
Plastic limits, water content	Rock and rock mass strength, excavatability
Shear parameter, friction angle and cohesion	Cleavage strength
Earth pressure coefficient	Abrasiveness (Cerchar Abrasiveness Index)
Cobble size and cobble proportion, uniaxial compressive strengths	Water inflow, permeability, strata water flow conditions
Water content and water pressure	Karst manifestation, cleavages, gaps
Organic components, lime content	
Tendency towards liquefaction	



Hvilke undersøkelser (generell ingeniørgeologi)

Kommune-delplan / mulighets-studie

Tid

bygging

- Geologi (bergartsgrenser, løsmasser, svakhetssoner etc.)
  - Innhenting av eksisterende geologisk informasjon (kart, naboprosjekter, bergblotninger)
  - Supplerende geologisk kartlegging
    - Eks. Q metode, RMR, Rmi (også sikring)
  - Boringer og geofysiske undersøkelser
    - Kjerneboring
    - Totalsonderboring
    - Seismikk
    - Evt. optisk televiewing
  - Overvåkning/dokumentasjon
    - Poretrykk
    - Setninger
    - Dokumentasjon (MWD data sonderboring, TBM data, kartleggingsdata fra drift)

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Hvilke undersøkelser (TBM)

- Borbarhet / bergmekanikk (egne tema av Sindre Log og Javier Macias, Nick Barton)
  - Drilling Rate Index™, Enaksiell trykkfasthet, Brazilian Tensile Strength
  - Abrasivitet: Cutter Life Index™, kvartsinnhold, mineralogi, (LCPC, Cerchar Abrasivity)
  - Oppsprekking (avstand mellom sprekker påvirker bergmassens borbarhet, men også orientering)

- Undersøkelsene utføres tidlig i (reguleringsplansnivå), men også til dokumentasjon, tvister, endringer under bygging.

Eksempel undersøkelser oppsprekkingsgrad bergmasse (Bruland 1998)

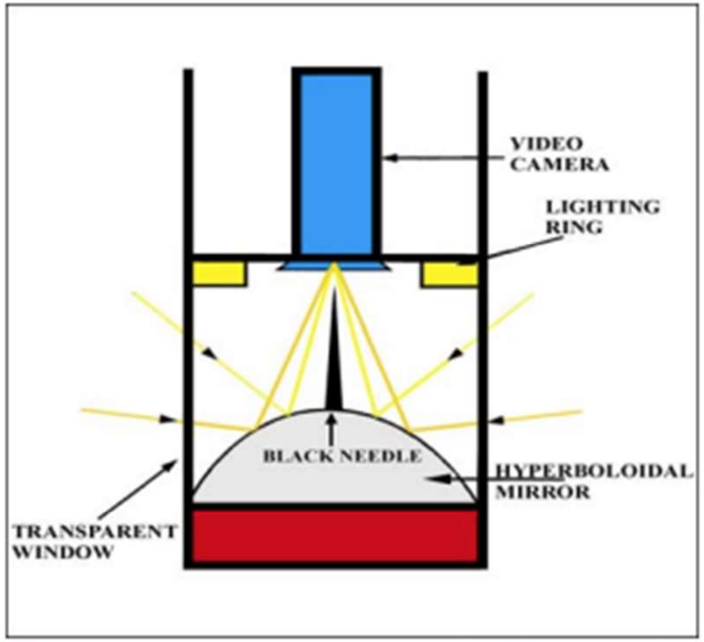
Oppsprekkingsklasse (Sprekker = Sp / Stikk = St)	Midlere avstand mellom svakhetsflater [cm]
0	-
0-I	160
I-	80
I	40
II	20
III	10
IV	5

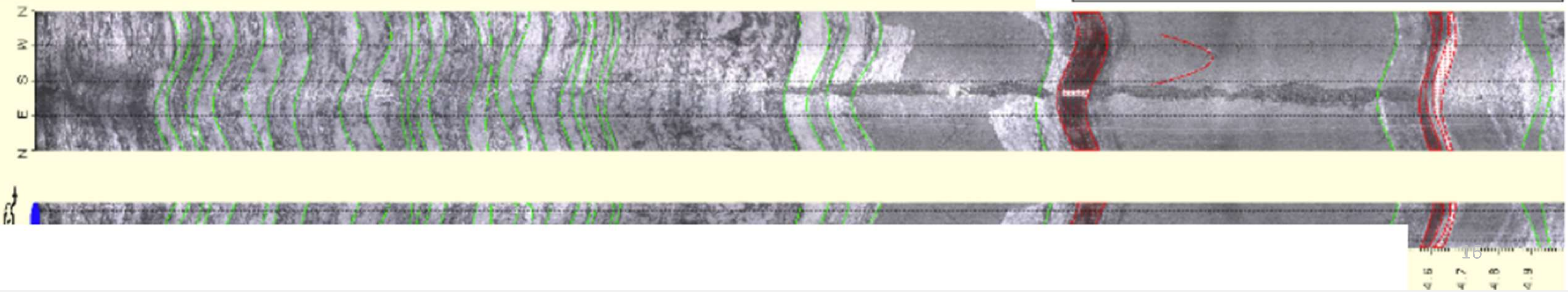
NGI

NGI

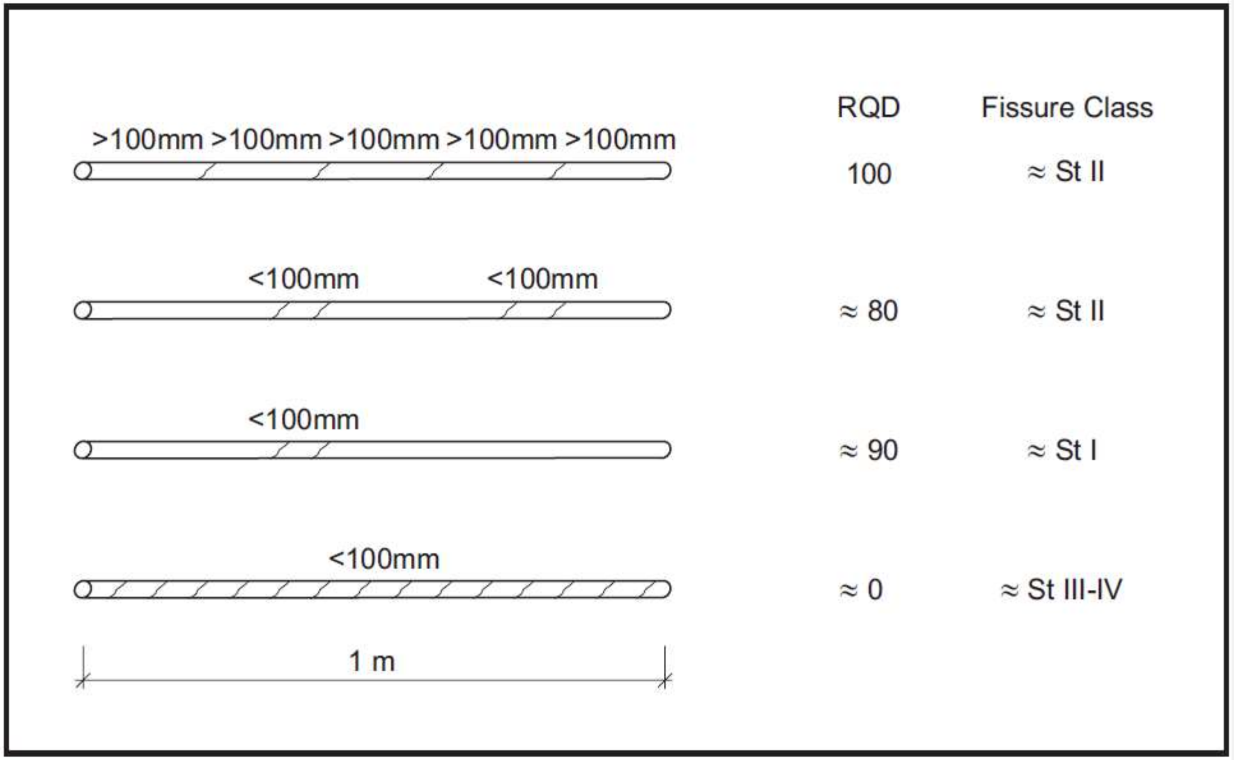
Optisk televiewing (NGU)

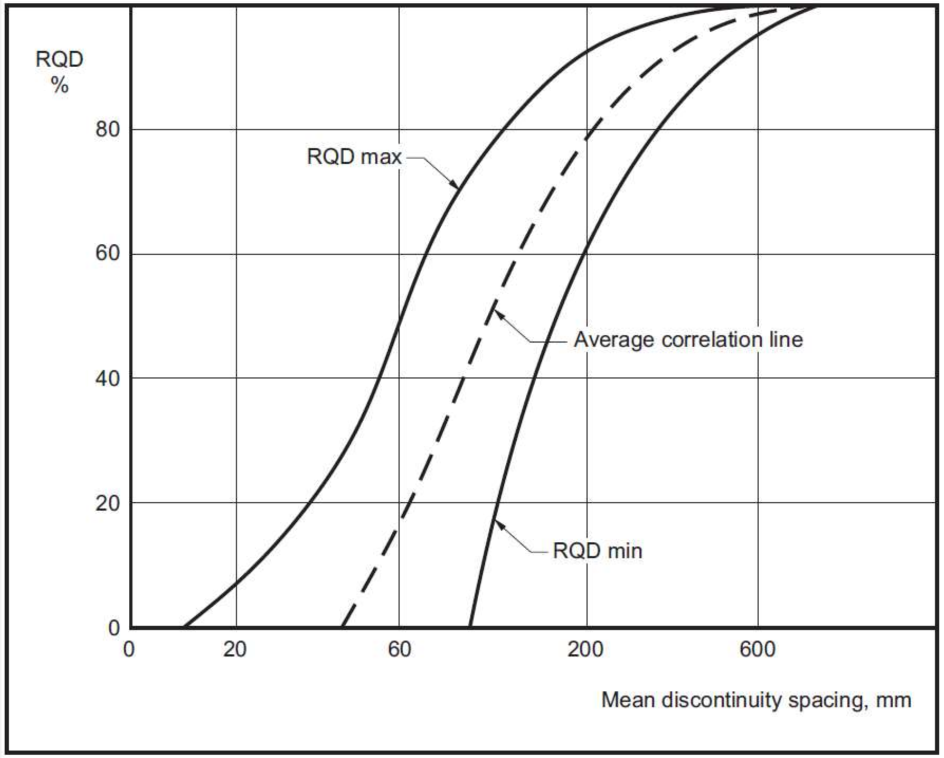
- Instrument for borhull 70-160 mm diam.
- Digital kamera som filmer mot et hyperbolisk speil
- Kamera filmer da borhullsveggen vinkel-rett





Eksempel undersøkelser oppsprekkingsgrad bergmasse (Fra Bruland 1998)





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Refraksjonsseismikk (NGU)

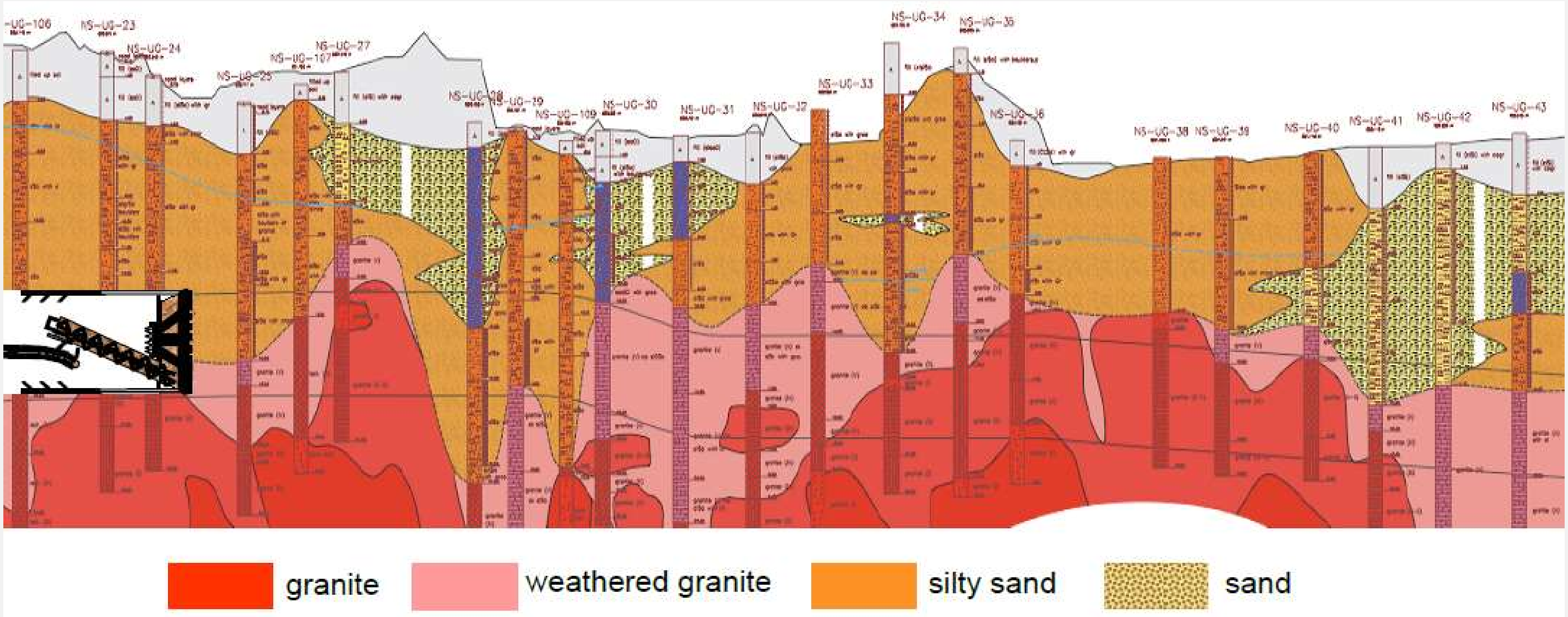
- Lydens forplatningshastighet endrer seg med massens elastiske egenskaper.
- Geofoner (land) eller hydrofoner (sjø) + seismograf måler refraksjon etter energikilde (slegge eller sprengstoff).

Jordarter	P-bølgehastighet (m/s)	Bergarter, ikke oppsprukket	P-bølgehastighet (m/s)
Torv	150 – 500	Sandstein	3000 – 3500
Leire (tørr)	600 – 1200	Kalkstein	4000 – 6000
Sand (tørr)	400 – 900	Dolomitt	2500 – 6500
Grus (tørr)	400 – 1000	Kvartsitt	5500 – 6000
Morene (tørr)	400 – 1600	Granitt	4800 – 5500
Leire (vannmettet)	1200 – 1600	Gneis	4700 – 5800
Sand (vannmettet)	1400 – 1800	Diabas	5700 – 6500
Grus (vannmettet)	1400 – 1900	Gabbro	6200 – 6700
Morene (løs)	1500 – 1900	Ultramafisk	6500 – 7500
Morene (hard)	1900 – 2800		

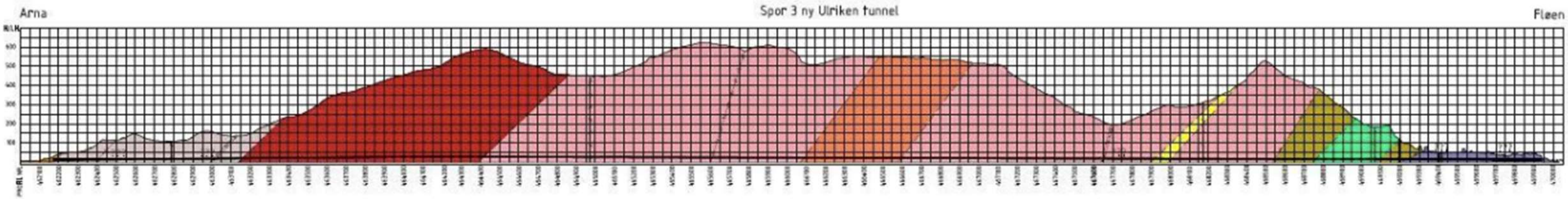
Hvilke undersøkelser, hydrogeologi

- Funksjonskrav for tillatt innlekkasje bestemmende (tema for Karl Gunnar Holter og Martin Stormoen)
  - Sensitive vannmettede løsmasser ?
  - Tetthetsmål for tunnelen
  - Identifisering av mulig lekkajser som kan hinder/forsinke TBM inndrift
- Hydrogeologi (som for boring og sprengning)
  - Vanntapsmålinger / Lugeon
  - Evt. brønnovervåkninger
  - Poretrykksmålinger
  - Berggrunnsgeologisk analyse: identifisere spesielt permeable bergarter eller sprekkesystemer

Eksempel metro tunnel i Singapore. > 20 kjerneborhull på strekning på < 1000 m.



Eksempel Nye Ulriken. (ingen boringer?) men paralell tunnel, samt nært UIB



TEGNFORKLARING

Berggrunnsgeologisk kart

Berggrunn

(Angitt i rekkefølge slik bergartene først forekommer fra Arna mot Bergen)

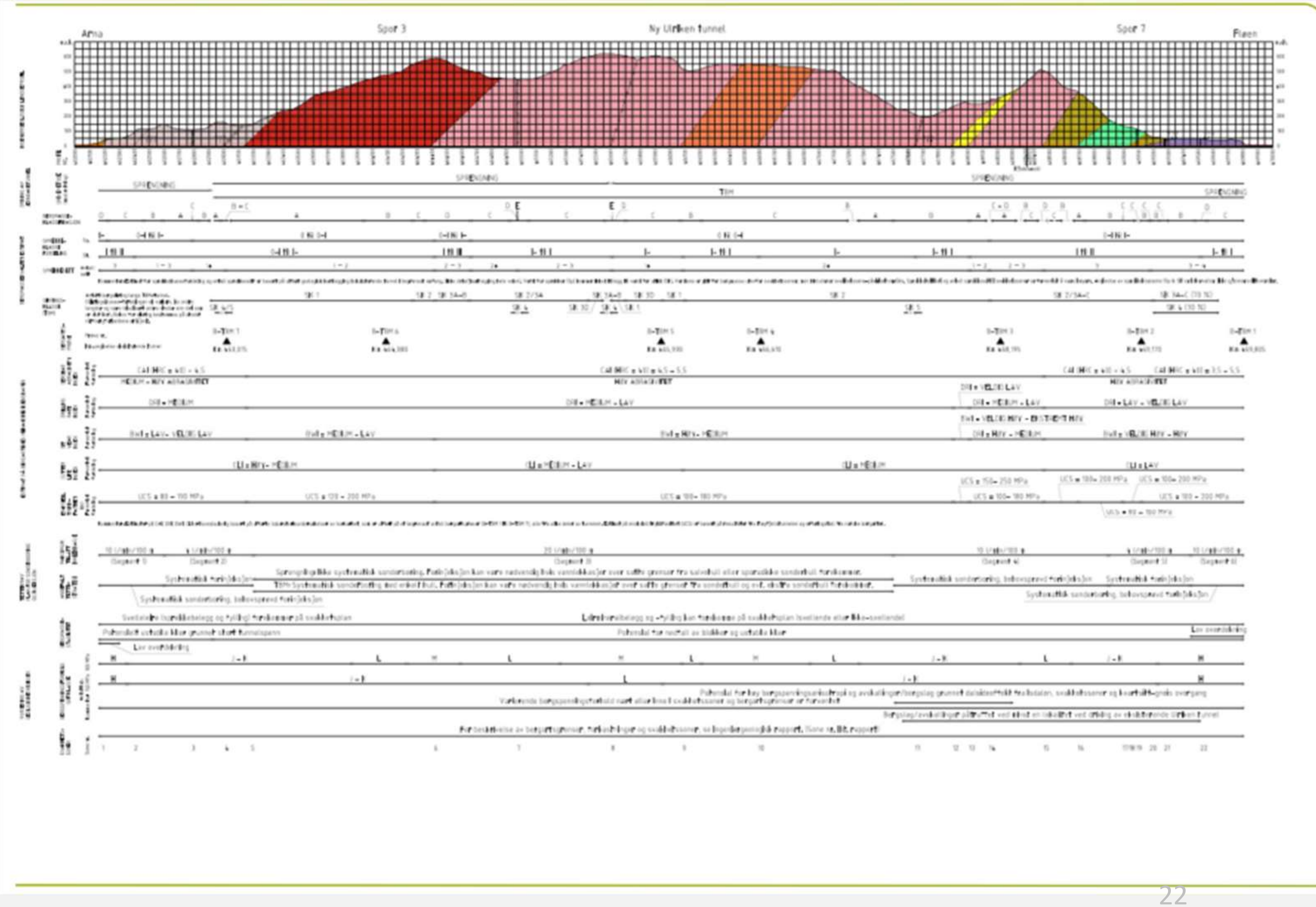
- Granittiske, syenittiske og monzonorittiske dypbergarter, for det meste charnockitter/granulitter
- Anortositt, stedvis også metagabbro
- Hovedsakelig granittisk gneis, stedvis med basiske bånd og linser, gjennomsatt av granittiske ganger
- Kvartsitt, kvartsittskifer, lokalt kvartsittkonglomerat
- Øyegneis og båndgneis, omdannet migmatittgneis
- Migmatitt og migmatittgneis, stedvis omdannet til øye- og båndgneis
- Amfibolitt, omdannet og sterkt deformert gabbro og grønnstein med bånd av trondhjemitt
- Amfibol-granatglimmerskifer, stedvis med lag av amfibolitt, grønnstein og kiselstein og ganger av trondhjemitt
- Mylonittgneis, for det meste granittisk

Antatt forløp av geologiske grenser og strukturer

- Skyveforkastning
- Bergartsgrense
- Liten svakhetssone
- Middels svakhetssone
- Stor svakhetssone

Ulriken med tolkninger og målinger i legend (Ongstad)

- Spenn av
  - DRI
  - CLI/CAI
  - UCS
  - Avstand sprekker/ stikk
  - Q-Verdi
  - Kvartsinnhold
  - Boreklasse TBM



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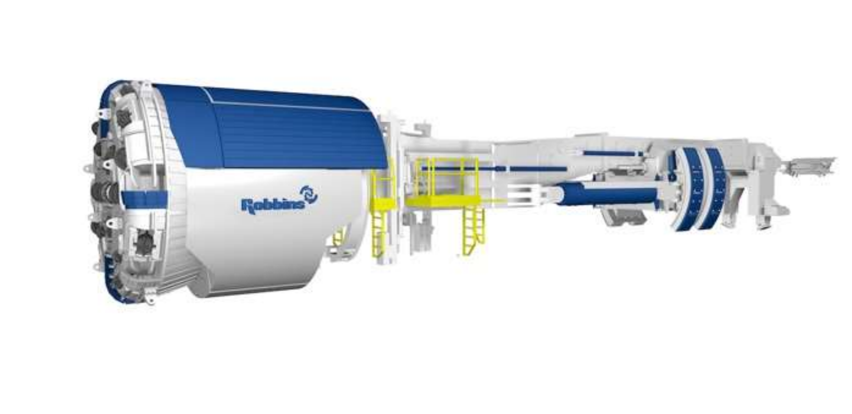
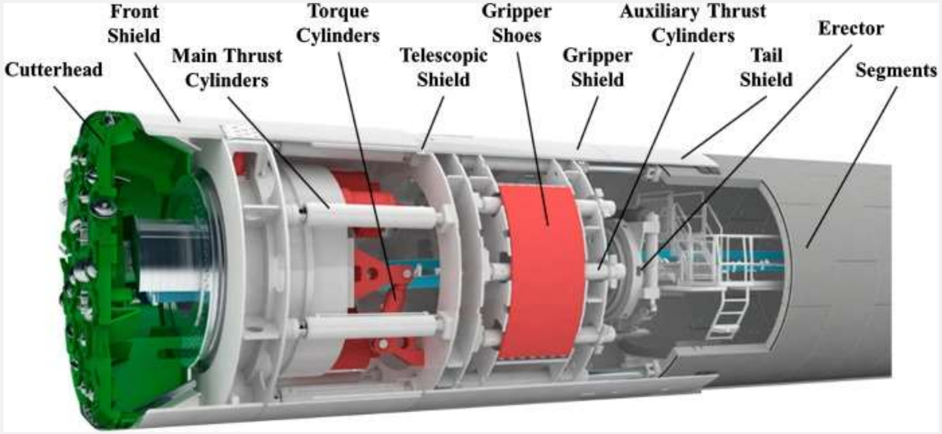
For Ulriken og åpne TBM-er (etter Ongstad)

- Risikobergarter
  - Mekanisk svake bergarter – stivhet til grippere
- Bergmassestabilitet
  - Detaljstabilitet med blokker og kiler
  - Total stabilitet med større kiler og evt. lav overdekning
  - Svakhetssonre, orienteering, karakter, lengde og plassering
  - Svelleleire potensiale





Fløyfjelltunnelen. Boret heng og sprengte vegger

- Boring gir pen kontur
- Vanskeligere ingeniørgeologsk kartlegging under driving, enn for b&s

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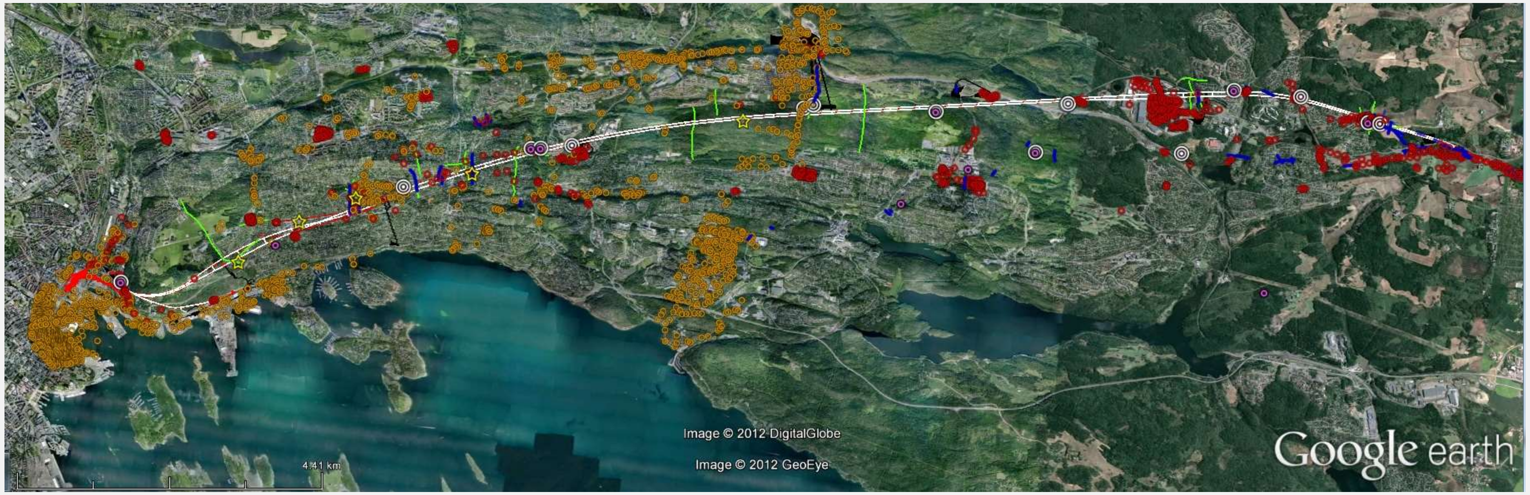
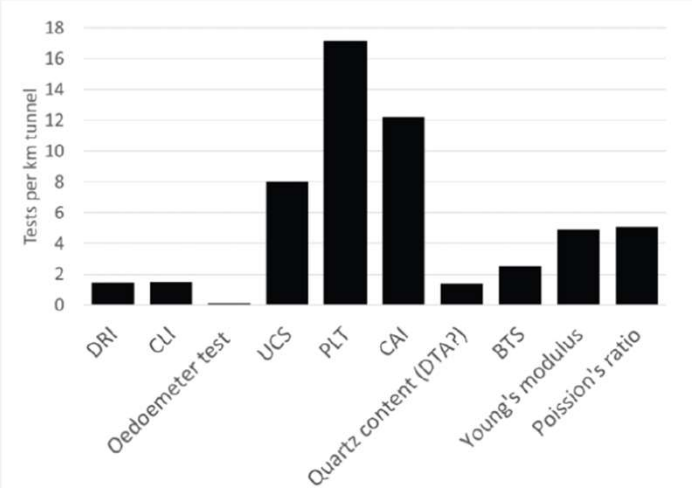
Follobanen (etter Gammelsæter)



Farge	Type	Antall	Kommentar
	Grunnundersøkelser		
(rød)	For Follobanen	420	Totalsonderinger og fjellkontrollboringer
(oransje)	Fra andre prosjekt	712	Sonderboringer (trykk/drei/dreie-trykk/enkel), fjellkontrollboringer, skovboringer, prøvesjaktinger og totalsonderinger
(rosa)	Bergprøver	32	Fra håndprøver og kjerneborhull
(gul)	Bergbrønner	14	
	Kjerneborhull	20	
(blå)	Seismikkprofil	59	
(grønn)	Resistivitetsprofiler	19	



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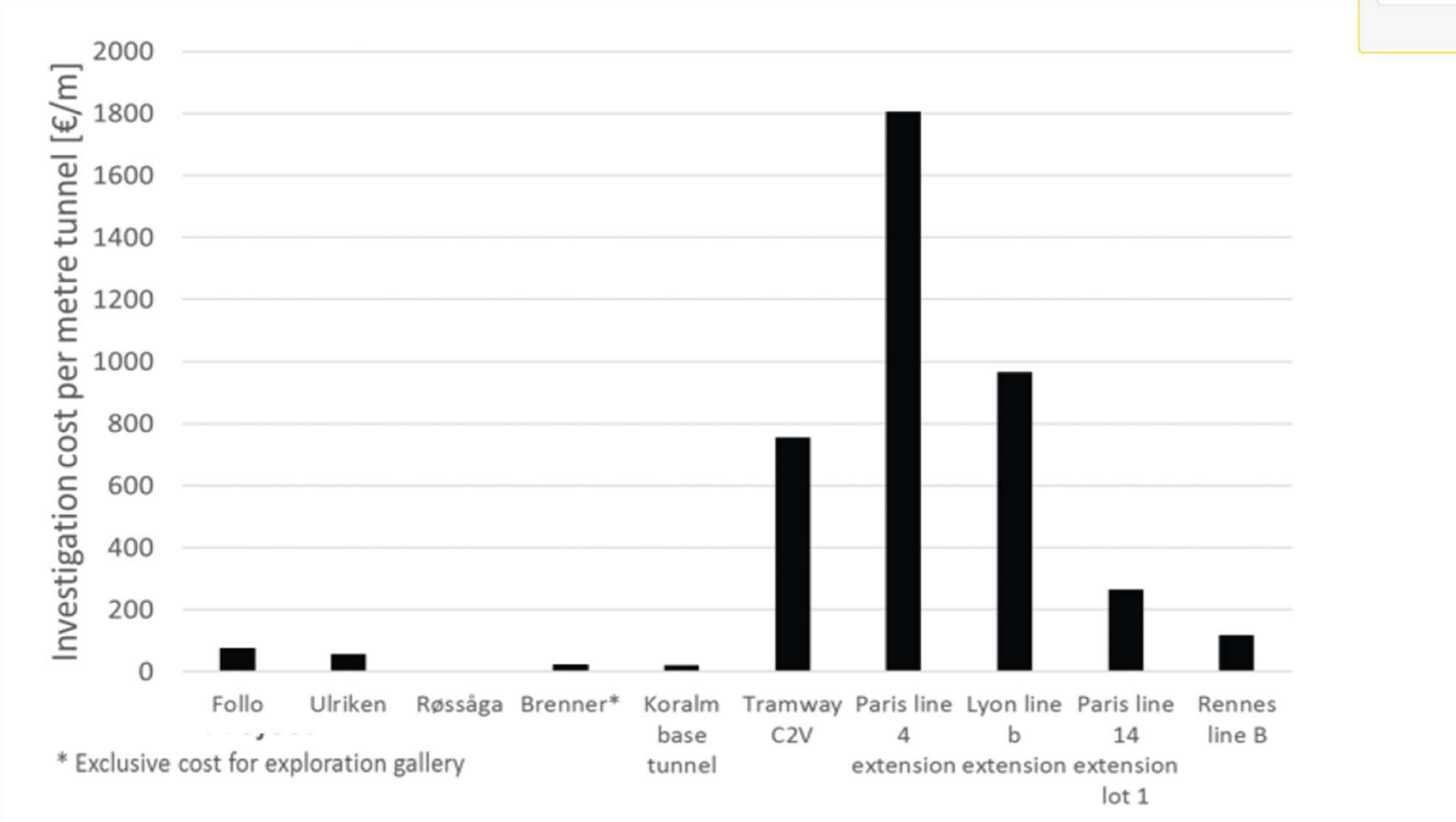
Jakobsen & Babendererde 2017 og ITA 2015.



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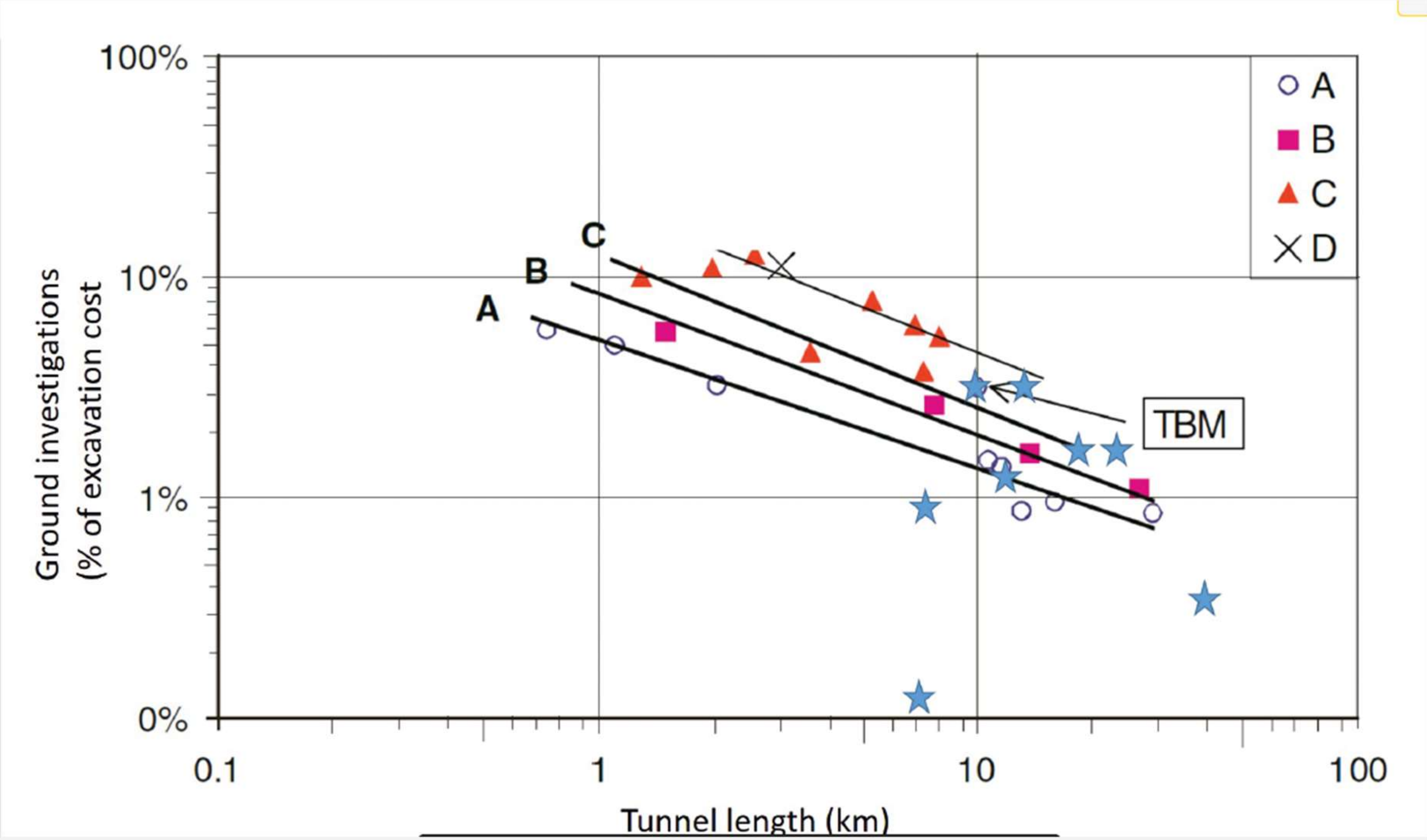
SVV var tydelig på Verdi/innvestering av undersøkelser (SVV publikasjon 101)



AFTES er tydelig på verdien av undersøkelser

- Trendlinje som viser at økte undersøkelseskostnader gir lavere kostnadsoverskridelser
- Grafen er basert på underjordsprosjekter (TBM i berg, løsmasser – men også cut&cover og boring og sprengning.

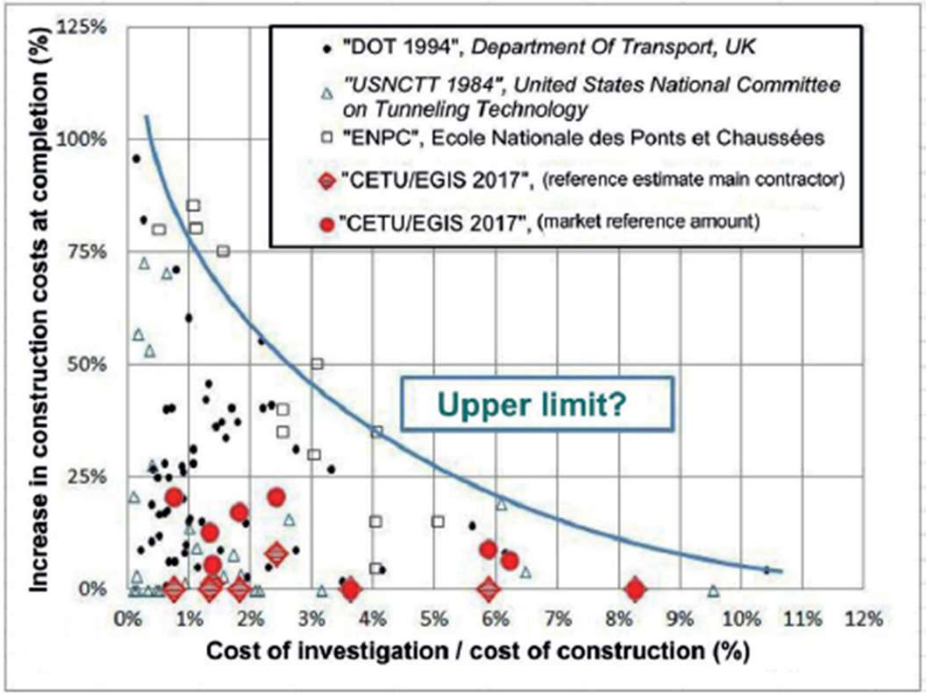


Figure 2: Relationship between construction cost overruns and investigation works. Source: Robert A. et al. (2017)

AFTES har ekvivalenttider / kapasiteter for ulike forundersøkelser

Surveys	Average rate of advance (8-hour shift)	Notes on rates of advance
Probing		
Conventional rotary coring	10-12 m per day	Range from 2-20 m per day
Percussion coring	6-8 m per day	
Vibrating coring	8-12 m per day	
Wireline coring	12-16 m per day	Up to 25-30 m per day
Sonic drilling	30-40 m per day	
Destructive drilling	40-60 m per day	
Field tests		
Installation of piezometer tubes + gravel pack	100 m per day	Excluding drilling
PVC tube injection sealing	80-100 m per day	
Pressure meter testing (standard test at 5 MPa)	8-12 m per day 8-12 tests per day	Core boreholes and tests
Cone penetrometer test	50-200 m per day	
Field vane shear test	10-12 tests per day	
Phicometer shear test	2 to 4 u per day	
Dilatometer test (Jack test)	2-3 tests per day	3-4 hours per test
Lugeon water pressure test	2-3 tests per day	
Lefranc water permeability test in open-hole borehole	2-3 tests per day	
Pumping tests	24-96 hours	depending on objective
Geophysical measurements		
Refraction seismic - 50 m system (weight drop)	5-8 systems per day	
Refraction seismic - 115 m system (explosive)	4 systems per day	24 traces
Refraction seismic - 235 m system		

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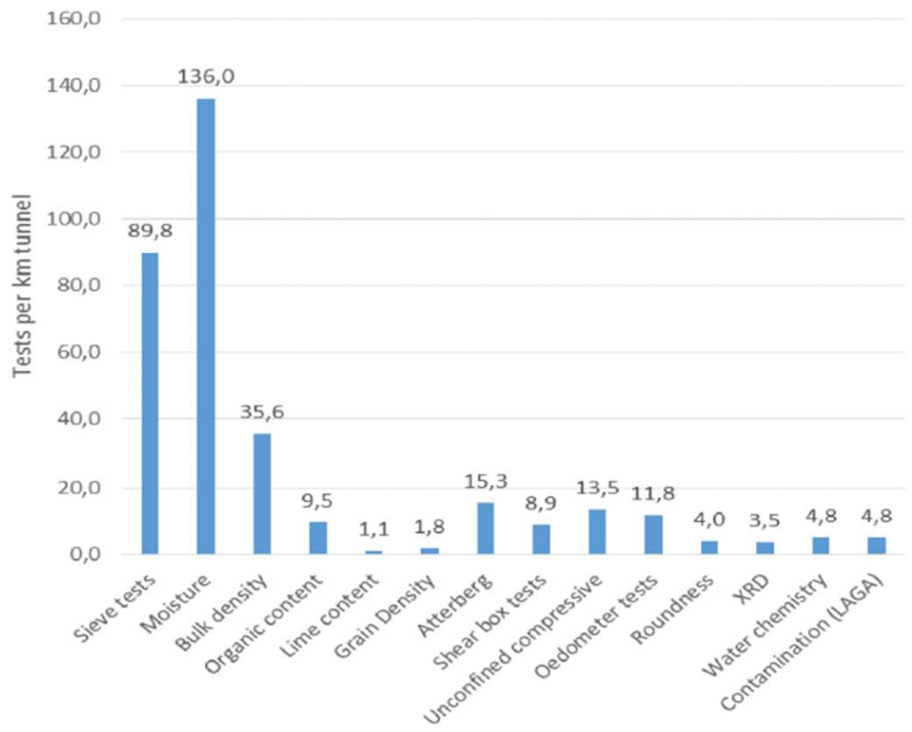
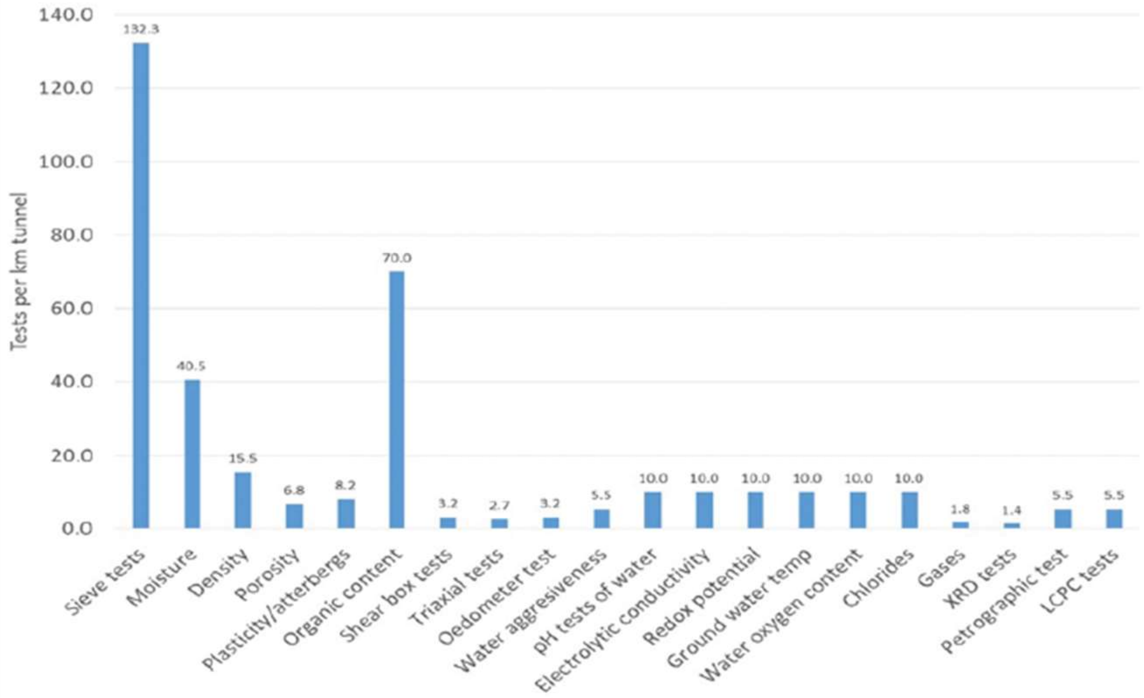
Tunneler i løsmasser – til sammenligning



Number of laboratory tests at A20 soft ground project in Germany.



Number of laboratory tests at the Wistula soft ground project in Poland.

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Oppsummering (mitt skjønn)

- Byggherrer må utføre tilstrekkelige undersøkelser til
  - Å kunne velge drivemetode (boring/sprengning, eller ulike varianter av TBM)
  - Undersøkelser må være tilstrekkelig for å gi tilbydere tilstrekkelig grunnlag til å prise mht. Inndrift/tid.
  - Evt. kan inndrift/tid oppgjøres basert på målinger/observasjoner under bygging
    - Vanskelig med lining tunneler
    - TBM-er som måleinstrument – vær klar over TBM-ens påvirkningsmuligheter på geologi
    - Utførelsesentepriser vs. totalentepriser

  - Teknisk burde byggherrer utføre undersøkelser så tidlig så mulig i planfase. I konflikt med tildelinger ?

  - Tetthet av undersøkelser: Ulike horisonter av bergmasser bør være beskrevet mht. borbarhet. I tillegg generelle ingeniørgeologiske vurderinger (overdekning, spesielt svake bergartslag/soner) bør være beskrevet.

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- ITA 2015. Working group 2 Research. Strategy for site investigation of tunnelling. ITA-AITES.
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- Håndbok R764 Anslagsmetoden, 2021.
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#påsikkergrunn

NORGES GEOTEKNISKE INSTITUTT
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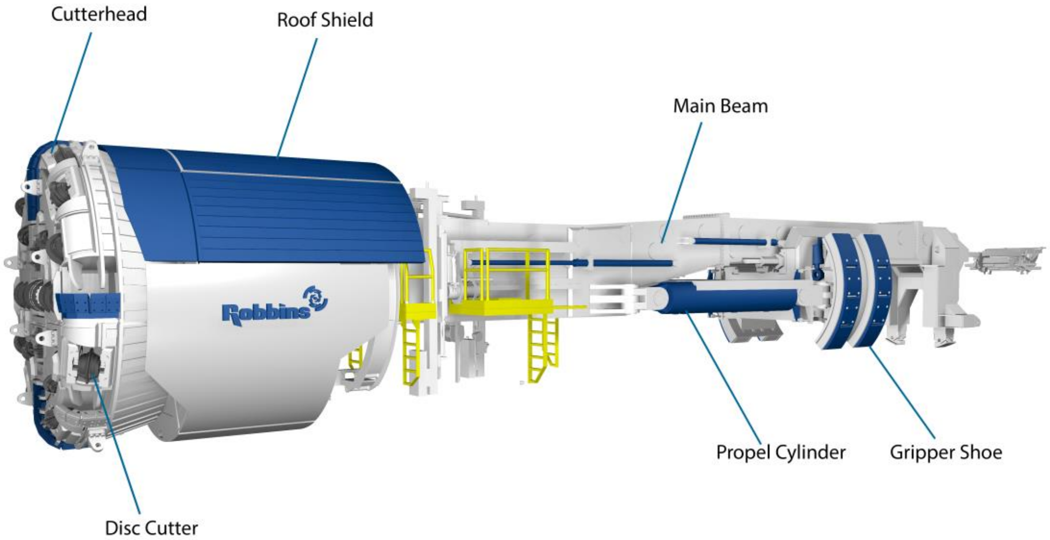
NTNU | Kunnskap for en bedre verden

Introduksjon til prognose modeller for TBM-boring

Amund Bruland, NTNU/ Helge-Ivar Frostad, NTNU

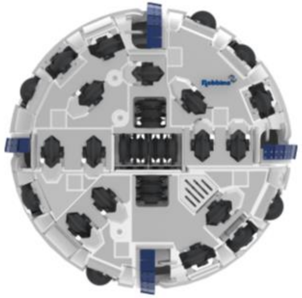
Introduksjon til prognose modeller for TBM-boring

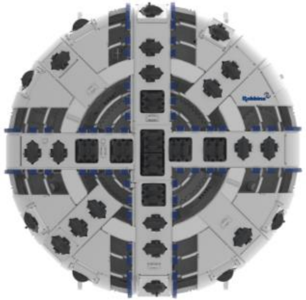
- En TBM (Tunnel Bore Maskin) benyttes i fullprofilprosjekter for driving av tunneler med varierende geologiske forutsetninger.



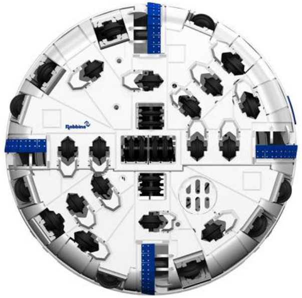
[1]. https://www.robbinstbm.com/products/tunnel-boring-machines/main-beam/main-beam-detail/

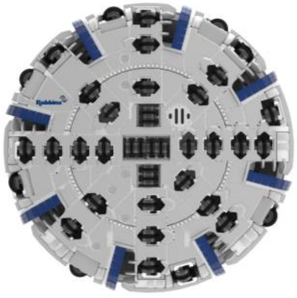
Det er derfor utviklet flere typer tunnelboringsmaskiner innen tunnelboringsindustrien

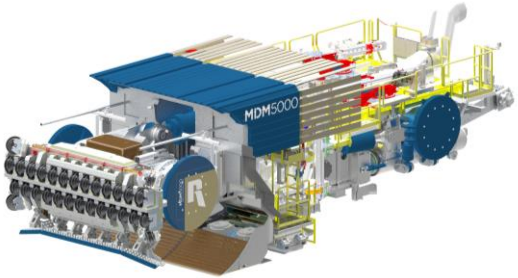

Main Beam
hard rock


EPBM
soft ground


Crossover
variable geology


Double Shield
fractured hard rock


Single Shield
massively fractured rock



MDM5000
access tunnels and long drifts

[2]. https://www.robbinstbm.com/

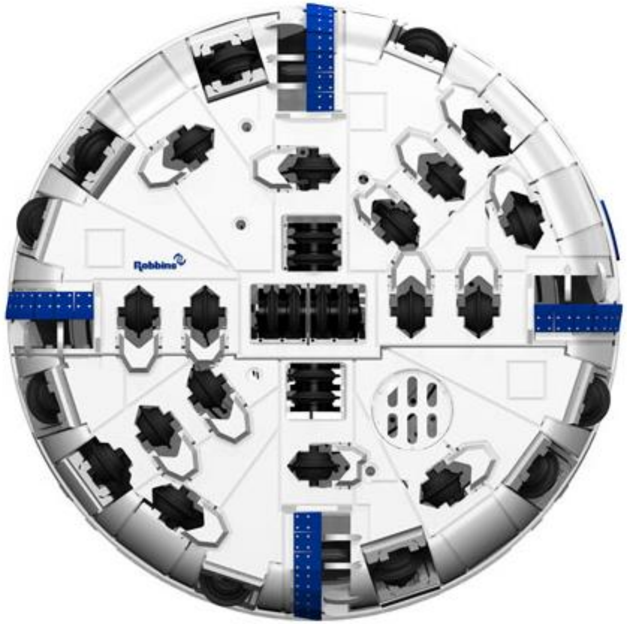
Prognosemodeller for TBM-boring

- Kostnadsestimater og ytelsesprognoser har stor innflytelse på planlegging og risikostyring i TBM prosjekter.
- Nøyaktige og pålitelige prognosemodeller kan bidra til å redusere risiko, forsinkelser og økonomiske prosjektoverskridelser.
- Det er blitt utviklet flere prognosemodeller for beregning av ytelsesestimater og kutterslitasje i f.eks. hardt berg de seneste tiårene.

Prognosemodeller for TBM-boring i hardt berg

Noen av disse er f.eks.:

- [3]. Gehring (1995)
- [4]. Colorado School of Mines (CSM) (1993, 1997)
- [5]. NTNU model (2000, 2016)
- [6]. Q_{TBM} (1999, 2000)
- [7]. RME (Bieniawski et al., 2006)
- [8]. MCSM Model (2002, 2014)
- [9]. Alpine model (2015, 2016)
- [10]. Farrokh et al. (2012)
- [11]. Hassanpour et al. (2011, 2016)
- [12]. Maidl (2008)
- [13]. Frenzel (2011)



[14]. https://www.robbinstbm.com/products/tunnel-boring-machines/double-shield/

Prognosemodeller i hardt berg

- Generelt for prognosemodeller:
  - Inndata: Geologi/berg – og maskin parmetere
  - Utdata: Inndrift- og produksjonsframdrift i tillegg til kutterlevetid
    - Noen modeller er imidlertid utviklet spesifikt for estimering av kutterlevetid

- De forskjellige modellene benytter forskjellige tilnærminger spesielt i forbindelse med inndataparametere som geologi/berg egenskaper. Ved sammenligning av modeller kan dette utgjøre en utfordring.

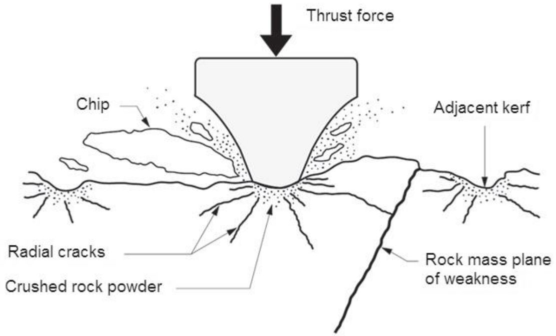
Prognosemodeller i hardt berg

Eksempler på forskjellige tilnærminger i inndataparametere:

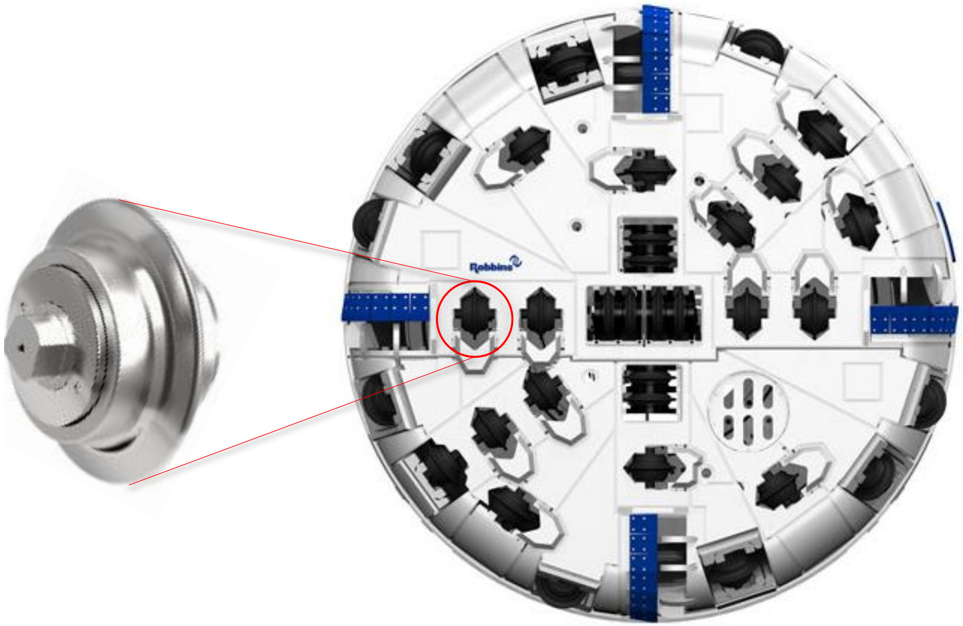
- Gehring (1995): UCS, rock mass fabric.
- Colorado School of Mines (CSM) (1993, 1997): UCS, BTS.
- NTNU model (2000, 2016): DRI, porosity, degree of fracturing, orientation, CLI, quartz content.
- QTBM (1999, 2000): Q-value (with RQDo), rock strength (UCS, PLT), density, porosity CLI, quartz content, induced biaxial stress on tunnel face.
- RME (Bieniawski et al., 2006): RMR parameters, DRI.
- MCSM Model (2002, 2014): UCS, BTS.
- Alpine model (2015, 2016): UCS, rock mass fabric, LCPC breakability, BTS, ‘y-intercept BTS or LBC approach’.
- Farrokh et al. (2012): UCS, BTS.
- Hassanpour et al. (2011, 2016): UCS, BTS.

Prognosemodeller i hardt berg

- Disk kuttere



[15]. Chip formation principle under a disc cutter (Modified from NTH, 1983) in (Macias, 2016) .



[16] [14]. https://www.robbinstbm.com/products/tunnel-boring-machines/double-shield/

Prognosemodeller i hardt berg

- Eksempler på utdata:
  - NPR (m/h)
  - AR (m/week)
  - Cutter ring life (h/c)
  - Cutter ring life (sm^3/c)
  - Total tunnel time (weeks)
  - Delays
  - Total cost

Prognosemodeller i hardt berg

Beregningseksempel

- Inndata parametere TBM:
  - TBM diameter (m): 10.5
  - Cutter diameter (mm; inch): 483; 19
  - T (mm): 19.05
  - Numbers of cutters (N_o): 74
  - RPM (rev/min): 4.51
  - Thrust (kN): 20720
  - Torque (kNm): 5744.2
  - Installed power (kW): 4438.6
  - Cutter spacing (mm): 70.9

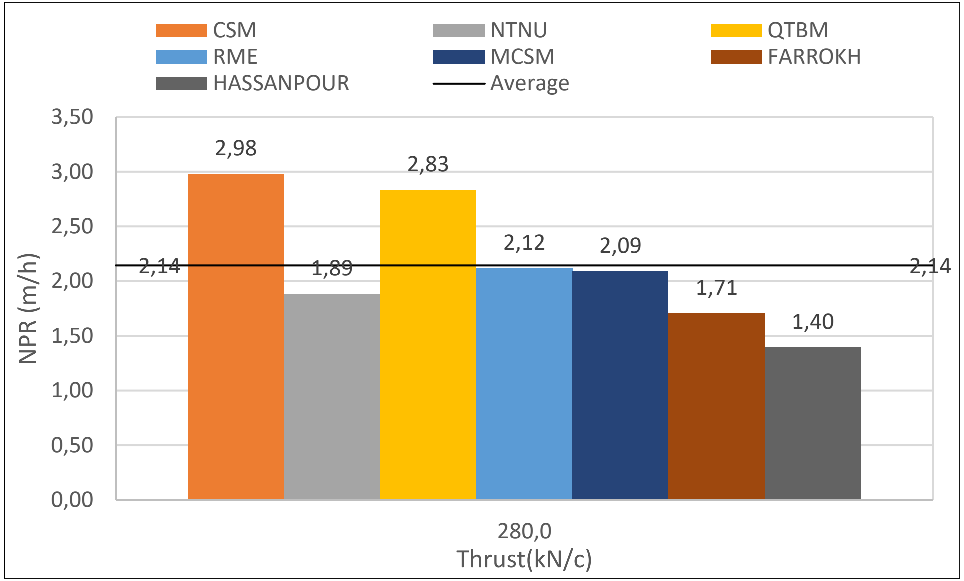
Inndata geologi/berg egenskaper:

- Tunnel length (m): 9500
- Overburden (m): 600
- σ_u (Mpa): 150
- σ_t (BTS) (Mpa): 6.40
- Fracture spacing (average cm): 40
- Quartz (%): 25
- Cerschar Abrasivity Index (CAI): 4.60

Prognosemodeller i hardt berg

Beregningseksempel

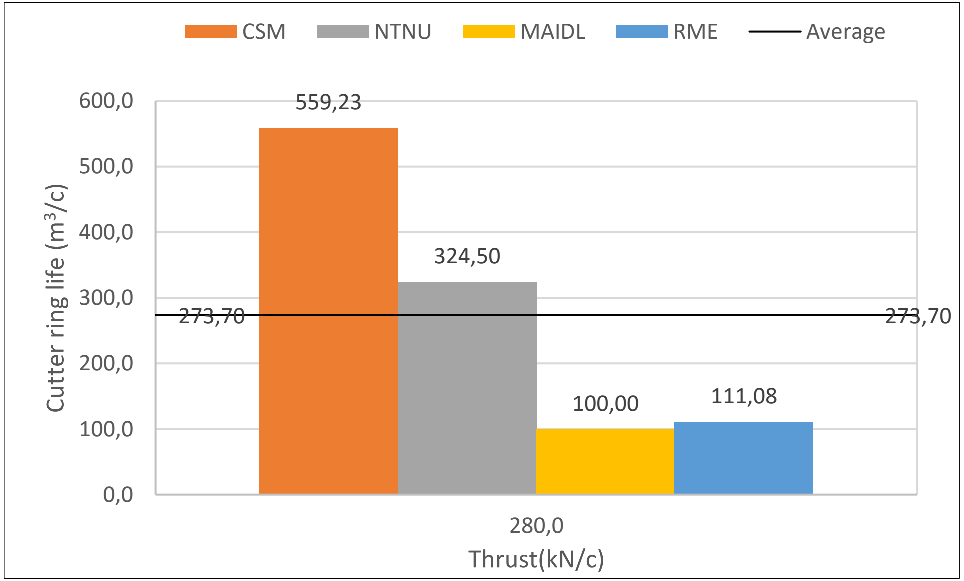
- <u>Utdata:</u>



Prognosemodeller i hardt berg

Beregningseksempel

- <u>Utdata:</u>



Modell differensiering

Penetration rate model	Output parameters
Gehring model	PR (m/h)
CSM model	PR (m/h)
NTNU model	**NPR (m/h), AR (m/week)**
Q_{TBM} model	**PR (m/h), AR (m/week)**
RME	**PR (m/h), (m/week)**
MCSM model	PR (m/h)
Alpine model	PR (m/h)
Farrokh	PR (m/h)
Hassanpour	PR (m/h)

Cutter ring life model	Output parameters
Gehring model	(fm^3/ring)
CSM model	(m^3/c)
NTNU	(h/c), (sm^3/c)
Maidl	(m^3/ring)
RME	(m^3/c)
Frenzel	(m^3/c)

NTNU

DRI, porosity,

degree of fracturing, orientation,

CLI, quartz content

QTBM

Q-value (with RQDo), rock strength (UCS, PLT), density, porosity, CLI, quartz content, induced biaxial stress on tunnel face

RME

RMR parameters, DRI

Oppsummering

- TBM teknologien utvikler seg kontinuerlig noe som bør være en viktig driver for kontinuerlig oppdatering av ytelsesprediksjoner og kutterlevetidsvurderinger.

- Resultater fra forskning resulterer i en bedre forståelse av tunnelboreprosessen som kan benyttes til videreutvikling og revisjon av eksisterende prognosemodeller.

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JMConsulting-Rock Engineering

Gelogisk Risiko i TBM-tunneler

Javier Macias, PhD

Rock Engineering Consultant and Researcher

JMConsulting-Rock Engineering AS

Bergteknikk for TBM - Boring i hardt fjell

10.01.2024, Oslo

NORSK BERGMEKANIKKGRUPPE

Rock Engineering

Outline

- What is Risk?
- Geological Risk in hard rock TBMs
- Geological risk mitigations
  - Design
  - Construction
- Takeaways

Outline

- What is Risk?
- Geological Risk in hard rock TBMs
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  - Construction
- Takeaways

Risk

- “The possibility of something bad happening” (Cambridge Dictionary)
- “Risk is what is left when you think you have thought of everything” (GoodReads - Carl Richards)

Risk

- Risk is always involved in rock tunnels
- Geology is the main source of uncertainty in geotechnical engineering (Wood, 1994)
- *"Uncertainty is a situation in which something is not known, or something that is not known or certain"* (Cambridge dictionary)

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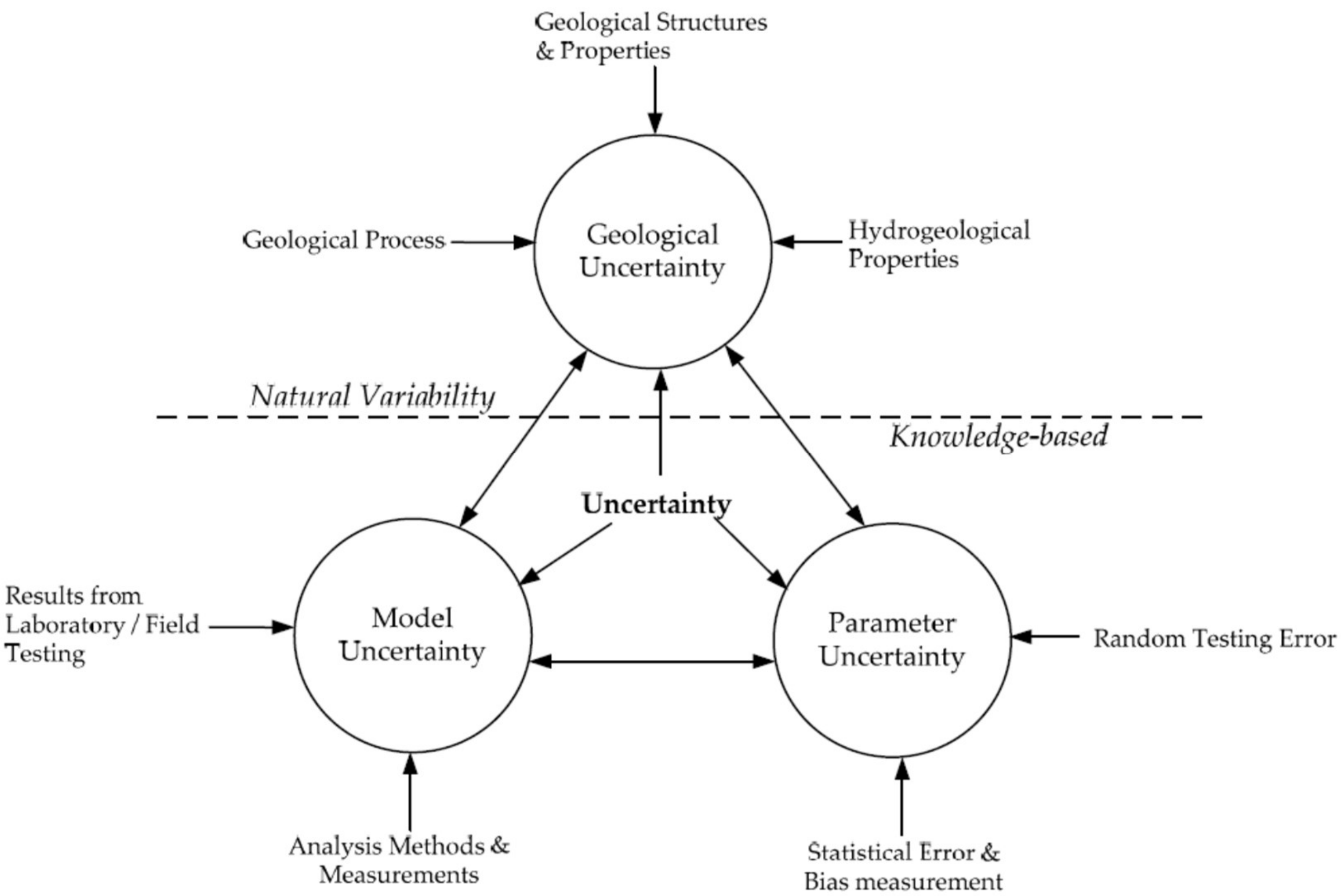
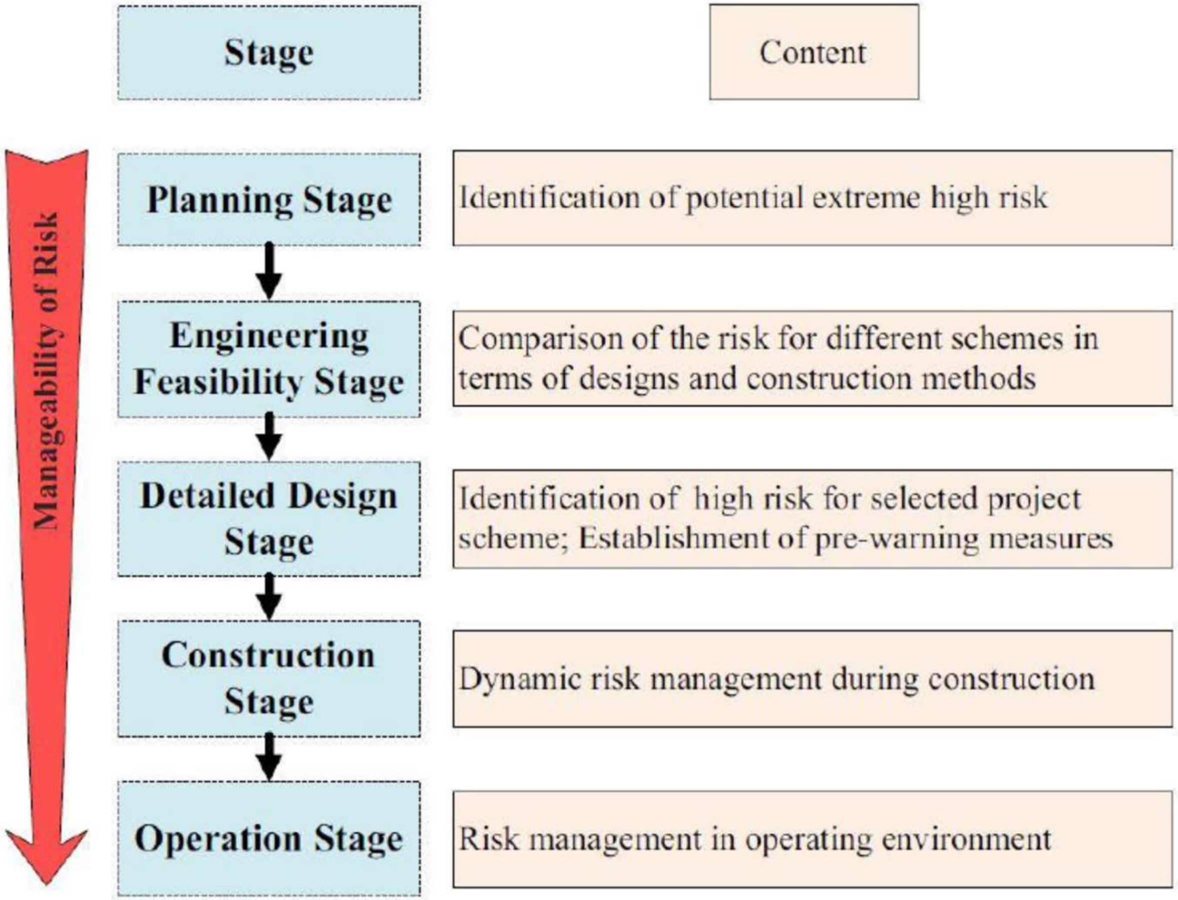
Risk

- **Uncertainty:**
  - **<u>Aleatoric uncertainty</u>** (natural variability)
    - Cannot be reduced
    - Only quantified
  - **<u>Epistemic uncertainty</u>** (“lack of knowledge”)
    - Reduced by means of obtaining more information
    - More investigations

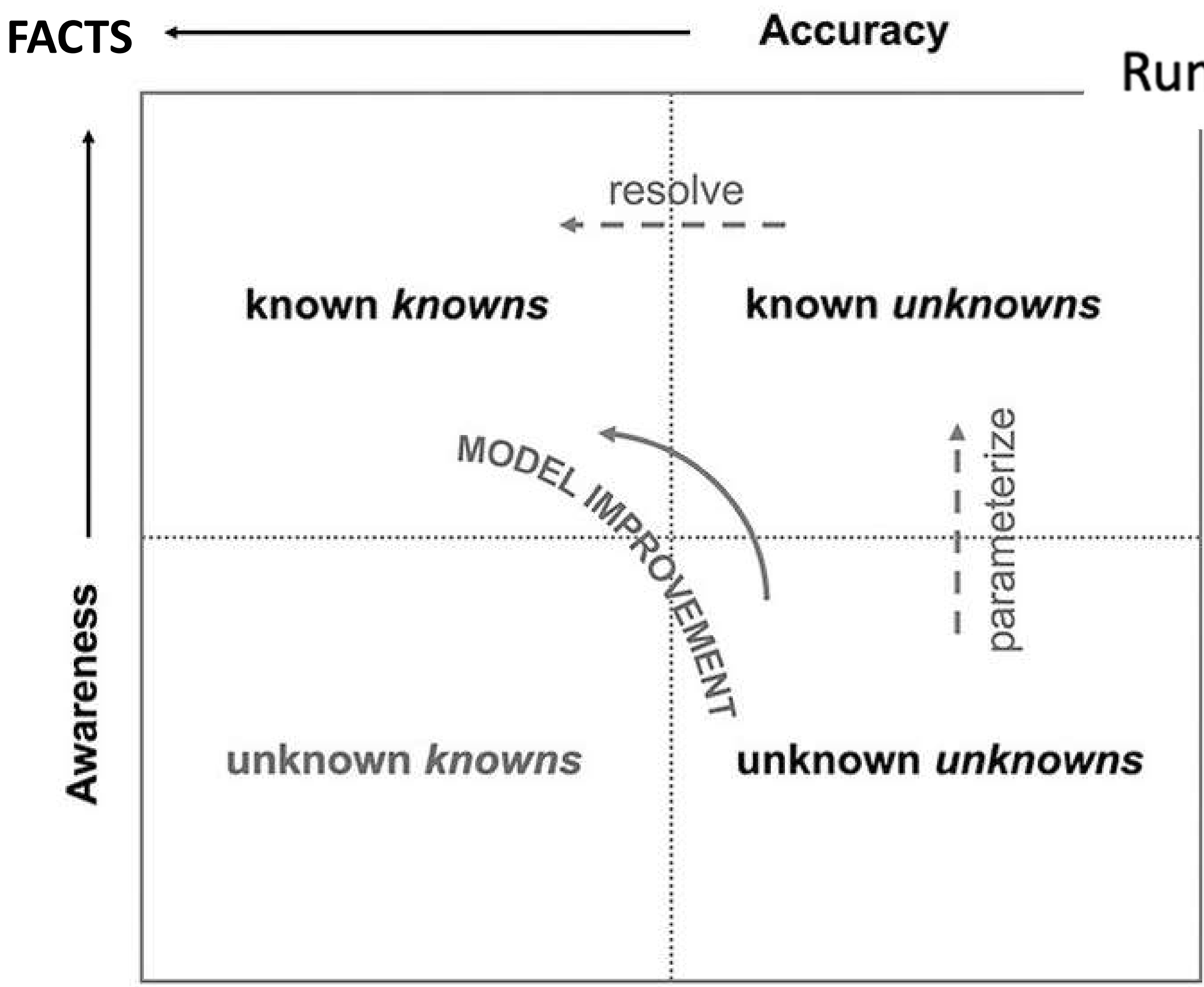
Risk


Geological Structures & Properties
Geological Process
Geological Uncertainty
Hydrogeological Properties
Natural Variability
Knowledge-based
Uncertainty
Results from Laboratory / Field Testing
Model Uncertainty
Parameter Uncertainty
Random Testing Error
Analysis Methods & Measurements
Statistical Error & Bias measurement

Risk


Stage
Content
Manageability of Risk
Planning Stage
Identification of potential extreme high risk
Engineering Feasibility Stage
Comparison of the risk for different schemes in terms of designs and construction methods
Detailed Design Stage
Identification of high risk for selected project scheme; Establishment of pre-warning measures
Construction Stage
Dynamic risk management during construction
Operation Stage
Risk management in operating environment

Risk

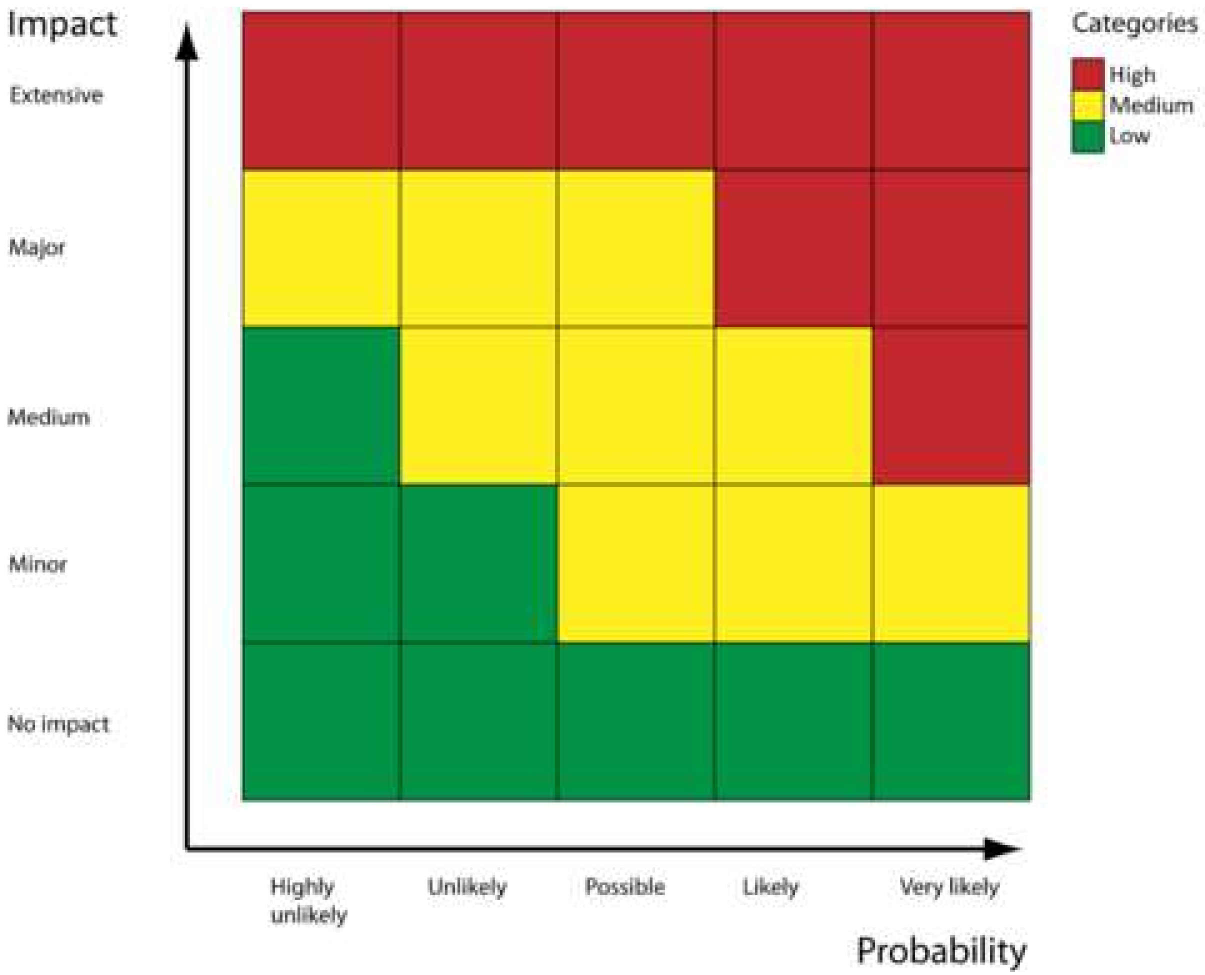


Rumsfeld Knowledge Matrix

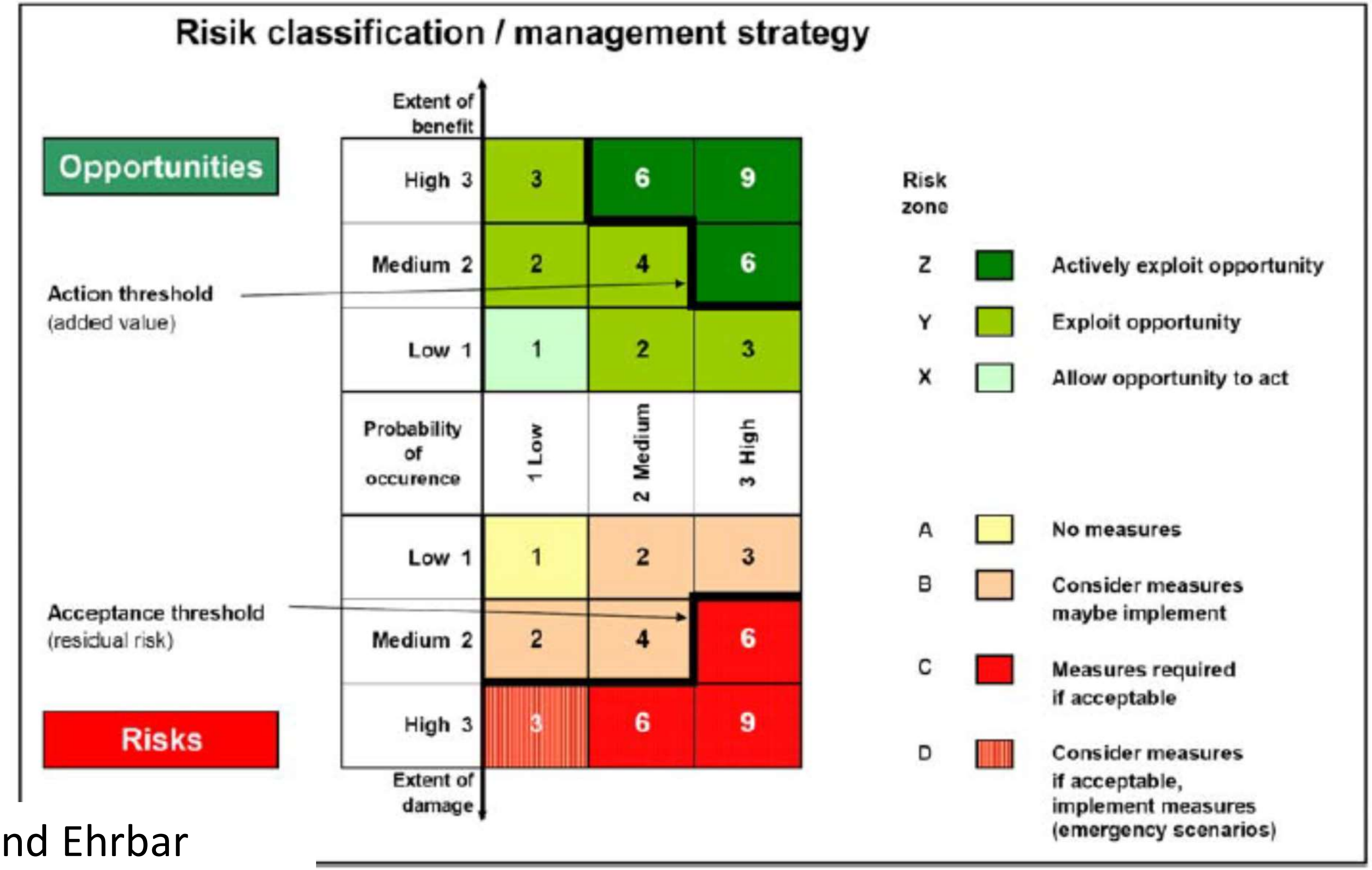
*"As we know, there are **known knowns**; there are things we know we know. We also know there are **known unknowns**; that is to say we know there are some things we do not know. But there are also **unknown unknowns**—the ones we don't know we don't know."*

- Donald Rumsfeld, Former US Secretary of Defense

Risk


Impact
Extensive
Major
Medium
Minor
No impact
Categories
High
Medium
Low
Highly unlikely
Unlikely
Possible
Likely
Very likely
Probability

Risk



2011, Lieb and Ehrbar

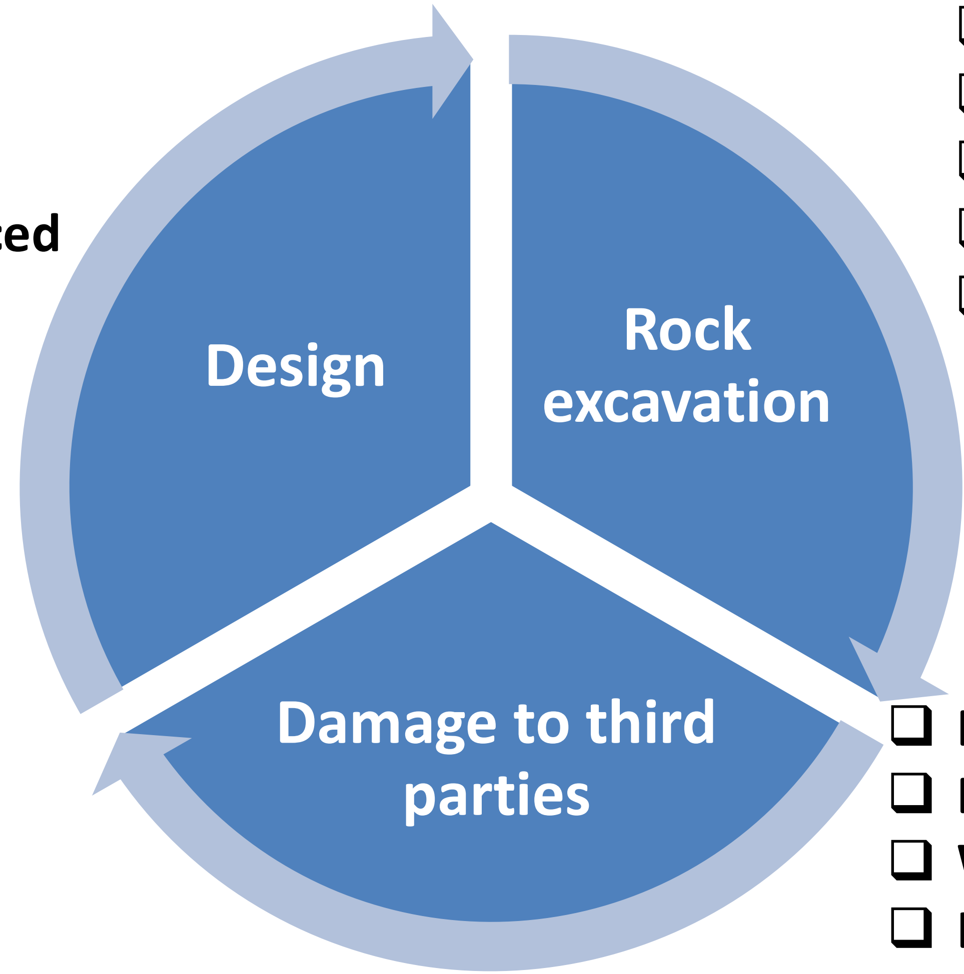
Outline

- What is Risk?
- Geological Risk in hard rock TBMs
- Geological risk mitigations
  - Design
  - Construction
- Takeaways

Geological uncertainties

- ❑ Gravity driven
- ❑ Stress induced
- ❑ Water influenced

- ❑ Drillability
- ❑ Energy to break up rock
- ❑ Stand-up time
- ❑ Initial support
- ❑ Ground water conditions



- ❑ Damage to other structures
- ❑ Environmental/social impact
- ❑ Workers safety
- ❑ Long term stability

Geological Risk in hard rock TBMs

Type	Event	Risk Factor	Probability Score
A. Geological Factors	A1	Squeezing/Swelling ground	4
	A2	High rock stresses and unanticipated rock material behavior	5
	A3	Mudstone/shale rock units softening more than anticipated	4
	A4	Massive Sandstone/Siltstone rock units bedding	4
	A5	Crossing of fault zones or mix ground conditions	5
	A6	Large water inflows, and/or higher pressures, than anticipated	5
	A7	Encountering unexpected large aquifer	5
	A8	Insufficient geological data	4
	A9	Overbreak or block detachment in front of cutter head	3
	A10	High abrasivity of Rock Mass	3
	A11	Unexpected muck characteristics	4
	A12	Encountering big rocks in soft rock matrix	4
	A13	Excess strain energy buildup in strong, stiff/brittle rock	5
	A14	Ground Contains large amount of quartz	5
B. Construction Management Factors	B2	Lack of coordination with supplier/ higher consumption of spare parts	4
	B3	Improper assembly and/or maintenance	3
	B4	O&M and Fuel supply from Power Plant	4
	B5	Conveyor disposal point is too congested due to insufficient capacity	4
	B6	Lack of communication	3
	B7	Additional Rock Support suggested by Geologist at Site	4
	B8	Improper/unsuitable procedures, materials, equipment, or crew	4
	B9	Lack of training and indoctrination	3
	B10	Equipment not properly calibrated or inexperienced operators	4
	B11	Lack of maintenance of the main bearing	3
	B12	Survey control errors	4
	B13	Not following manufacturer's guidelines	4
	B14	[illegible]	[illegible]
C. Design Factors	C1	Machine under-designed and/or underpowered; higher stresses than anticipated	5
	C2	Design is overly conservative	3
	C3	Selection of TBM Machine	5
	C4	Incomplete factory acceptance test	4
	C5	Improper Rock support design	4
	C6	Design of cutter head	5
	C7	Design of cutter size, torque, thrust force	5
	C8	Improper Excavation Span	5

Sharafat et al. (2021)

Geological Risk in hard rock TBMs

- Faulted rock
- Large water inflows
- High stress
  - Squeezing/spalling
- Low to very low rock boreability
- High abrasivity rock
- MFC/Blocky rock mass

Geological Risk in hard rock TBMs

- Faulted rock
- High stress
  - Squeezing/spalling
- Large water inflows
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- Low to very low rock boreability
- High abrasivity rock

TBMs in faulted rock

Significant impact of faulted rock on hard rock TBMs

Why?

- Low flexibility of the method
- Very sensitive to changes in geology
- High cost

TBMs in faulted rock

Some additional geotechnical problems for hard rock TBMs in faulted rock:

- Cutterhead jamming
- Large water inflow/chimeney formation
- Removal of overbreak
- Cutter and cutterhead damages
- …

Water inflow / erosion of faulted rock

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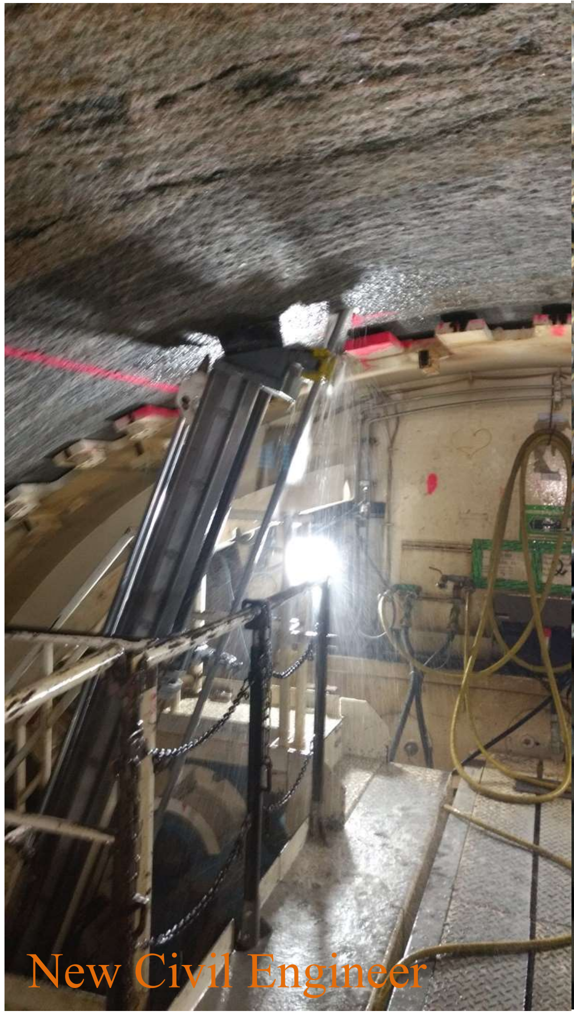
Bolting and rock "straps"

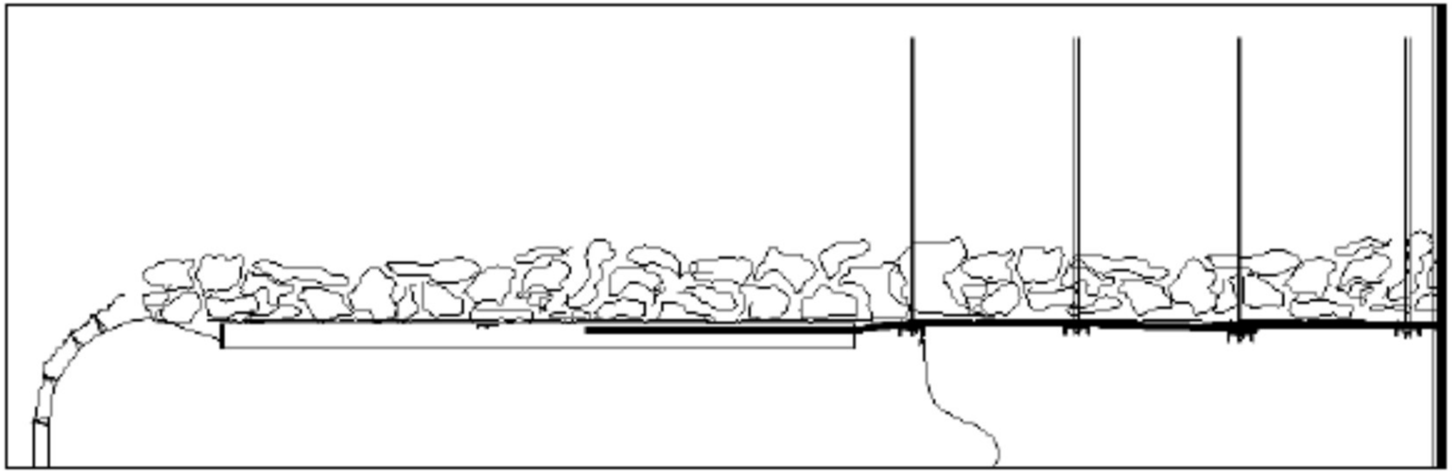
Blocky ground

Bolting and rock "straps"

Bolting and wire mesh



Mc-Nally support system

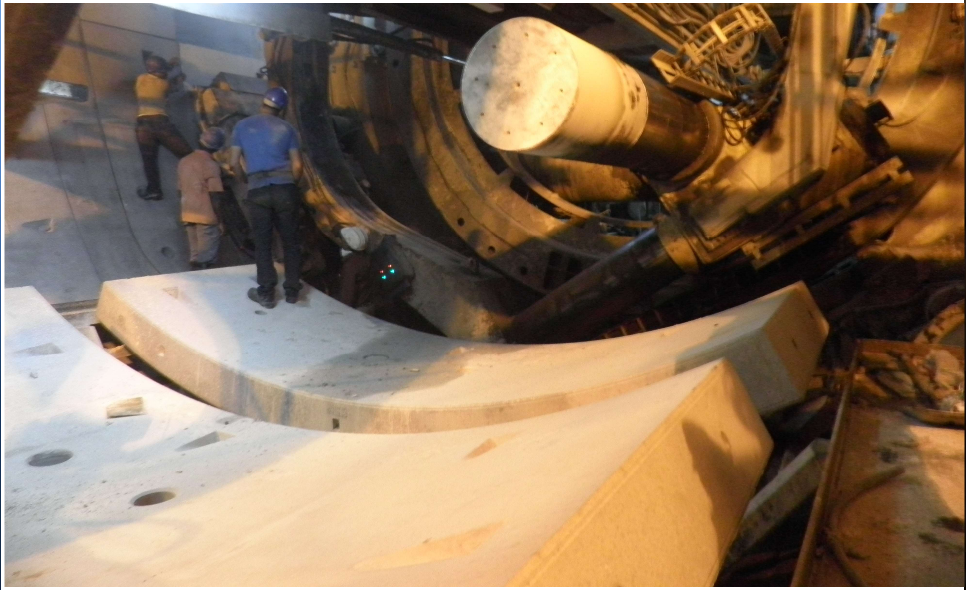


Steel ribs and wire mesh

And sprayed concrete?

Pre-cast segmental lining

- Reinforced concrete segments
- Shield machines



Tunneltalk (2016)

Shield machines in faulted rock

- General advantages
- Risk to become 'trapped'
  - with blocky rock and squeezing conditions
- Specially with Double Shield TBMs and faulted rock with short stand-up time

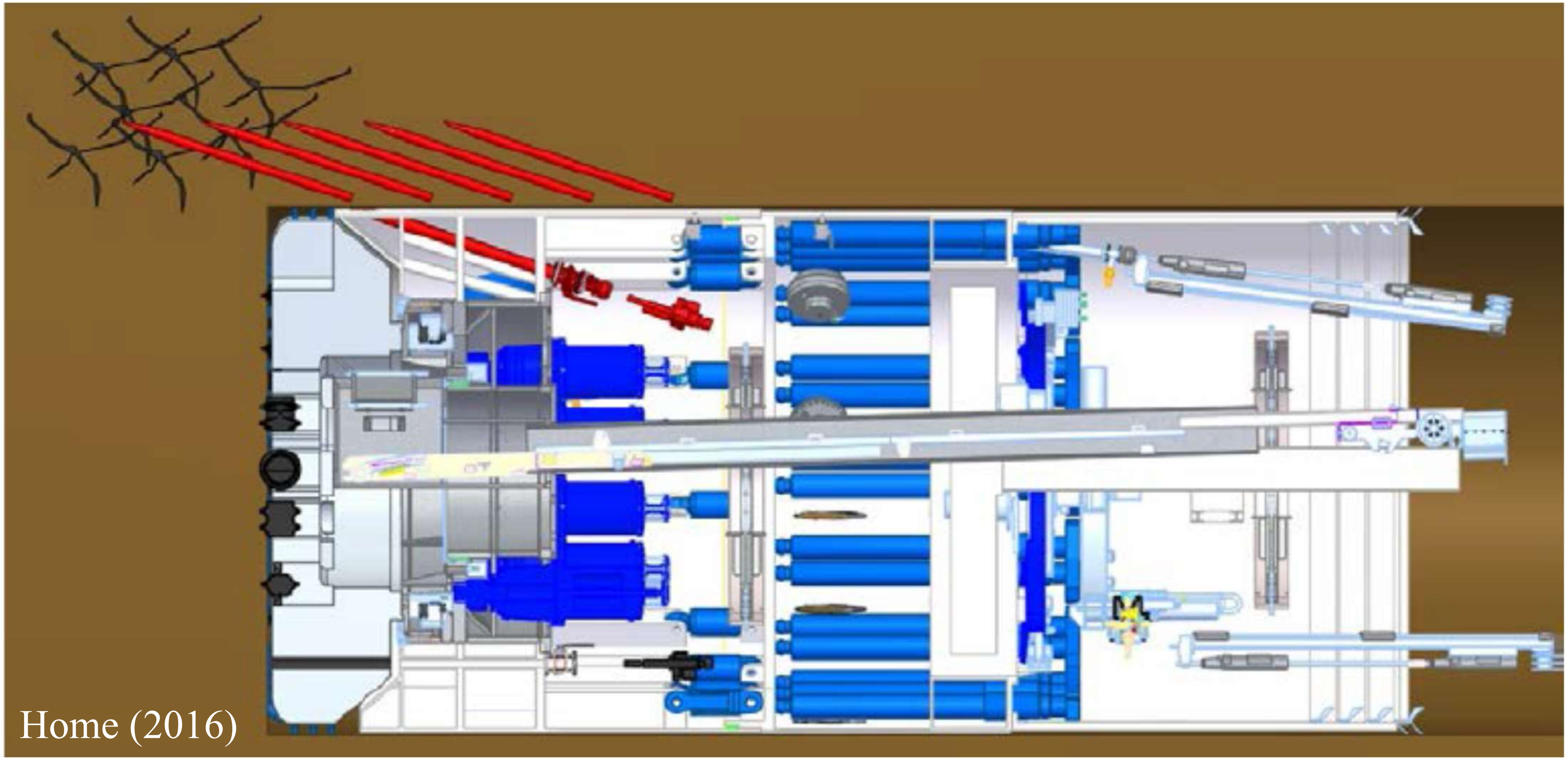
Summary of 'new' TBM systems

In addition to the "traditional":

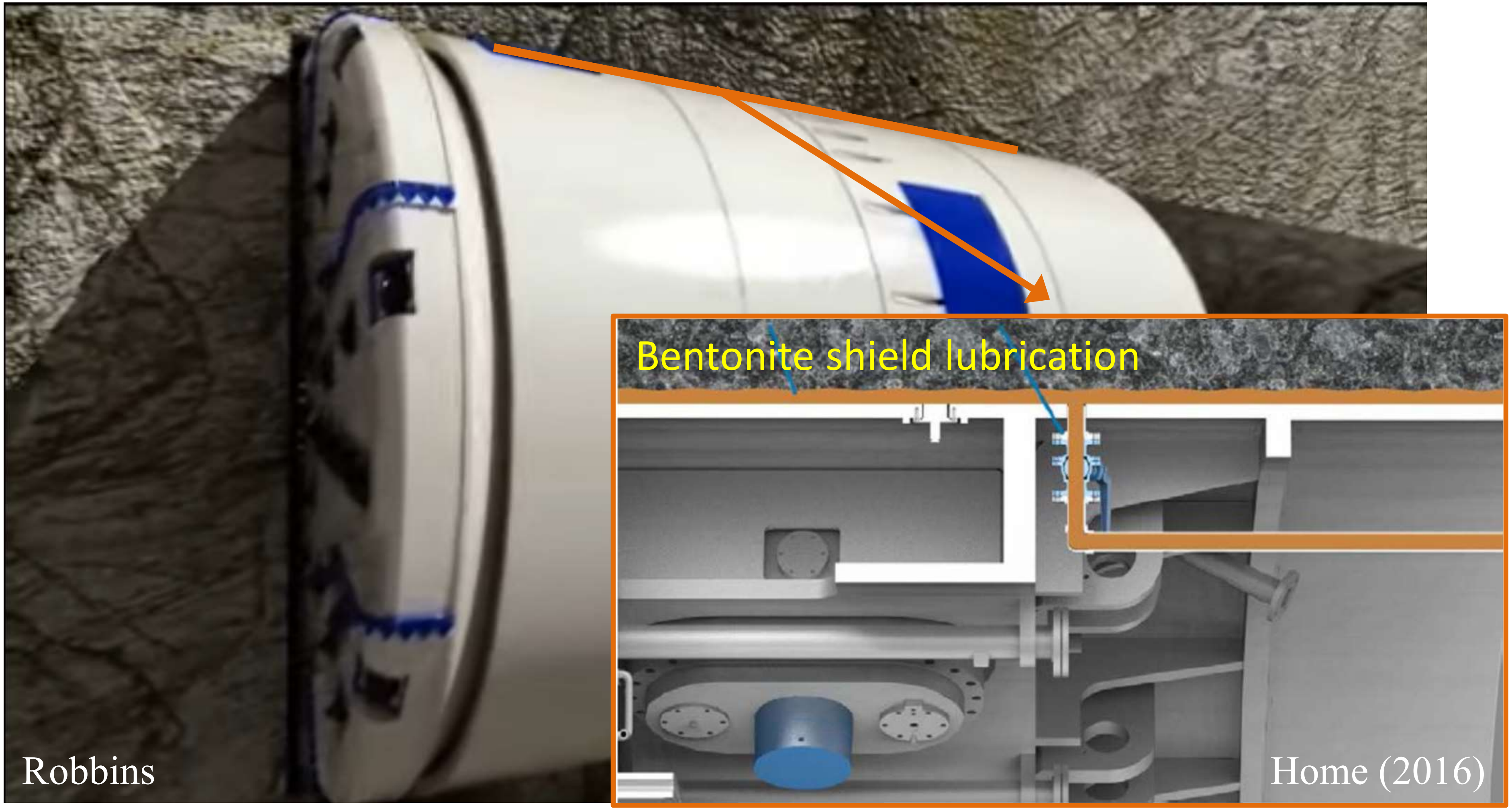
- Multi-speed cutterhead drives
- Shield design for continuous advance
- Convergence measuring system
- Cutterhead inspection camera
- Improve ground detection (e.g. probe drilling, seismic…)
- Improvement in ground treatment ahead

Home (2016)

Spiling and pipe umbrella in TBMs



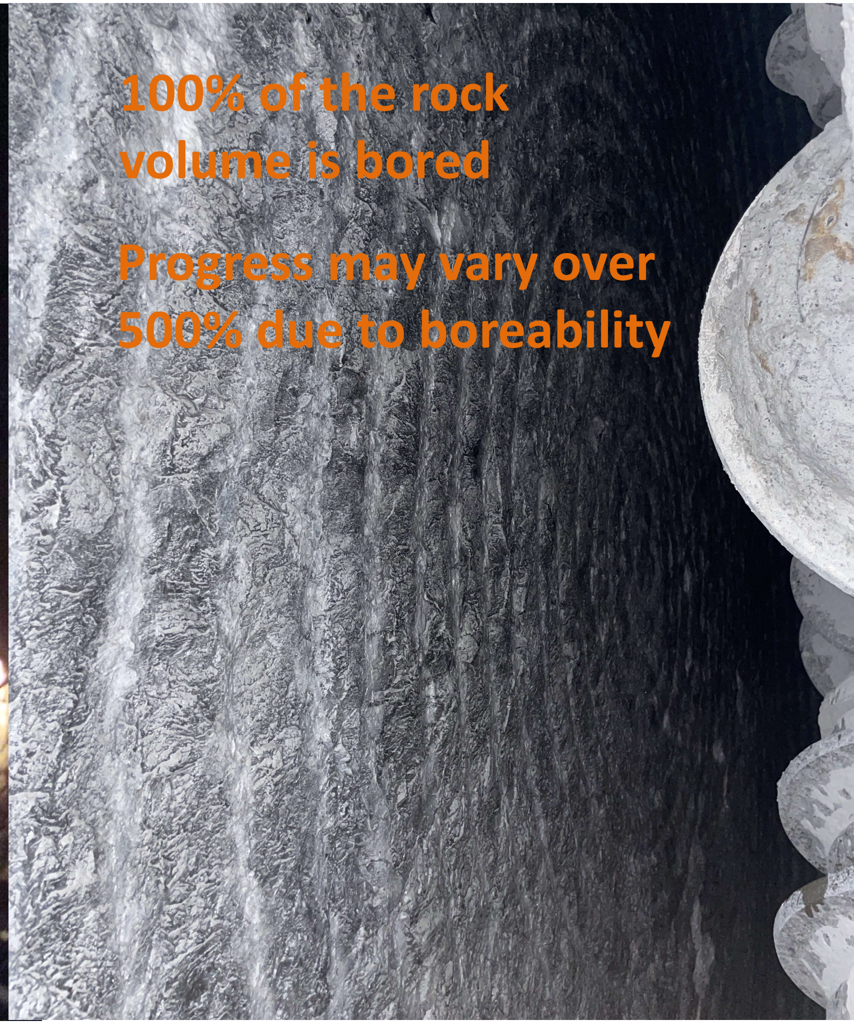
Shield machines in faulted rock



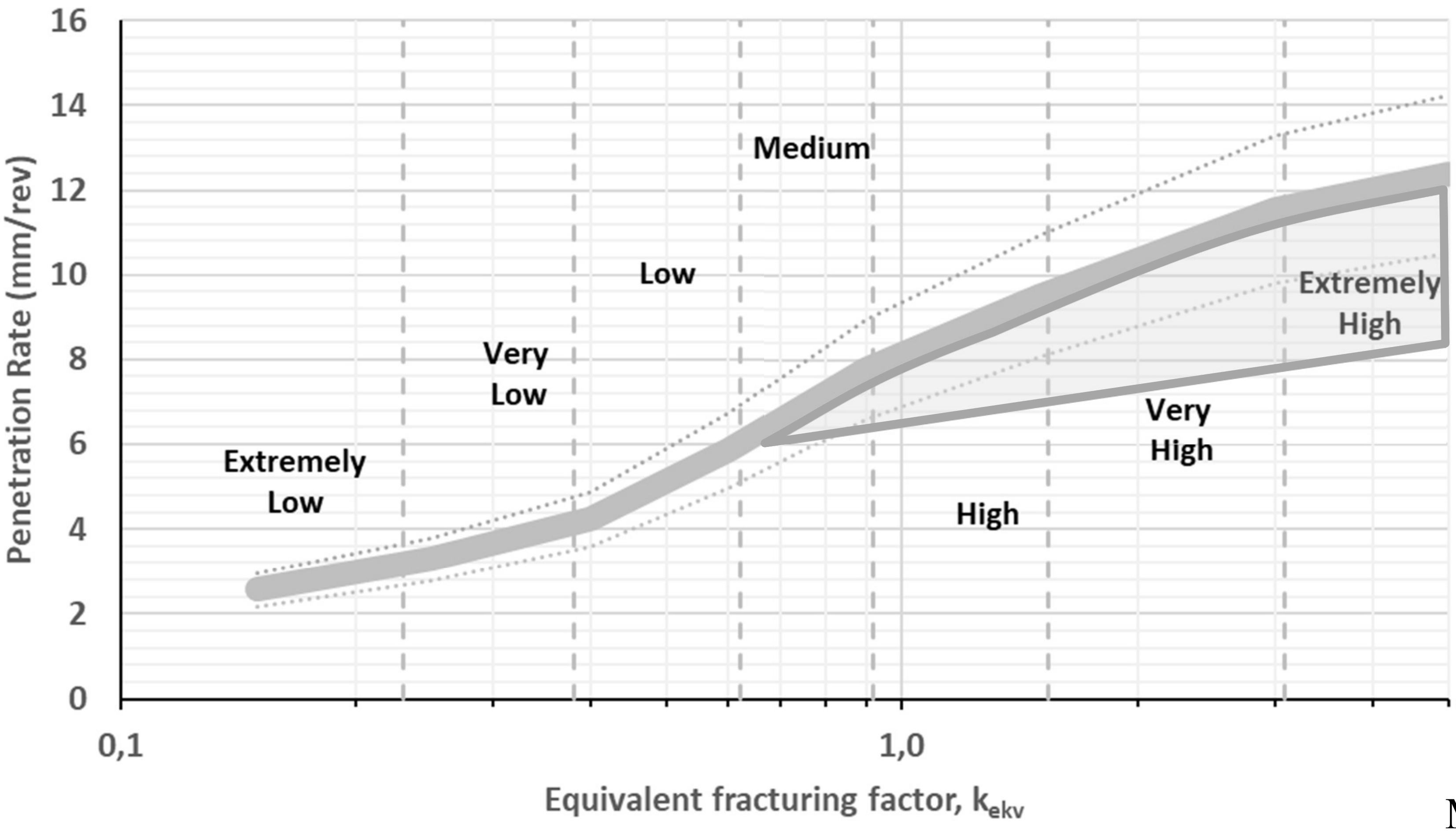
Geological Risk in hard rock TBMs

- Faulted rock
- High stress
  - Squeezing/spalling
- Large water inflows
- MFC/Blocky rock mass
- **Low rock boreability**
- **High abrasivity rock**

Geological Risk in hard rock TBMs

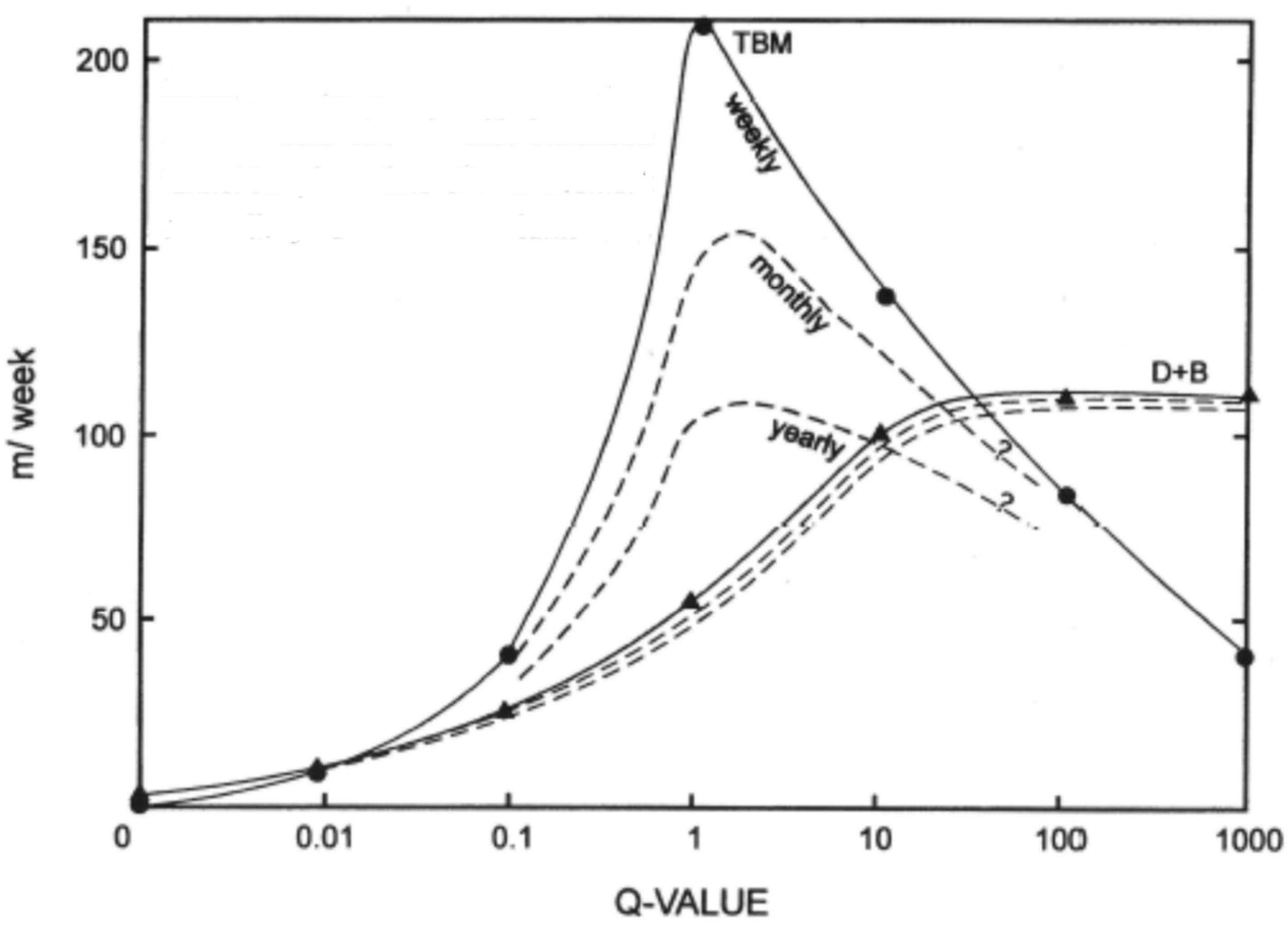


Low Rock Boreability



Macias (2016)

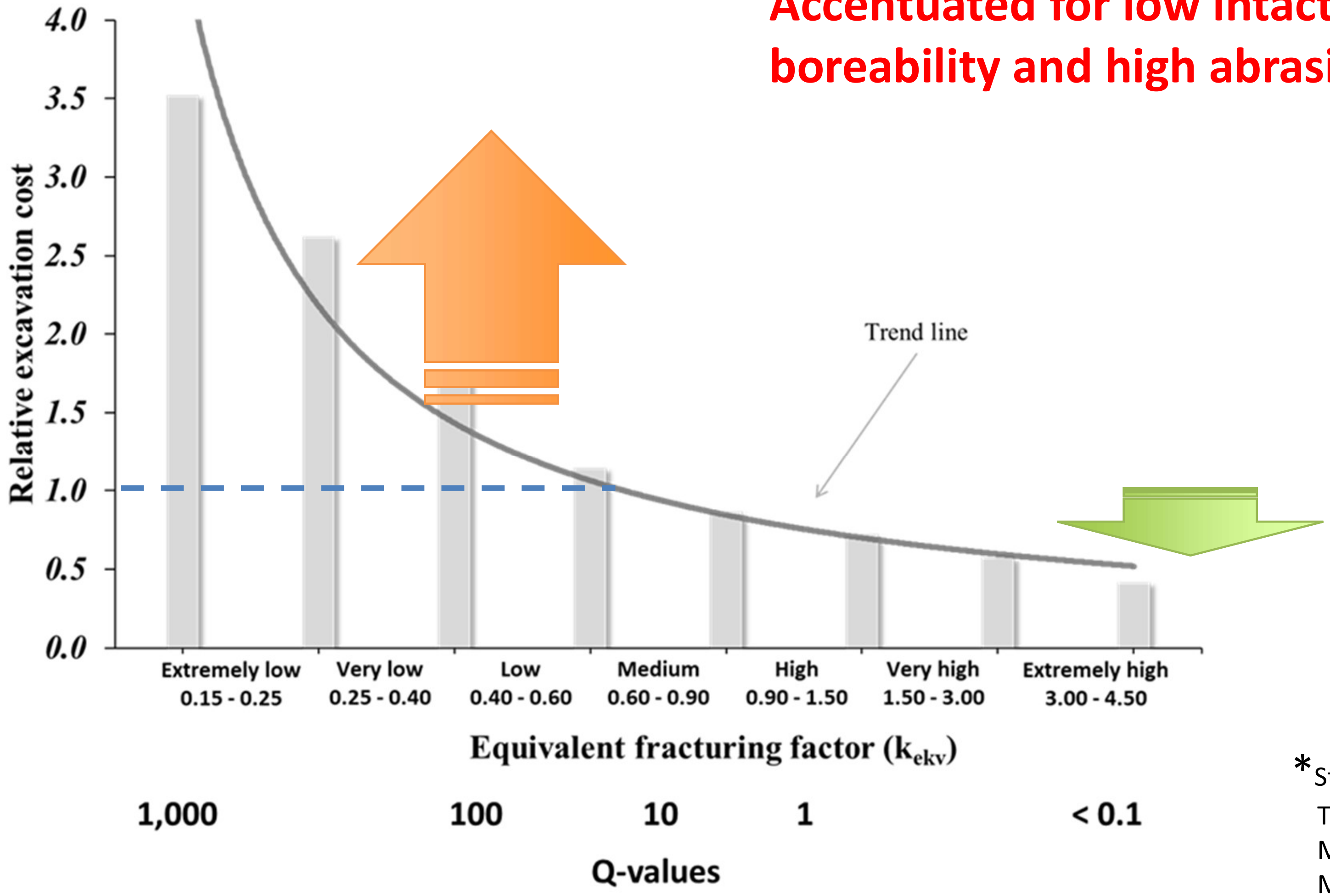
TBMs in faulted rock



Barton (2000)

Low Rock Boreability

Accentuated for low intact rock boreability and high abrasivity!



*Standard TBM spec.
TBM 7 m diameter
Medium DRI
Medium abrasivity

Macias (2016)

Geological risk in hard rock TBMs

- ❑ Gravity driven
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- ❑ Drillability
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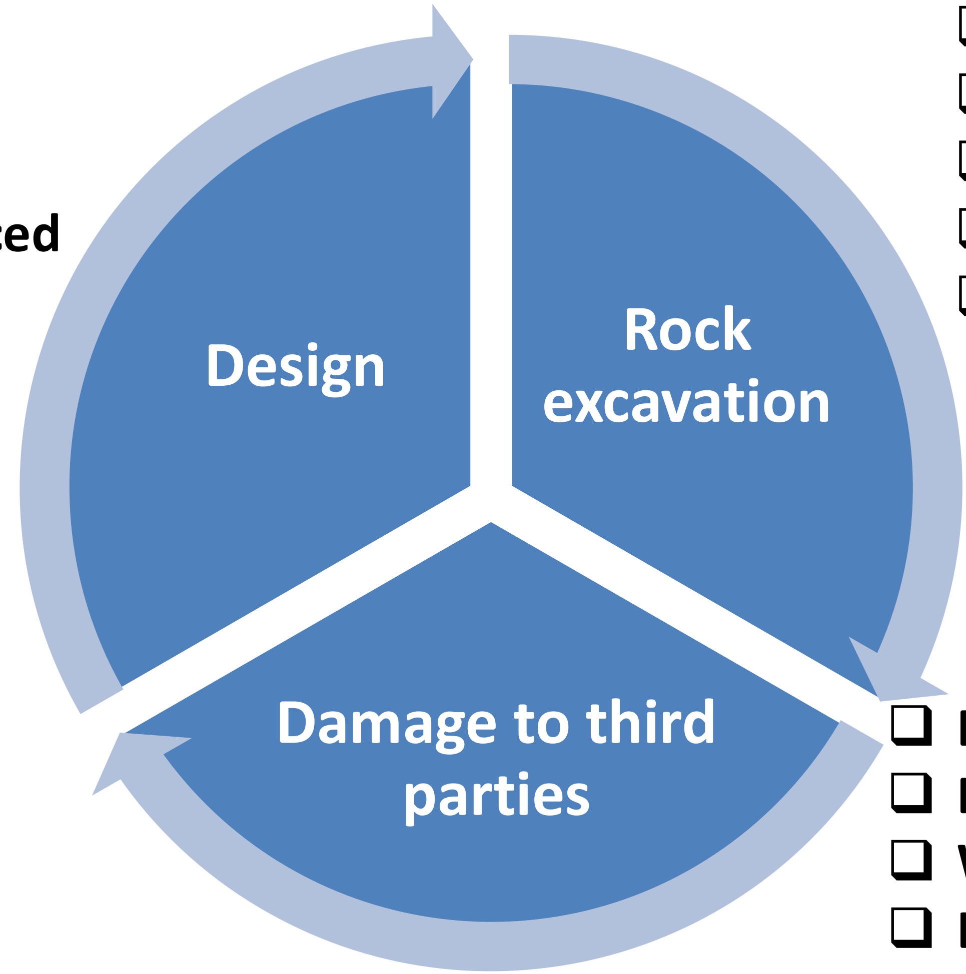

- ❑ Damage to other structures
- ❑ Environmental/social impact
- ❑ Workers safety
- ❑ Long term stability

Schedule and cost

Geological risk in hard rock TBMs

GEOLOGICAL RISK	TUNNEL FINAL DESIGN	ROCK EXCAVATION	SCHEDULE/ COST	Others: SHA Environment
Faulted rock	😬	😬	😬	😬
Large water inflows	😬	😬	😬	😬
Low Boreability	✅	😬	😬	🤔
High abrasivity	✅	😬	😬	🤔
High rock stress	😬	😬	😬	😬
MFC/blocky rock mass	😬	😬	😬	😬

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Outline

- What is Risk?
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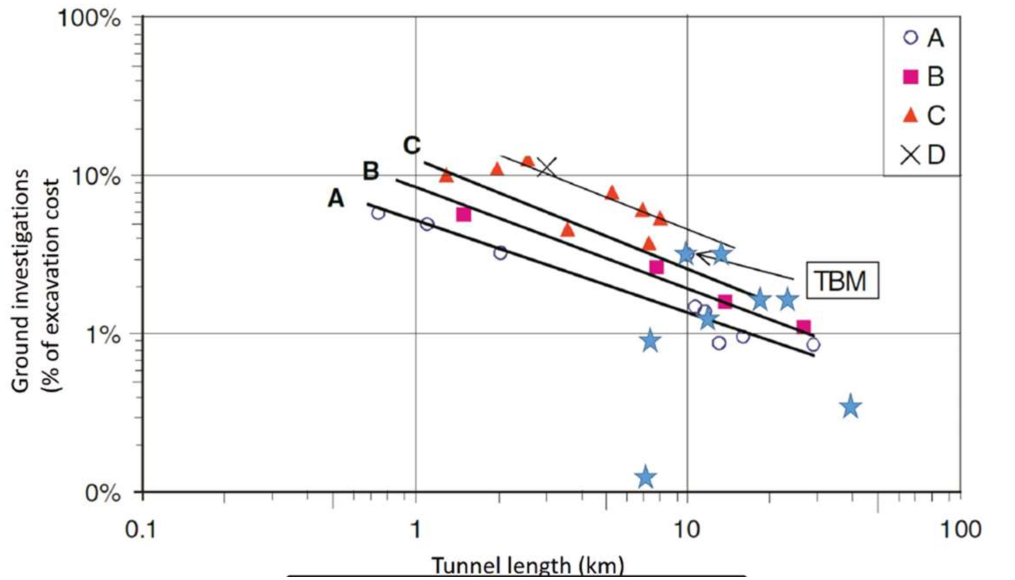
Geological risk mitigation

- Geological risk mitigation during **design**:
  - Indentification and evaluation of the geological risks
  - Good level of geological investigation
    - Reduce uncertainty and Increase precision
  - Extra evaluation to try to find **Unknown Uknowns**
  - Some of the most common in hard rock TBMs:
    - Faulted rock
    - Large water inflows
    - High stress
    - MFC/Blocky rock mass
    - Low to very low rock boreability
    - High abrasivity rock

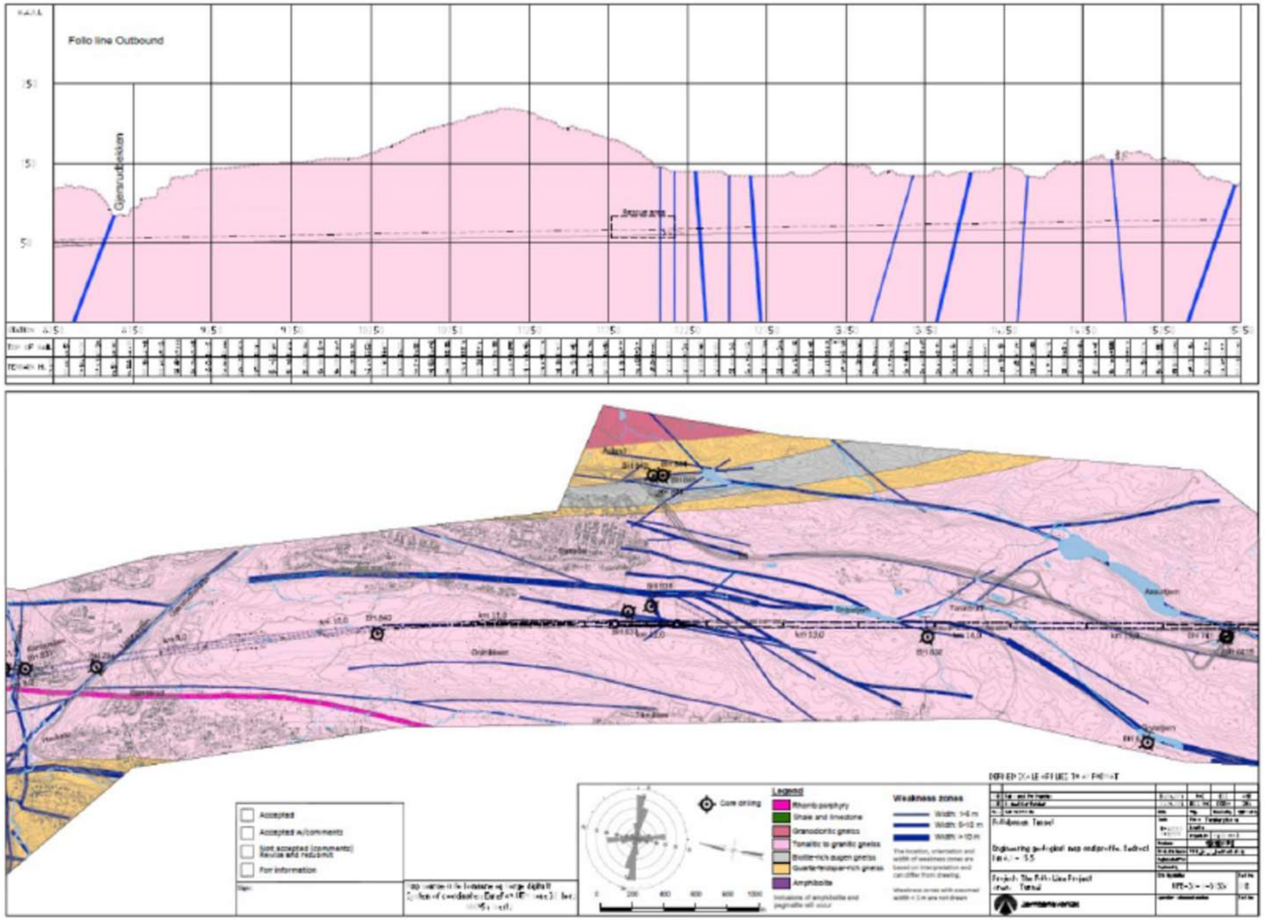
Geological risk mitigation

- <u>Geological risk mitigation during **design**</u>:
  - Appropriate investigation
  - In hard rock, more emphasis on the (lack of) rock mass fracturing outside highly fractured and/or fault zones



Geological risk mitigation

- <u>Geological risk mitigation during **design**:</u>



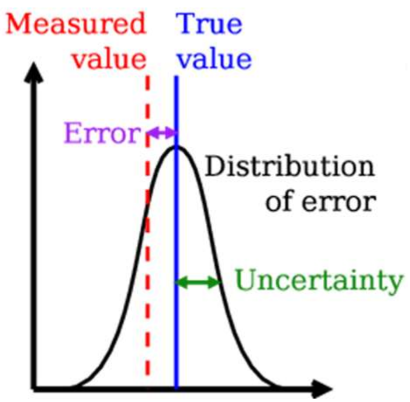
Gammelsæter and Grasbakken (2021)

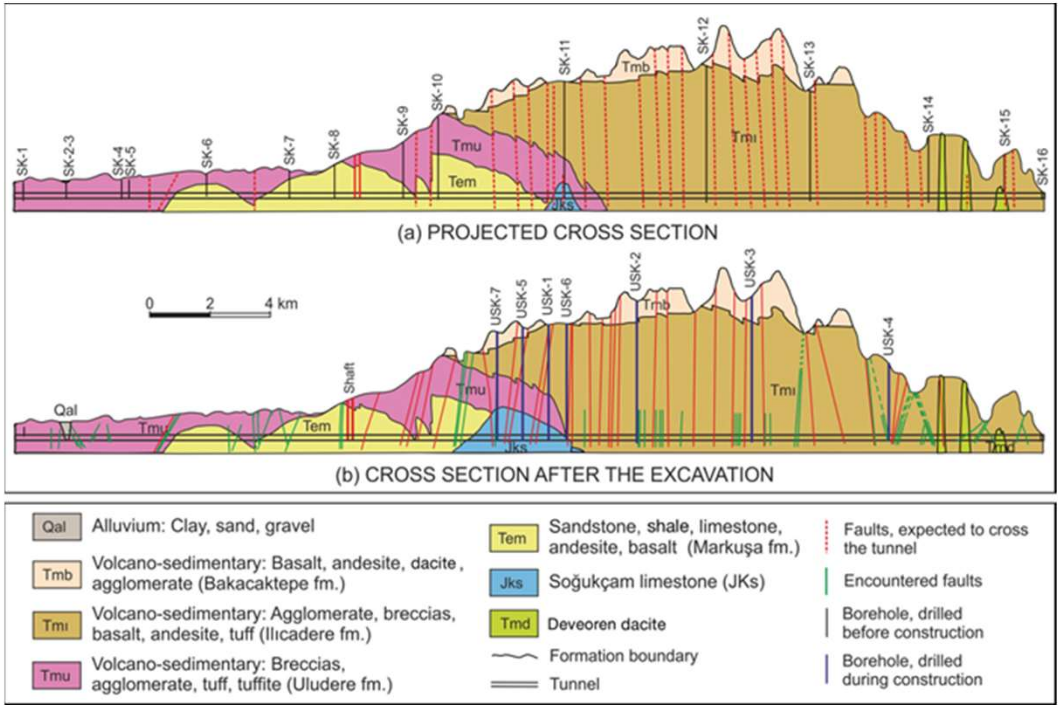
Geological risk mitigation

- Geological risk mitigation during **design**:
  - Selection of the machine from design phase
  - Machine designed to comply to the most challenging rock mass conditions at the project
    - Cutterhead and cutter design/quality
    - Robust main bearing
    - Machine specifications (i.e., power, torque…)
    - TBM system
    - Proper equipment (i.e., probe drilling, grouting,rock support…)
    - …

Geological risk mitigation

- <u>Geological risk mitigation during excavation</u>:
  - ***It is not possible to make an exact model of the geology along the tunnel through pre-investigations***





Geological risk mitigation

- Geological risk mitigation during excavation:
  - *It is not possible to make an exact model of the geology along the tunnel through pre-investigations*

The contracts must contain tools to handle variations in the rock mass properties (excavation time and cost)

Geological risk mitigation

Example of risk sharing methodologies:

- **Compensation system** for (only) 'adverse' deviations from the baseline:
  - Based on deviations from rock properties (intact and rock mass) – only adverse;
  - Based on TBM prediction systems: 'Model to model comparison'.
- **Unit price** systems:
  - Based on rock parameters;
  - Field penetration tests - boreability classes
  - Actual data – boring hours, cutter changes, grouting,…

Geological risk mitigation

- Geological risk mitigation during **excavation**:
  - Continuous pre-investigation ahead the face
    - Continuous probe drilling
    - Televiewing
  - Water control/Pre-treatment
    - «Post grouting will not solve a poor pre-grouting»
  - Optimal machine operation
  - Optimal machine maintenance
  - Optimal cutter management

Outline

- What is Risk?
- Geological Risk in hard rock TBMs
- Geological risk mitigations
  - Design
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- Takeaways

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Takeaways

- TBM tunnelling in hard rock involves much higher geological risk than D&B tunnelling
- Predictions (time and cost) should include the potential impact of the geological risks
- Uncertainty is inherent to geology
  - We can reduce uncertainty but not eliminate it

Takeaways

- It is not possible to make an exact model of the geology along the tunnel through pre-investigations
- The contracts must contain tools to handle variations in the rock mass properties (excavation time and cost)


Thank you!
Questions?
Javier.Macias@JMC-RockEng.com

Forinjeksjon og vannkontroll for TBM-boring i hardt berg

Karl Gunnar Holter
Teknisk ekspert ingeniørgeologi og bergteknikk
kgh@ngi.no

NBG, Bergteknikk for TBM i harde bergmasser
10. januar 2024

Innhold

- Vannkontroll i TBM borede tunneler – hovedtyper av tekniske løsninger
  - Drenerte tunnelkonstruksjoner med en kontrollert vanninnlekkasje
  - Helt vanntette og udrenerte tunnelkonstruksjoner
- Forinjeksjon i TBM-borede tunneler
  - Spesielle forhold og utfordringer sammenliknet med B&S
  - Tekniske løsninger
- Vannkontroll med tett udrenert betongelementkledning
  - Oppbygning av kledning og metodikk for utførelse
  - Spesielle utfordringer i hardt berg
- Noen eksempler fra utførte prosjekter
- Oppsummering

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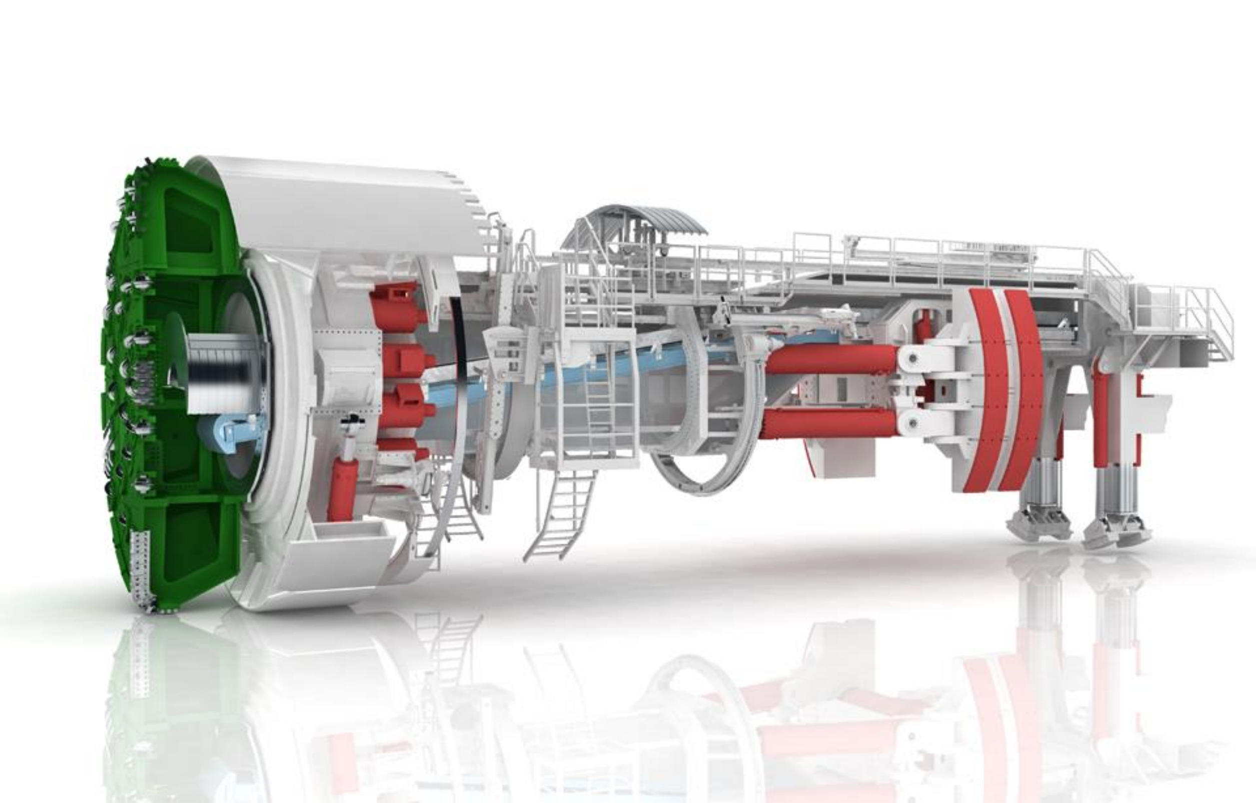
To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

1a: **Drenert tunnel**, med kontrollert innlekkasje av vann

Åpen gripper TBM med bergsikring med bergbolter og sprøytebetong



Kilde for grafikk : Herrenknecht A

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

1a: **Drenert tunnel**, med kontrollert innlekkasje av vann

Åpen gripper TBM med bergsikring med bergbolter og sprøytebetong

Kilde for grafikk : Herrenknecht AG

NGI

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

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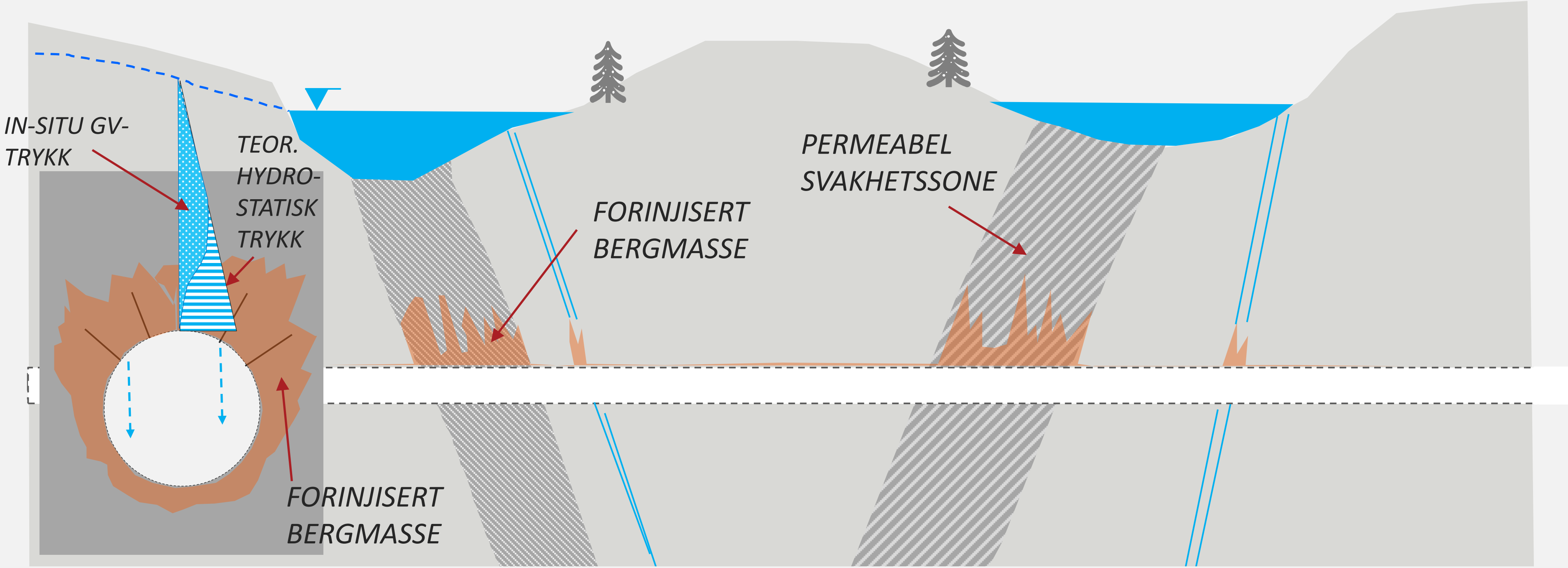
Åpen gripper TBM med bergsikring med bergbolter og sprøytebetong



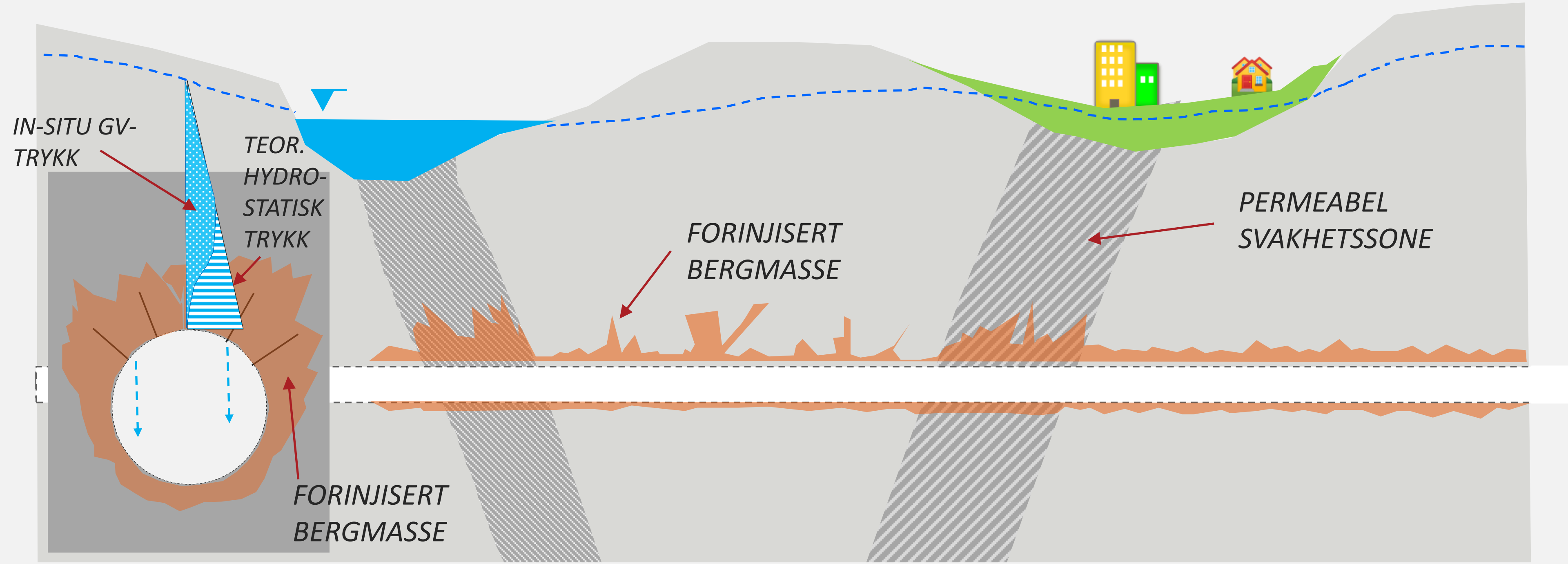
Kontrollert innlekkasje av vann:

- Akvifer har lav sensitivitet for skadekonsekvenser. Tettemålet fastsettes for å unngå store vanninnlekkasjer
- Behovsprøvd forinjeksjon for å tette partier i bergmassen med høy permeabilitet

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

1b: **Drenert tunnel**, med kontrollert innlekkasje av vann

Åpen gripper TBM med bergsikring med bergbolter og sprøytebetong



Kontrollert innlekkasje av vann:

- Forinjeksjon med tettemål for å opprettholde poretrykk i løsmasseavsetninger
- Systematisk injeksjon

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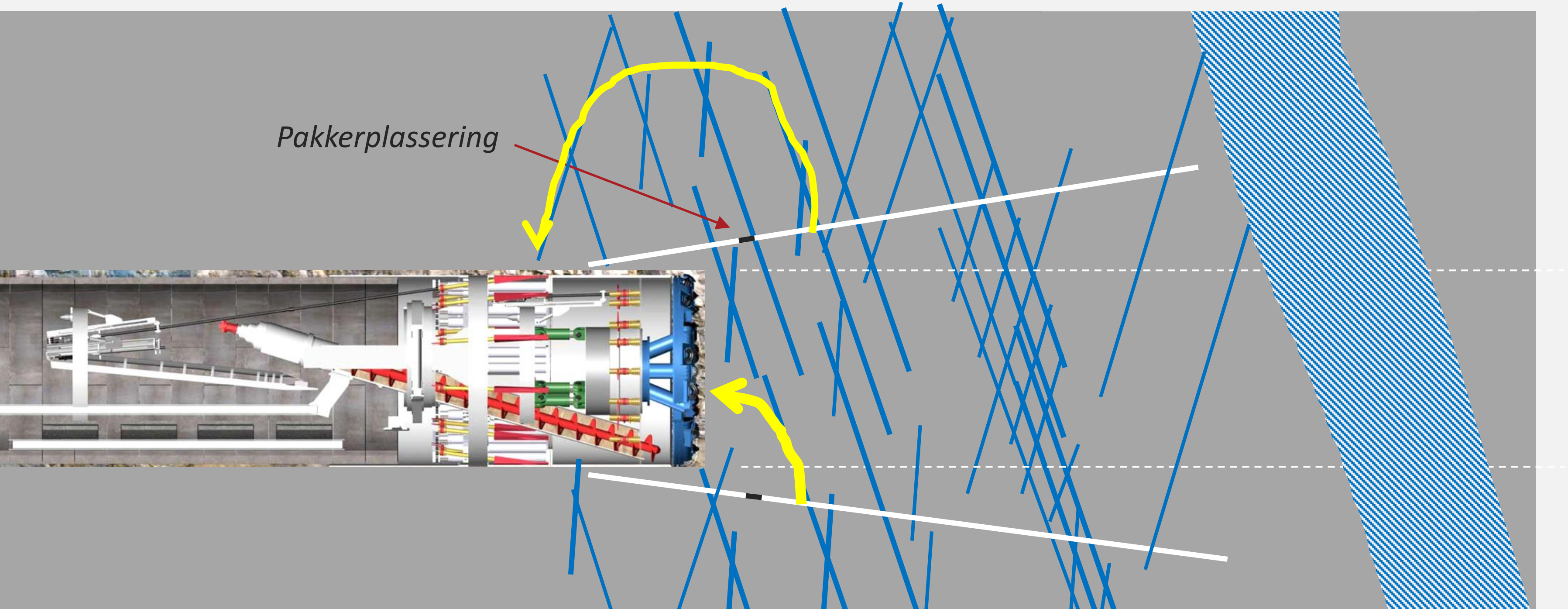
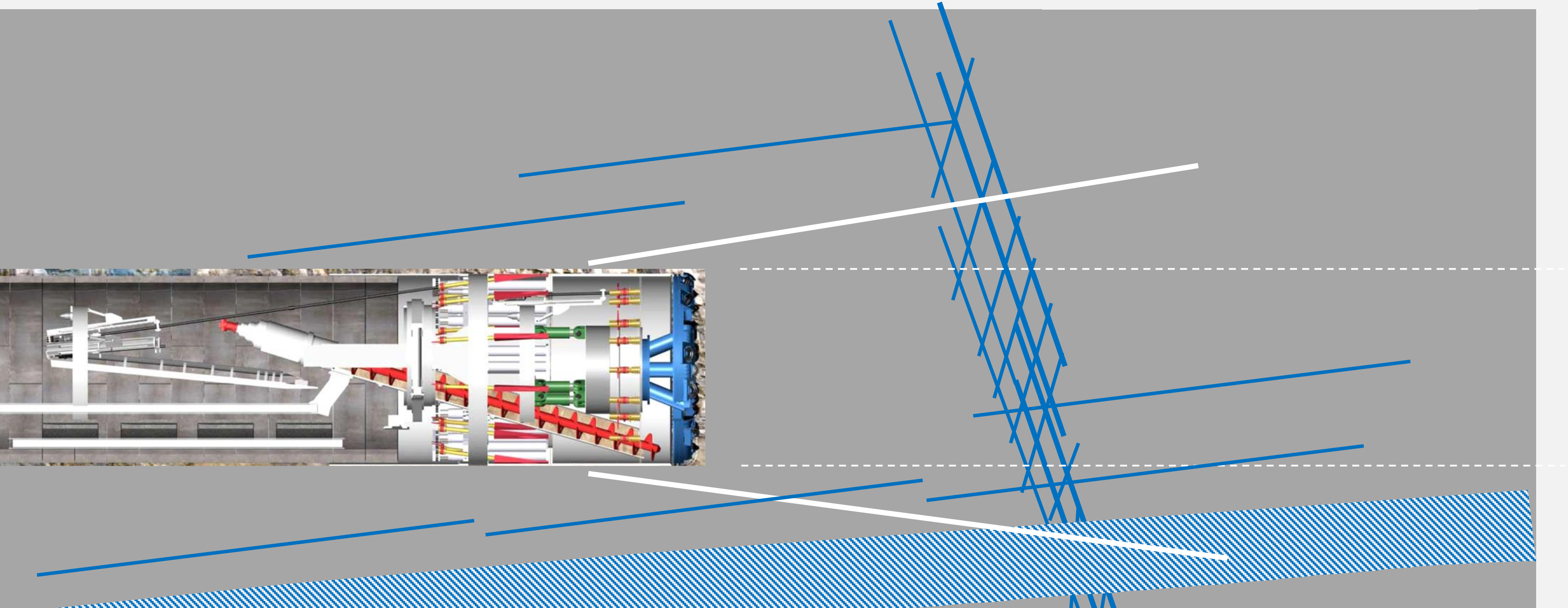
Spesielle utfordringer med forinjeksjon foran TBM

- Borhullsansett
- Logistikk
- Redusert fleksibilitet: redusert sikt og mulighet for rask håndtering av **utganger** av injeksjonsmasse
- Spesielt krevende å bore injeksjonshull i såle
- Forinjeksjon på tidskritisk linje: Svært kostbar nedetid



Spesielle utfordringer med forinjeksjon foran TBM

- Borhullsansett
- Logistikk
- Redusert fleksibilitet: redusert sikt og mulighet for rask håndtering av utganger av injeksjonsmasse
- Spesielt krevende å bore injeksjonshull i såle, viktig ved **flattliggende svakhetssoner**
- Forinjeksjon på tidskritisk linje: Svært kostbar nedetid



Spesielle utfordringer, forinjeksjon foran TBM

- Borhullsansett
  - Ansett ca 4-6 m bak stuff
  - Som oftest låste posisjoner
  - Spiss vinkel til bergkontur, lett å få "skrens" med borkrone ved ansett
  - Fast/last vinkel/retning for boring
- Logistikk, praktisk arrangement
  - Pakkerstaver må skyves betydelige lengre inn sammenliknet med B&S
  - Større avstand (=stor slangelengde) fra injeksjonsrigg til injeksjonspunkt
- Redusert fleksibilitet
  - Det går noe tid før en utgang blir oppdaget
  - Injeksjonsmasse kan grise til og kontaminere TBM borhode
  - Hullposisjoner kan bli "oppbrukt", TBM må bores noen m frem for å kunne foreta oppfølgende injkeksjon
  - Ofte hensiktsmessig å bore lengre hull enn i B&S, 35 – 40 m hullengder
- Injeksjonsboring i såle
  - Borkaks fra lanhhullsboring samler seg I sale og blokkerer hull, vansker med utspyling under boring og plassering av pakkere
  - TBM kaks som samler seg i såle
- Tidskritisk, svært dyr stopptid
  - Betydelig høyere stopptidskostnad sammenliknet med B&S

Løsninger på spesielle utfordringer, forinjeksjon foran TBM, må forberedes/spesifiseres:

- Borhullsansett og boring
  - Porter/ansettrør gjennom TBM skjold
  - Borutrustning: styrestenger, stivere borutrustning, høy ytelse på bormaskiner
  - Stangsiftautomatikk og mulighet for effektiv boring av lange hull (ca 40 m)
  - Teleskopisk forlengelse av portrør gjennom skjoldet
- Logistikk, praktisk arrangement
  - Tilrettelagte praktiske løsninger med staver og pakkere for raskest mulig betjening
  - Forbedret kommunikasjon fra injeksjonsrigg til injeksjonspunkt
- Redusert fleksibilitet
  - Helhetlig metodikk, sekvens av boring og injeksjon
  - Injeksjonsmasse med relativt rask settingtid
- Injeksjonsboring i såle
  - Teleskopisk forlengelse av portrør I sale, sug/spyleutrustning ved
  - Boring og injeksjon av sålehull før resten av skjermen bores opp
- Tidskritisk, svært dyr stopptid TBM
  - Helhetlig metodikk
  - **Fokus på reduksjon av nedetid TBM**
  - Oppgjørsform som insentiverer entreprenøren for effektiv og helhetlig tilnærming

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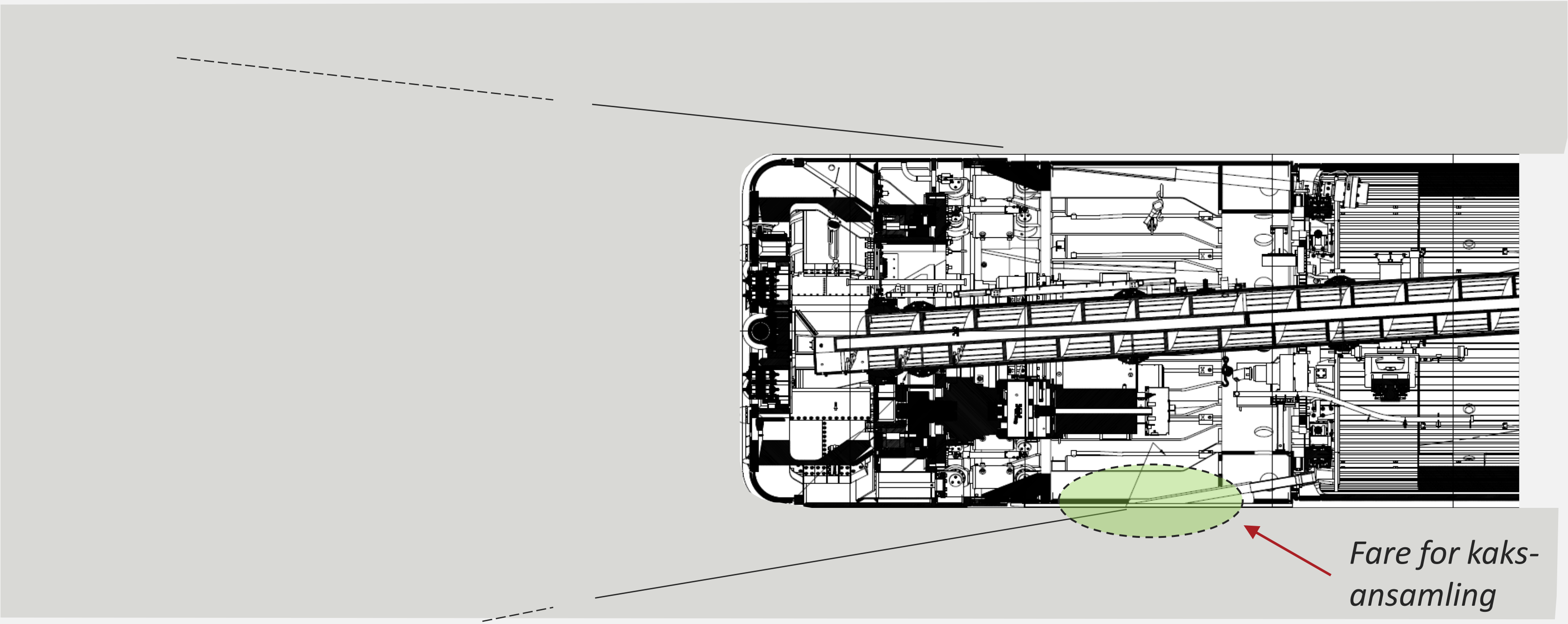
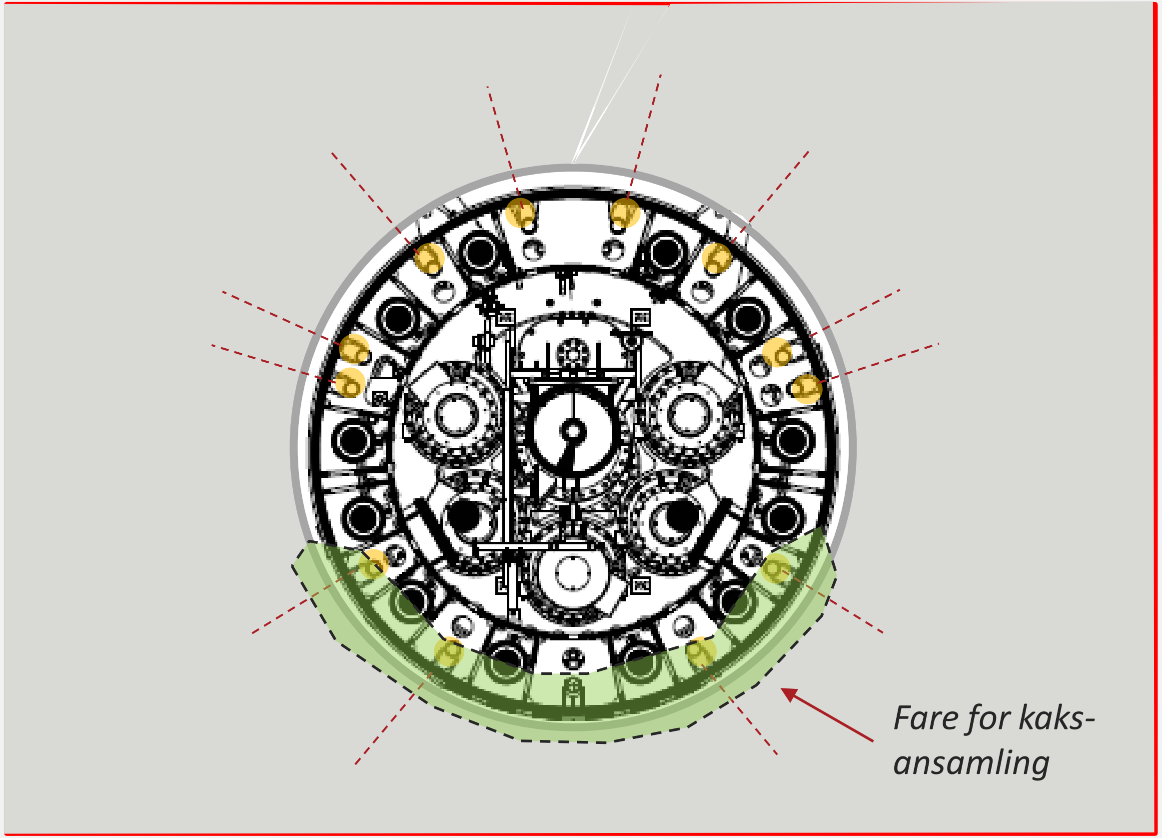
Viktig utfordring som må løses

Injeksjonsboring i såle

- Kaks-ansamling i nedre del av tunnelkonturen
- Teleskopisk forlengelse av portrør I sale, sug/spyleutrustning ved
- Boring og injeksjon av sålehull før resten av skjermen bores opp



Vannkontroll med tett og udrenert betongelementkledning



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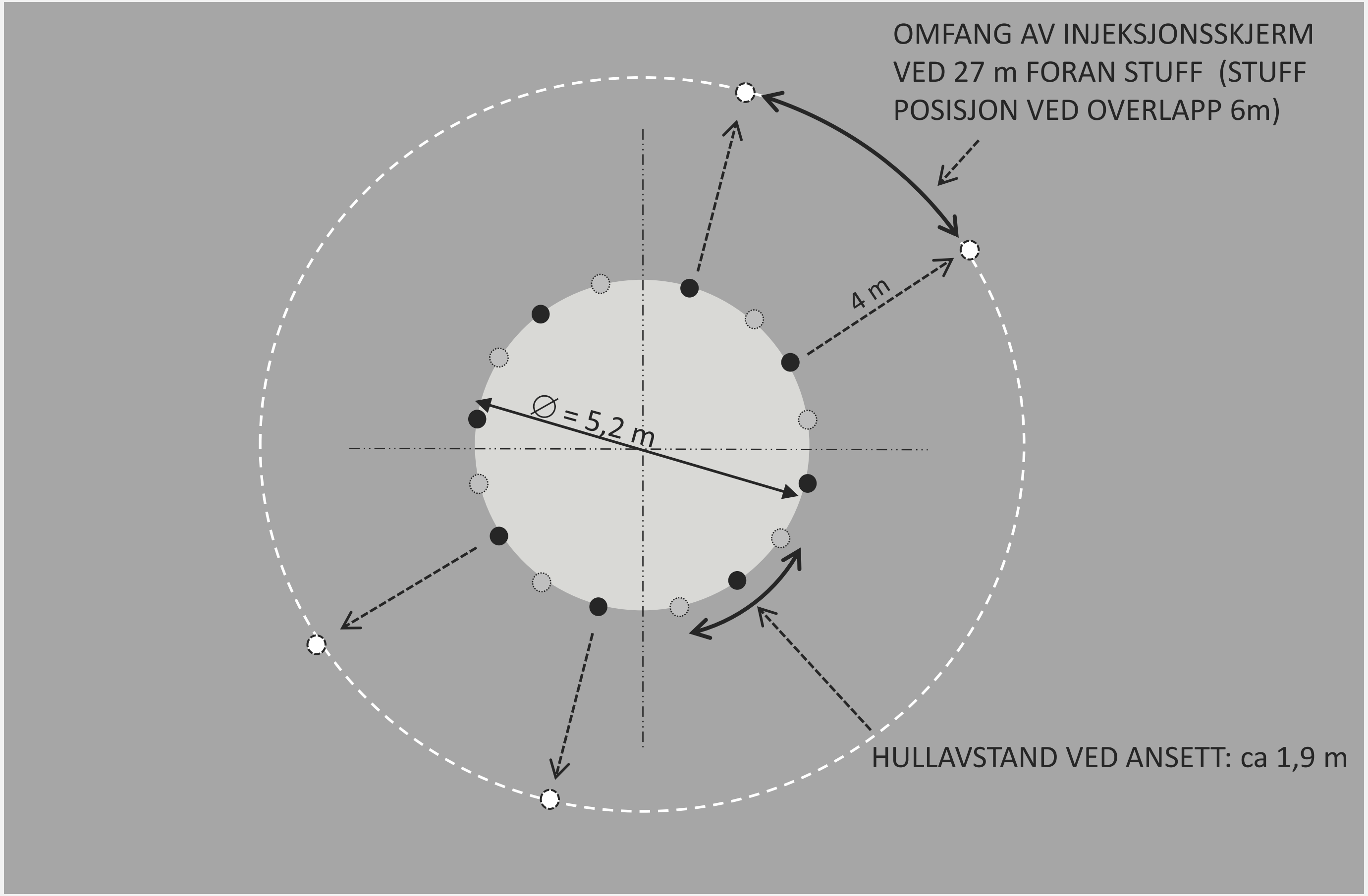
Injeksjonsmetodikk

- Viktig å definere tettemål:
  - Permanent tetting ved forinjeksjon ?
  - Midlertidig tettebehov ved forinjeksjon
  - Ved midlertidig tetting ved forinjeksjon: fokus på behovsprøving **“hvor tett er godt nok”**
- Fokus på redusere stopptid så mye mye som mulig
  - Bruke oppdeling av skjermer når det er hensiktsmessig (primær + sekundærskjermer) spesielt ved større lekkasjer og komplisert hydrogeologi
  - Minst mulig injeksjonsboring og minst mulig masseforbruk for å oppnå planlagt tetteresultat

Injeksjonsmetodikk med oppdeling av skjermer

Eksempel fra Oslo VAV, E5 råvannstunnelen



NGI

Injeksjonsblandinger

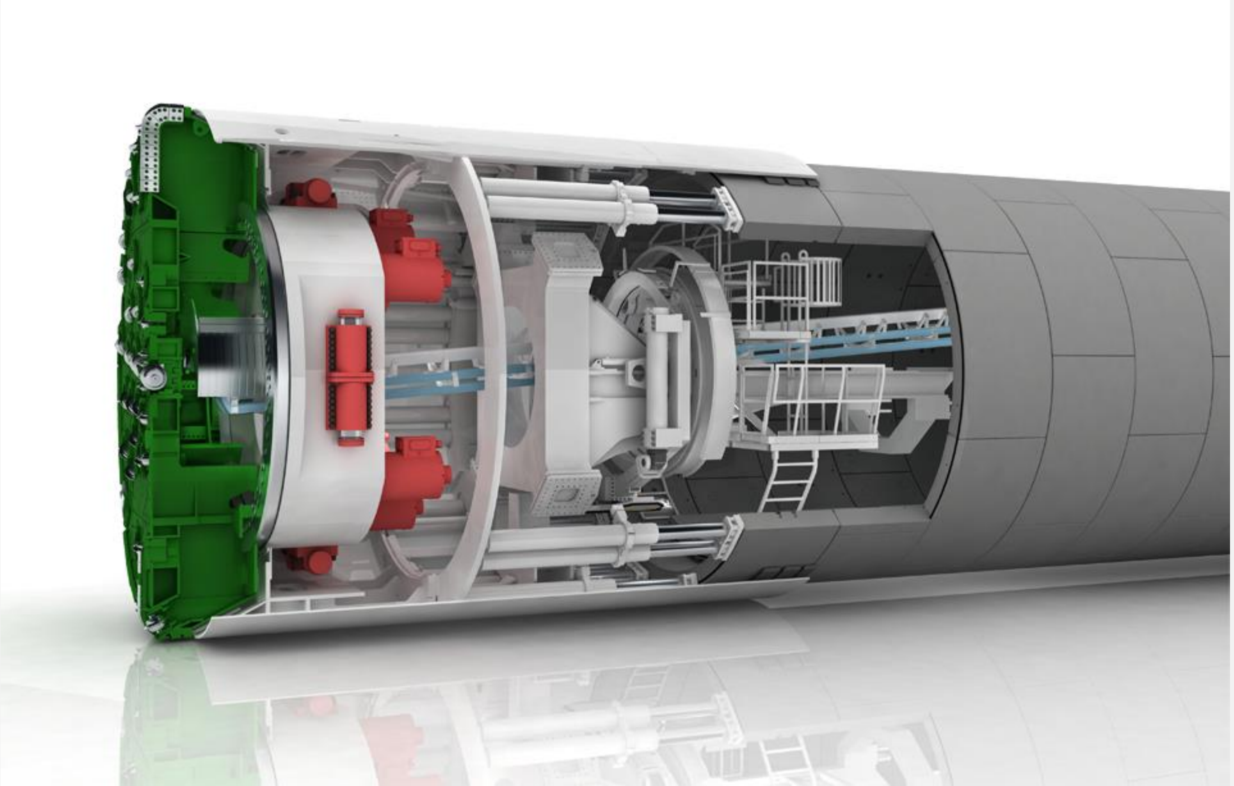
- Fokus på å oppnå tettemål så raskt som mulig
- Teknisk ytelse spesielt viktig
  - Herdetid: rask, men lenge nok “åpen” til at 100-150 m pumpelengde er mulig
  - Herdetid 2-4 timer ofte meget fordelaktig
  - **Spesifikasjon av injeksjonsblandinger og materialer** som gir god nok tetting, og rask herding
  - Raskere herding enn det som har vært tradisjonelt forlangt i Statens Vegvesens og Bane NORs prosesskoder

NGI

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

1c: **Drenert tunnel med betongelementkledning**, med kontrollert innlekkasje av vann

Skjold-TBM med betongelementkledning som punkteres med hull for å tillate en kontrollert innlekkasje



Kilde for grafikk : Herrenknecht AG

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

1c: **Drenert tunnel med betongelementkledning**, med kontrollert innlekkasje av vann

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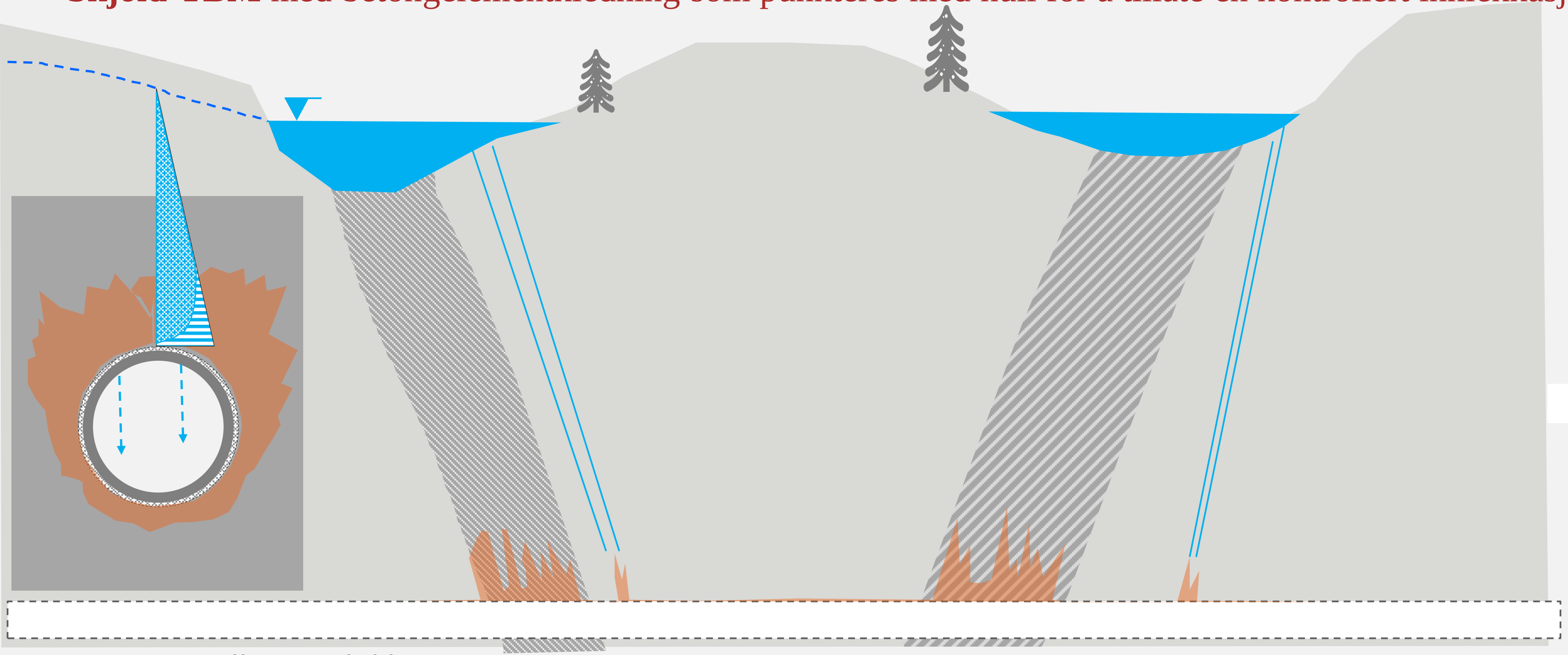
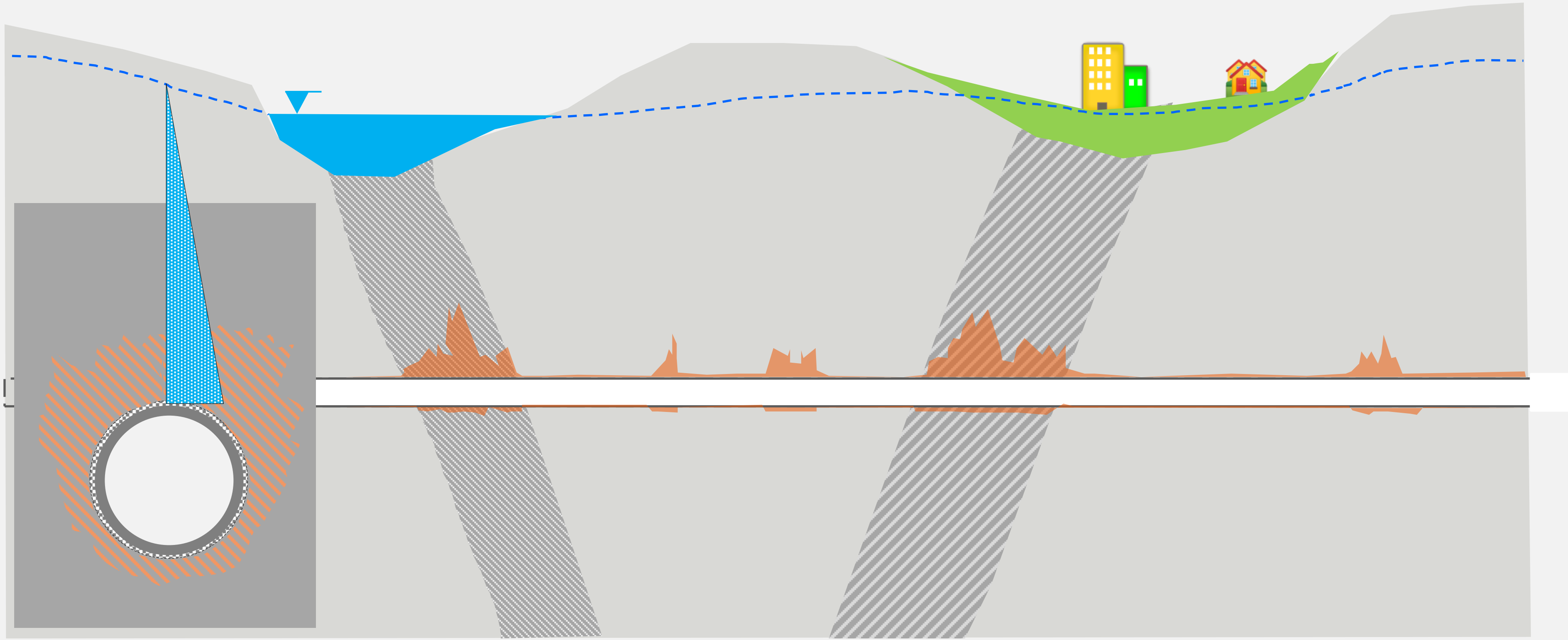


Kontrollert innlekkasje av vann:

- Tettemål basert på (1) driftstekniske forhold på TBM og bygging av kledning og (2) unngå drenering av tjern etc
- Behovsprøvd forinjeksjon for å tette partier bergmassen som kan gi store lekkasjer

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

2: **Vanntett og udrenert tunnel**, med ingen innlekkasje av vann



Ingen innlekkasje av vann i permanent tilstand:

- Behovsprøvd forinjeksjon for å midlertidig tette partier bergmassen med høy permeabilitet
- Endelig tetting av av tunnelen med vanntett betongelementkledning

To hovedtyper tunnelkonstruksjoner med tanke på vannkontroll

2: **Vanntett og udrenert tunnel**, med ingen innlekkasje av vann

Blixtunnelen. Kilde: Bane NOR

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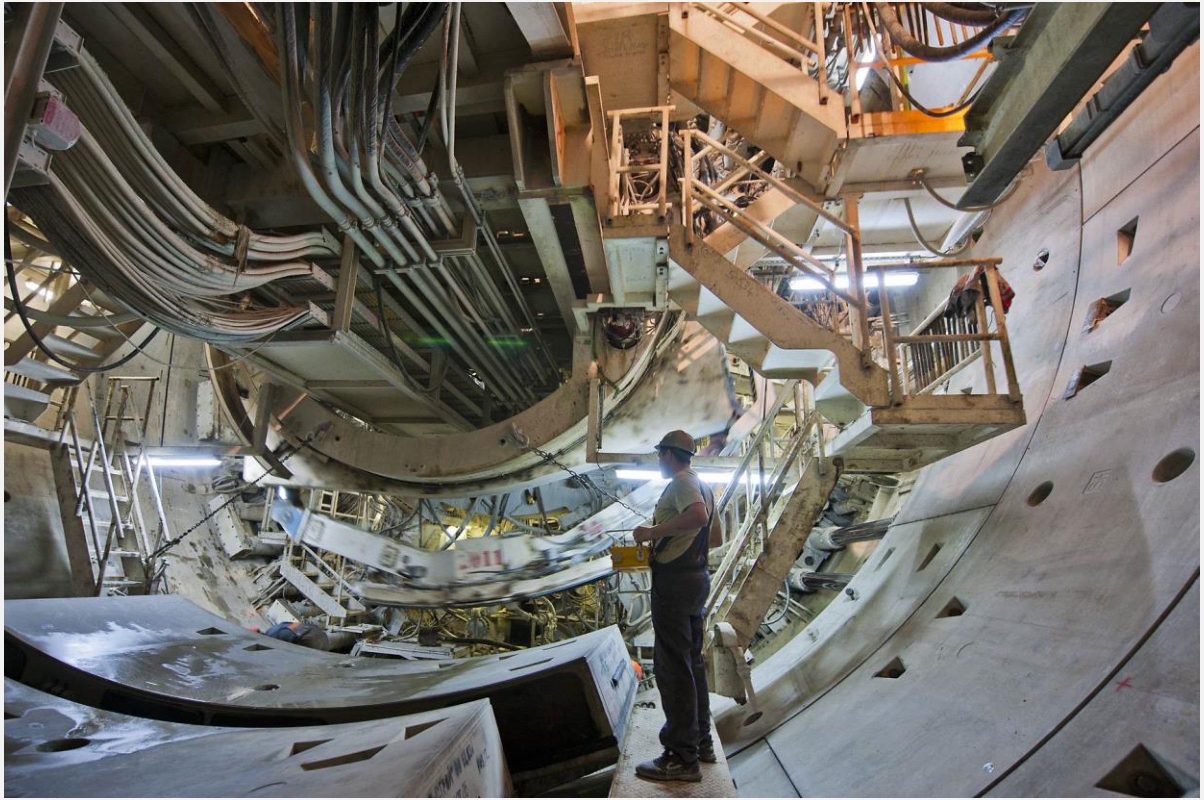
Betongelementkledning, oppbygning og montasje



Betongelementkledning, produksjon av elementer

NGI

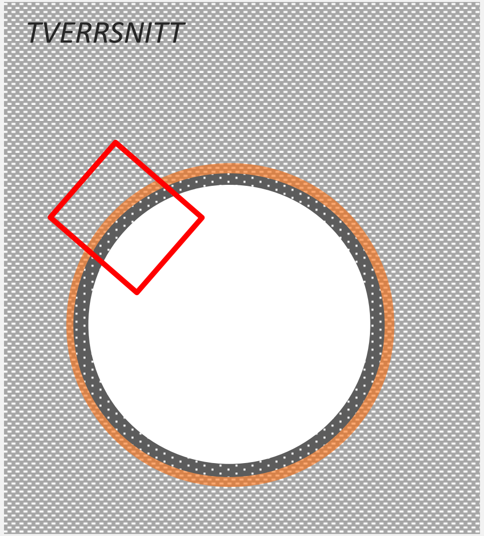
Betongelementkledning, oppbygning

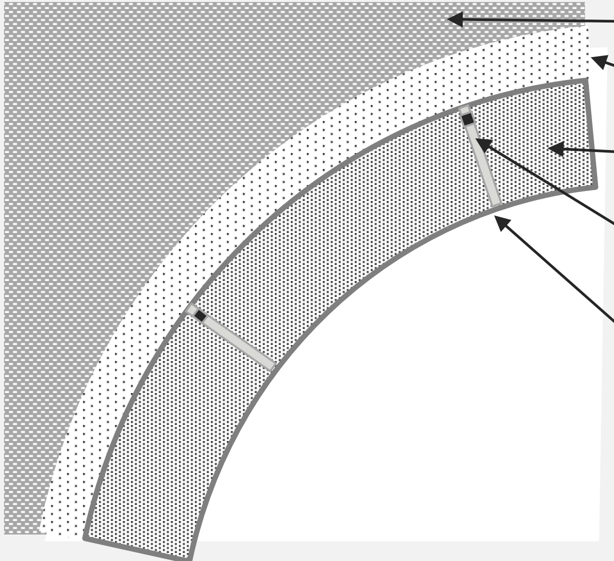
Oppbygning of funksjon

- Betongelementring, statisk og hydrostatisk bærende, vanntett
- Tetningspakninger mellom ringelementene, vanntetting
- Bakfyllmørtel, holder betongringen i stabil posisjon i utboret profil

Potensielle utfordringer

- Betongelementring, stiv konstruksjon, forutsetter tette fuger med noe deformerbarhet
- Krever presis montering av ringene, sårbart for lekkasjer, spesielt ved høyt hydrostatisk trykk
- To-komponent system for bakfyllmørtel mest benyttet: lav fasthet og emodul, sårbart for erosjon/utvasking ved lekkasjer





Vanntett og udrenert betongelementkledning i hardt berg, utfordring:

Blixtunnelen, Bane NOR

Lekkasjer gjennom utettheter i pakningene mellom betongelementene kombinert med frostbelastning

Lekkasjene ble tettet i byggefasen med etterinjeksjon

Blixtunnelen, februar 2021
Kilde for bilde: Aftenposten april 2021

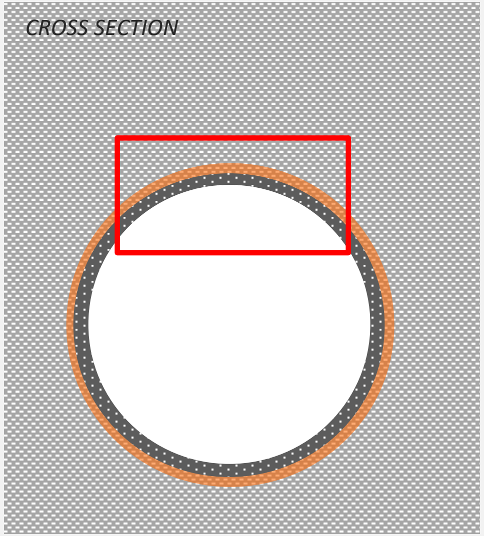
NGI

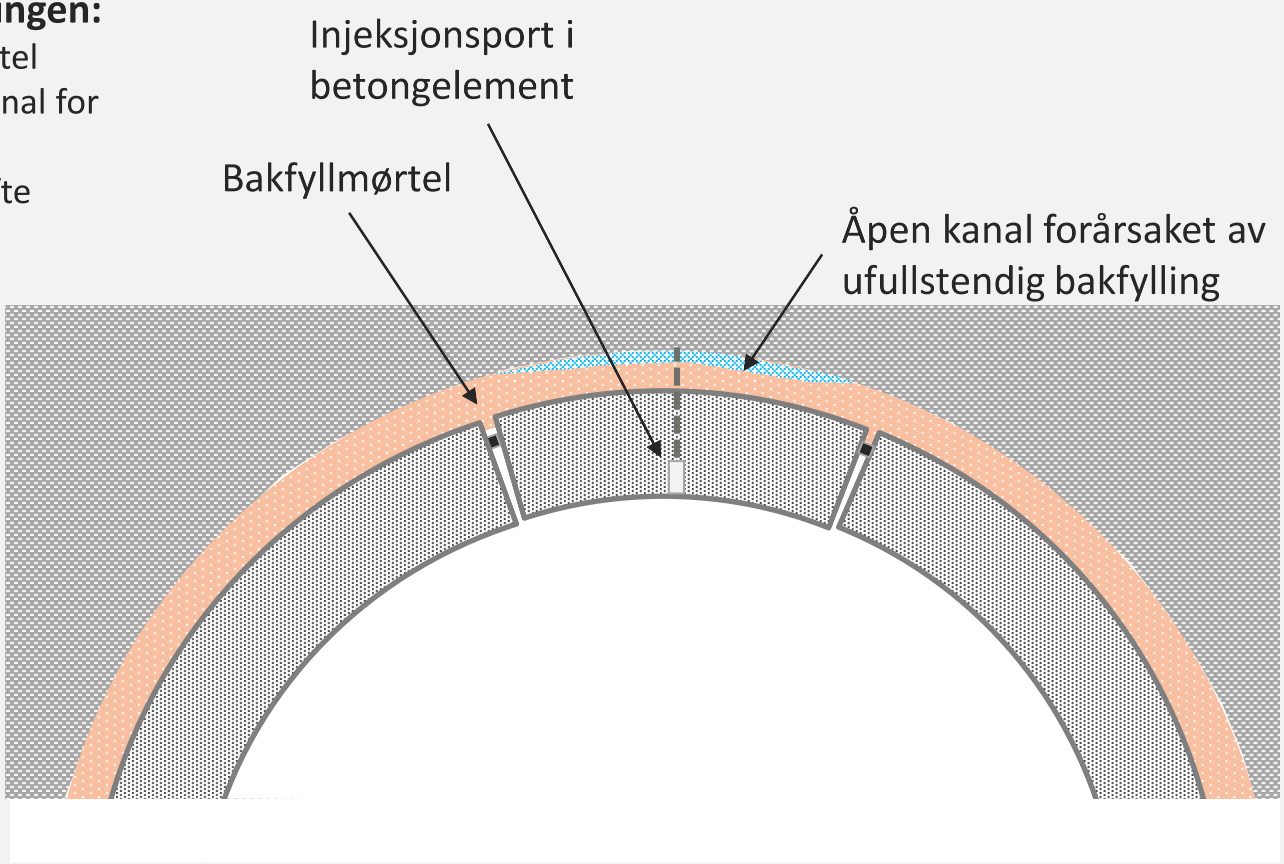
Utfordring: ufullstendig bakfylling av elementkledningen

Områder som krever spesielt fokus:

Hengområde bak betongringen:

- Ufullstendig fylling av mørtel
- Representerer en mulig kanal for vannstrøm
- Tertiær injeksjonsrunde ofte nødvendig





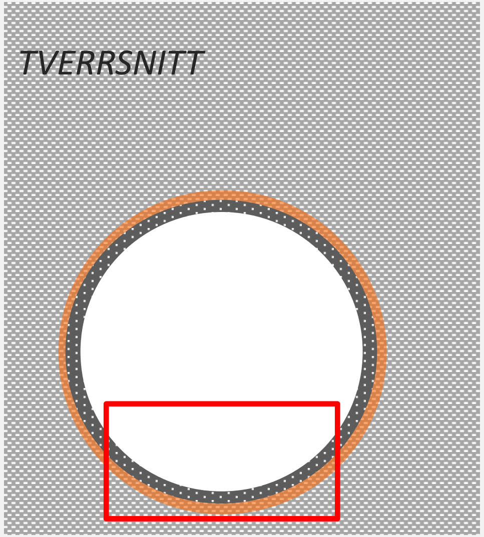
Utfordring: ufullstendig bakfylling av elementkledningen

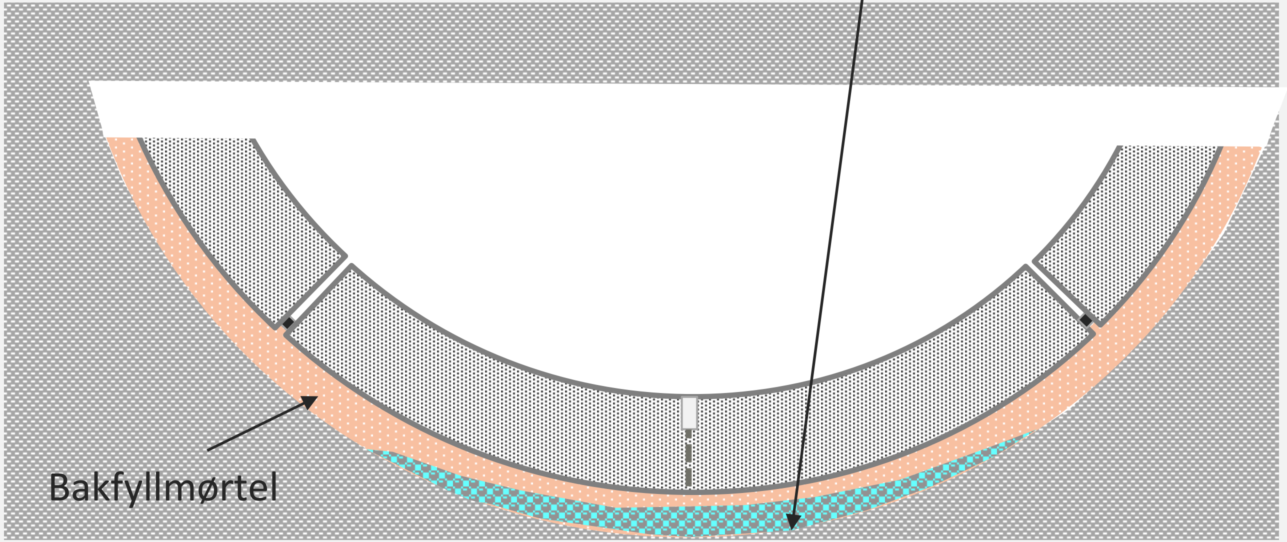
Områder som krever spesielt fokus:

Såleområdet:

- Kaks fra injeksjonsboring = permeabelt lag
- En potensiell kanal for langsgående lekkasje
- Tertiær injeksjonsrunde kan være nødvendig

Kaks fra injeksjonsboring
Kan forårsake ufullstendig
fylling av mørtel

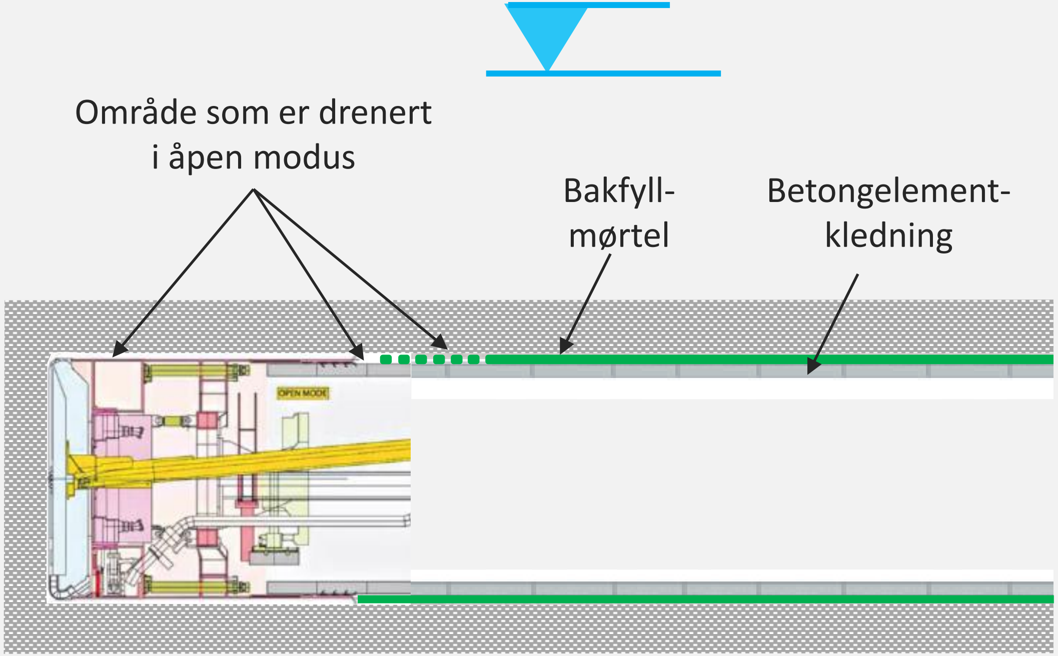




Hvorfor behov for forinjeksjon når det bygges tett kledning

Skjold TBM i åpen modus
= midlertidig drenert

- TBM borhode og fremre del av kledning drenert
- Boring og bygging av elementkledning skjer i drenert situasjon
- Drenert situasjon strekker seg bakover langskledning helt til fullstendig bakfylling er oppnådd
- Hydrostatisk trykk kan gi en trykkgradient og forårsake en vannstrøm i bakfyllingen langs tunnelen fremover mot TBM
- Derfor: behov for å redusere innlekkasjer for å vannstrøm langs tunnelkledning



Kilde for grafikk: Herrenknecht AG

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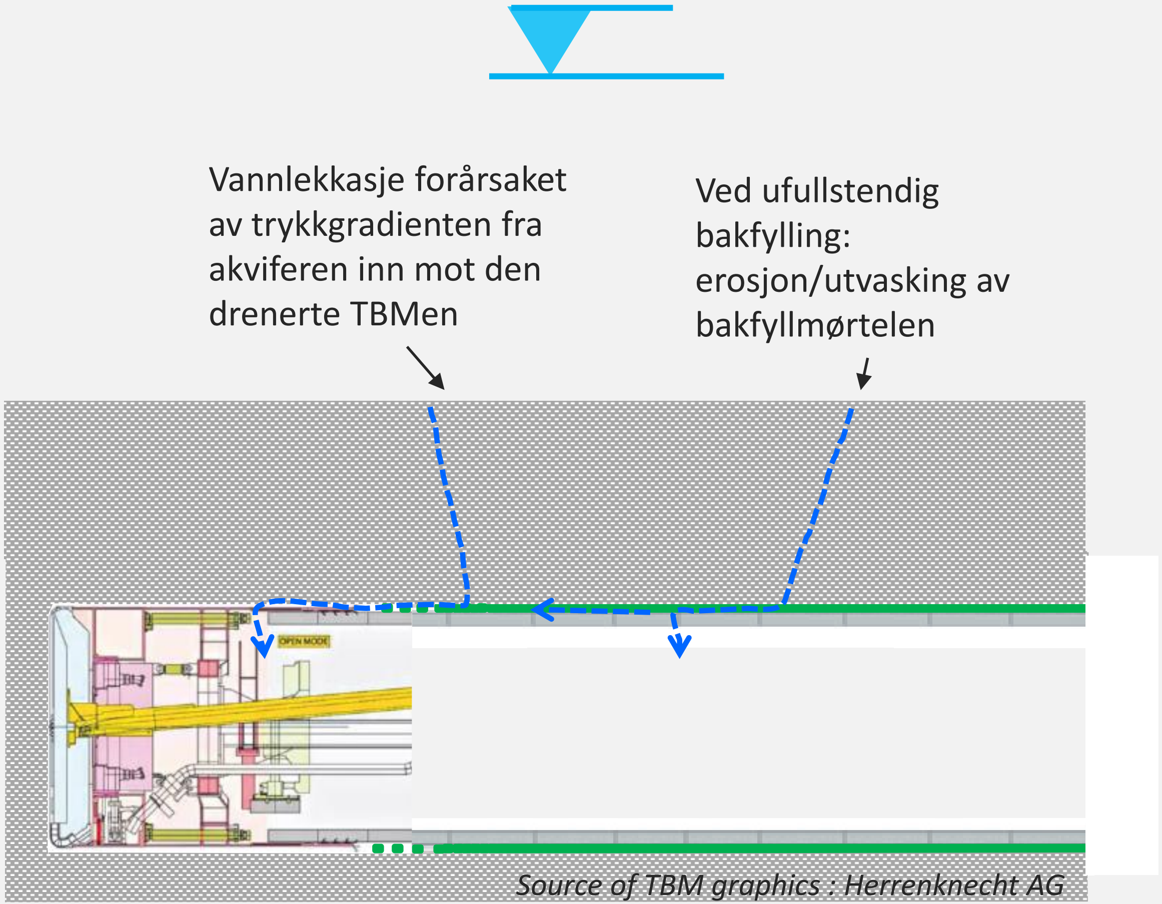
Hvorfor behov for forinjeksjon når det bygges tett kledning

Skjold TBM i åpen modus
= midlertidig drenert

- Svært viktig å lykkes med fullstendig bakfylling
- Metoder for å løse utfordringene må være på plass



Source of TBM graphics : Herrenknecht AG

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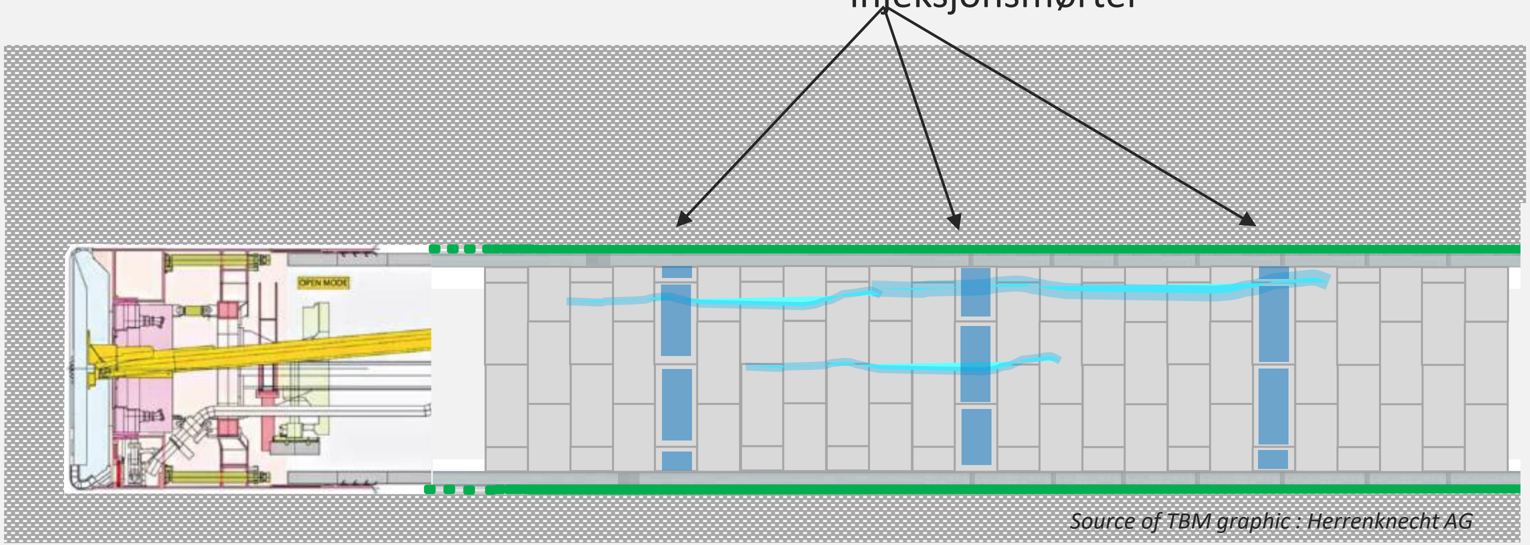
TBM betongelementkledning, redusere vannstrøm bak betongringen

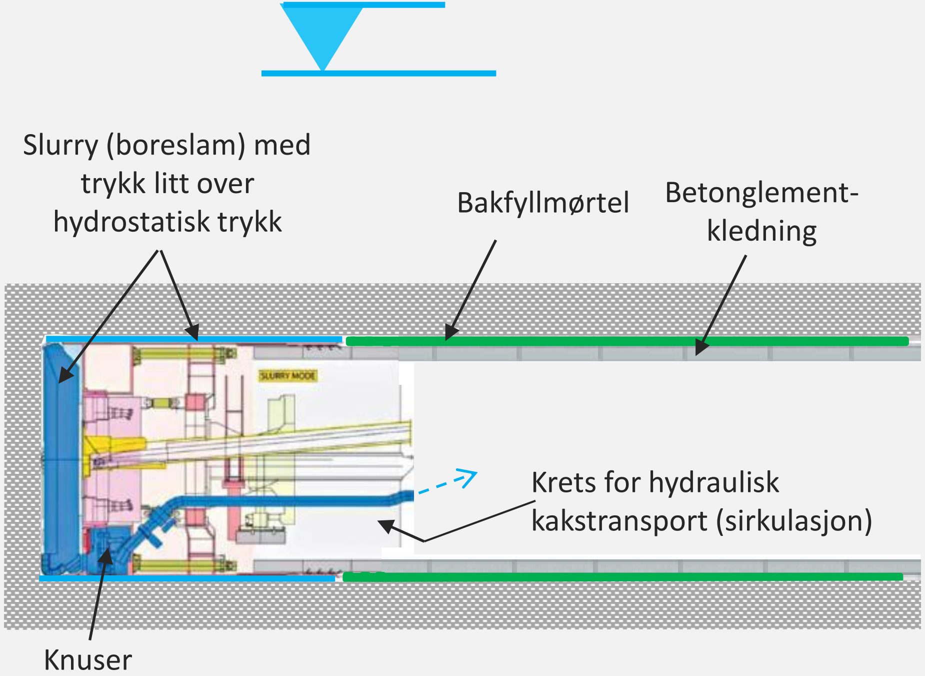
BullFlex ekspanderbare puter som fylles, «blåses opp» med en injeksjonsmørtel



Slurry TBM: boring i likevekt med hydrostatisk trykk.
Intet midlertidig tettebehov under boring og betongelementbygging

Lukket modus

- Borhodet er konstruert for operere med et borslam som fyller hele fremre del av borhodet og utsiden av skjoldet
- Pumpingen av bakfyllmørtel skjer i trykklikevekt med borslammet
- Hele TBM-systemet står derfor under et hydraulisk trykk som hindrer en drenering rundt borholdet
- Grunnvannsakviferen påvirkes ikke, ingen trykkgradient, ingen vannstrøm langs betongkledningen



Kilde TBM grafikk: Herrenknecht AG

TBM in unstable ground:

Unfavorable conditions may lead to collapse over shield and formation of a void
Grouting for void filling and temporary stabilisation

Void filling over TBM

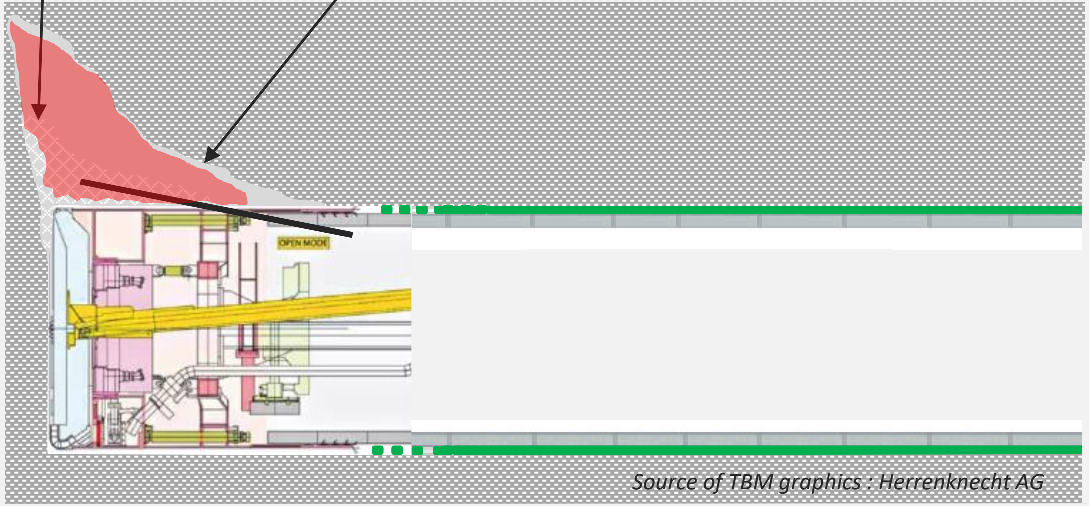
- Might be necessary as a temporary stabilisation solution over the TBM shield
- Purpose : void the void and prevent further collapse
- Temporarily increase the stability of the collapsed debris in order to enable the further advance of the TBM

Injection material technology:

- Cementitious and PU grouts tend to form too high mechanical strength and may cause jamming of parts in the TBM cutterhead
- Mineral based foam (polyureasilicate) will will form low enough strength too avoid difficulties in the TBM
- Strength is high enough to provide halting of the collapse and sufficient consolidation of the debris to enable TBM advance

Void with collapsed ground debris

Grouting of void area with a mineral expanding foam (**polyureasilicate foam** ideal)



Noen utvalgte referanseprosjekter

- VEAS avløpstunneler Oslo, 1977-1979
- Kárahnjúkar HEPP vannøverføringstunneler, Island, 2005-2009
- Arrowhead vannoverføringstunnel, California USA, 2008-2009
- Vanntunnel, Ny Vannforsyning Oslo, 2023-2027

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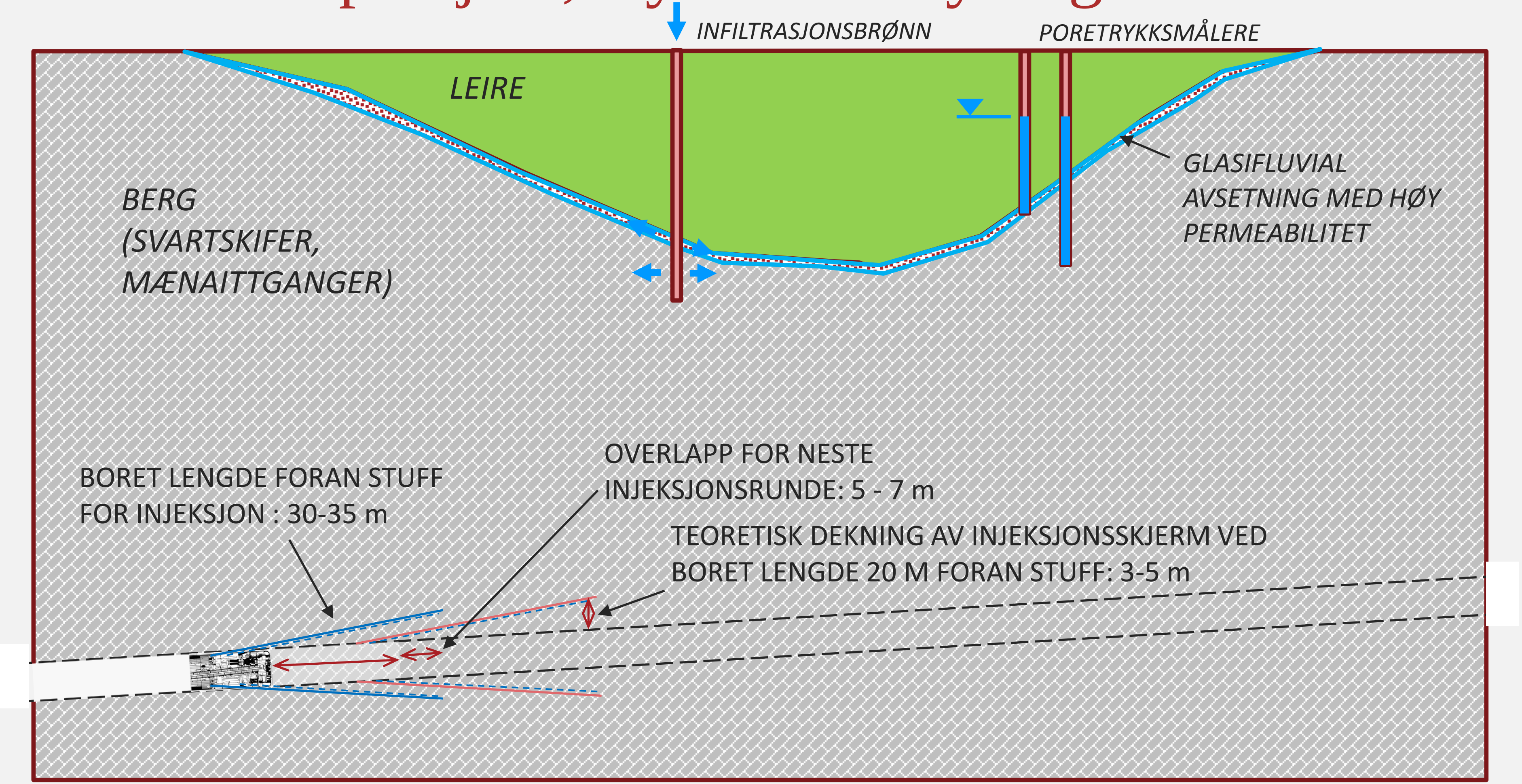
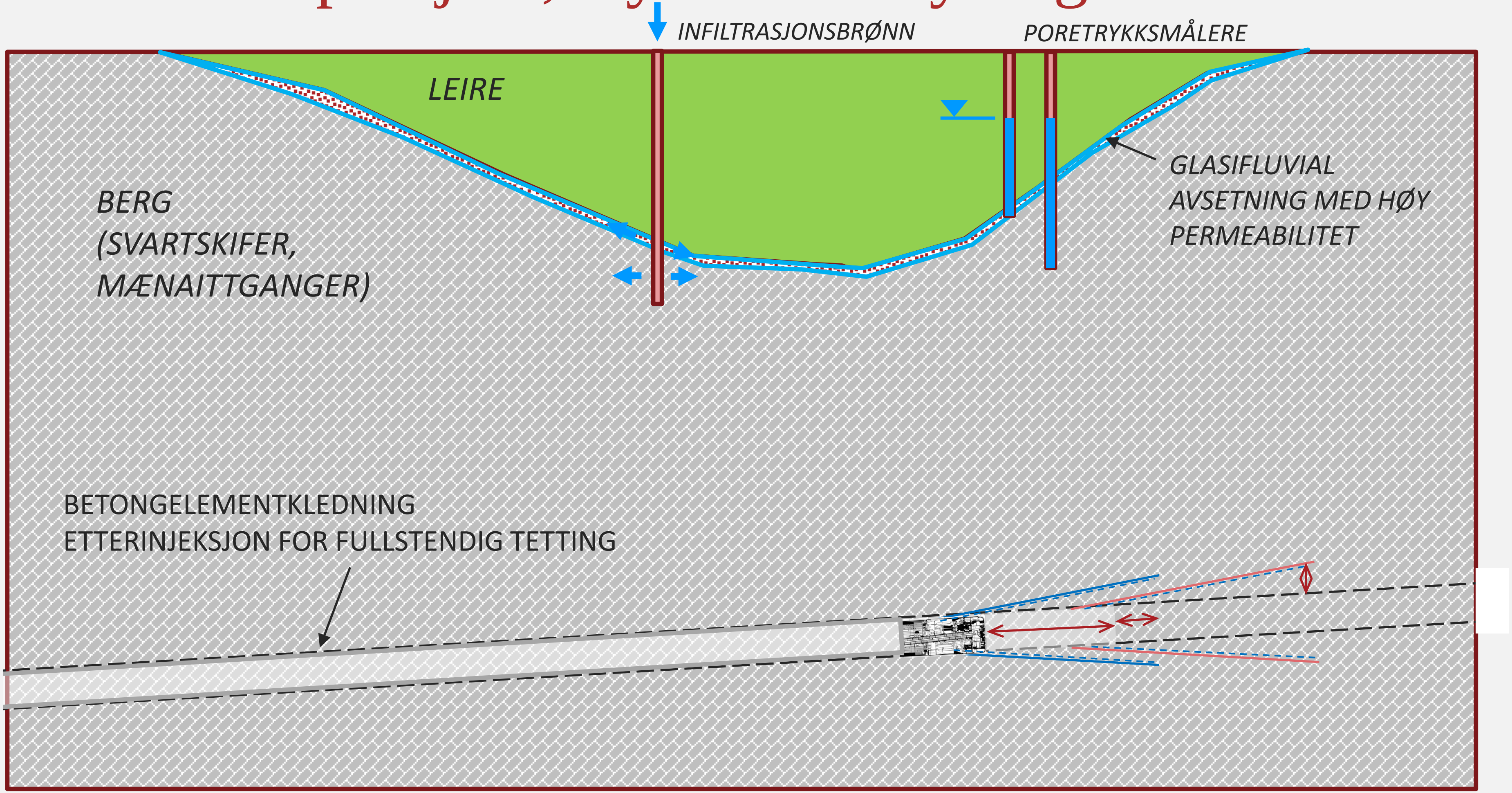
Referanseprosjekt, Ny Vannforsyning Oslo

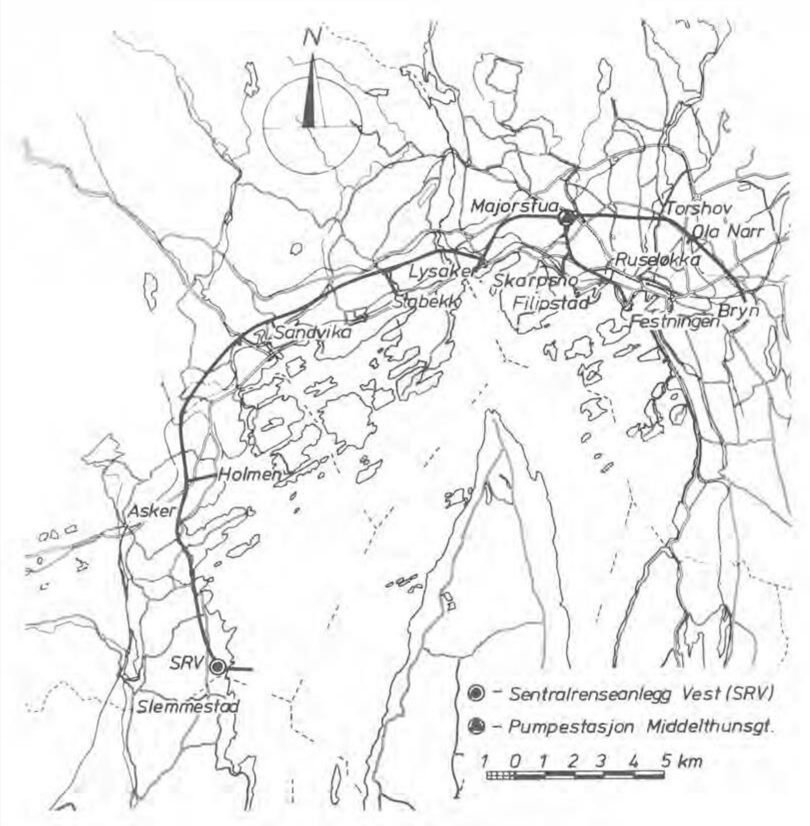


Referanseprosjekt, Ny Vannforsyning Oslo



Referanseprosjekt VEAS avløpstunneler Oslo, 1977-1979

- Viktig pilotprosjekt for TBM boring i sensitive urbane strøk med omfattende forinjeksjon
- Flere store enterpriser
- Meget gode erfaringer med forinjeksjon
- Kombinasjon normalsement og kjemisk (silikat-baserte injeksjonsmaterialer)
- Noe etterinjeksjon nødvendig
- Endelige lekkasjer 1-2 l/min/100m



Asting et. al 1980

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Referanseprosjekt VEAS avløpstunneler Oslo, 1977-1979

- Flere store enterpriser

Entreprise	Utsprengte tunneler	Borede tunneler	
		Type TBM	Tunnel-lengder
FESTNINGEN FILIPSTAD Entreprenør: Astrup & Aubert	1360 m		
OSLO SENTRUM Entreprenør: Astrup & Aubert U. entreprenør injeksjonsarb.: Entreprenørservice A/S	510 m	2 stk. Bouygues D = 3,0 m	10770 m
MAJORSTUA – FRANTZEBRÅTEN Entreprenør: Dipl. ing. Kaare Backer A/S & Co.	670 m	Robbins D = 3,15 m	4180 m
LYSAKER – SANDVIKA Entreprenør: A/F Høyer- Ellefsen/Murer	230 m	Wirth D = 3,35 m Atlas Midifaser 2,1x3,14m	8510 m 1000 m
SANDVIKA – SRV Entreprenør: A/F Furuholmen/ Prader	800 m	2 stk. Robbins D = 3,5 m	14200 m
Samlede tunnellengder	3570 m		37660 m

Asting et. al 1980

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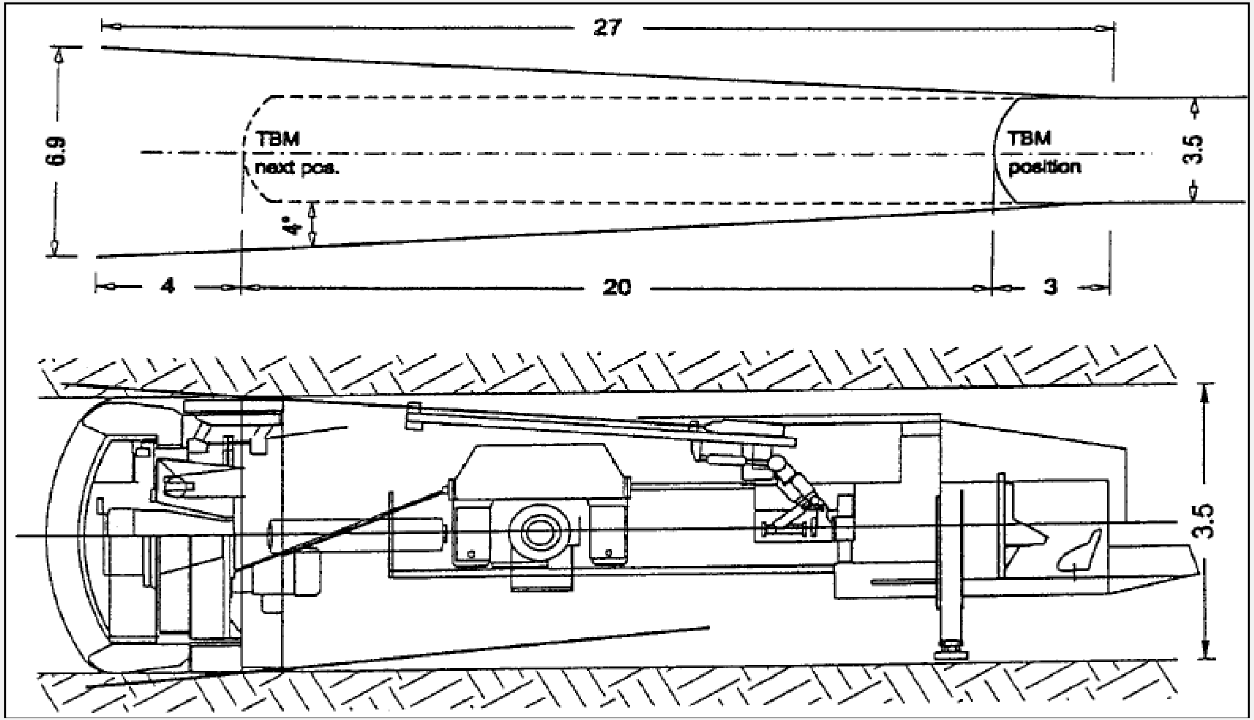
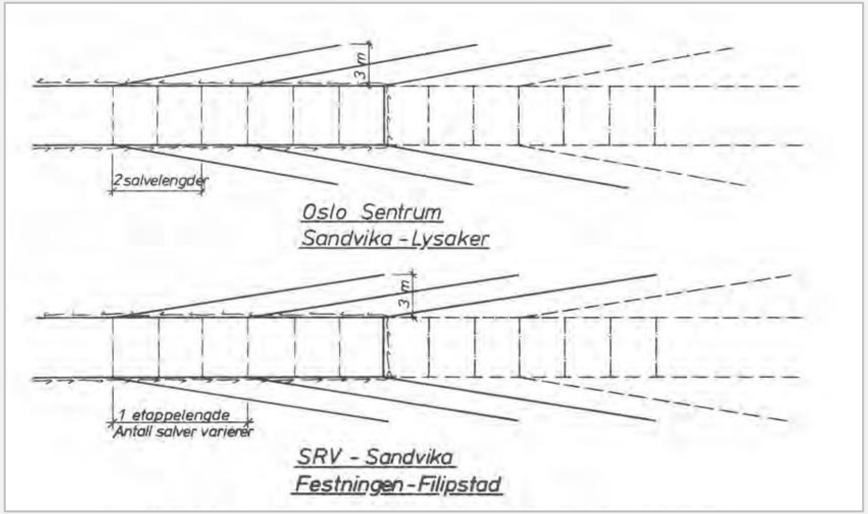
Referanseprosjekt VEAS avløpstunneler Oslo, 1977-1979

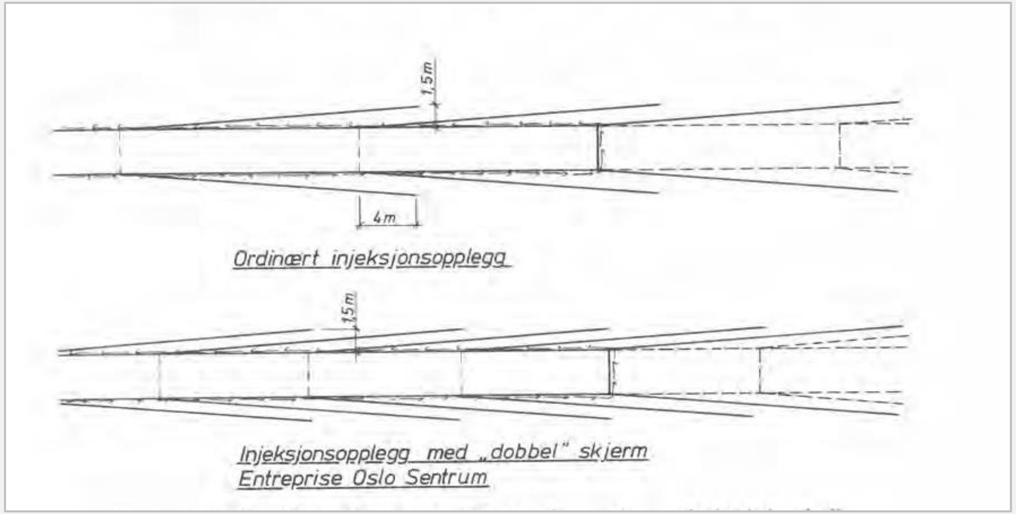
- Konfigurasjon av Robbins TBM , Prader-Furuholmen



Garshol, 1981

Referanseprosjekt VEAS avløpstunneler Oslo, 1977-1979





Asting et. al 1980

Konfigurasjon av injeksjonsskjermer for sprengte tunneler

Konfigurasjon av injeksjonsskjermer for TBM borede tunneler

NGI

Referanseprosjekt VEAS avløpstunneler Oslo, 1977-1979

Fra inspeksjon i VEAS tunneler i 2022

Foto: M. Stormoen, Oslo VAV

Synlig fylling av kjemisk injeksjonsmasse, sannsynligvis silikat.

NGI

Referanseprosjekt Kárahnjúkar HEPP, Island 2005 - 2009

- Ca 60 km vannoverføringstunneler
- 3 stk Robbins gripper TBM diam ca 7 m
- Hovedentreprenønør Impregilo (Italia)
- Kinesisk arbeidskraft på tunnelarbeider
- TBMer var forberedt for forinjeksjon med porter gjennom takskjold, utrustning for langhullsboring ble montert og injeksjonsrigg montert på vagg

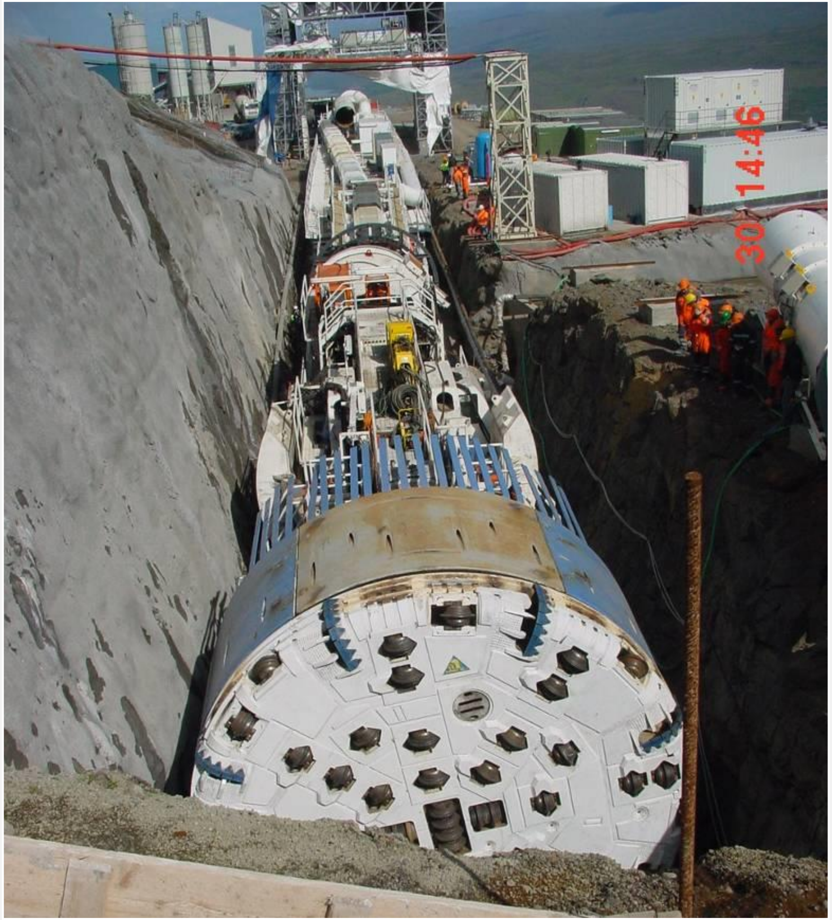


Foto: *Impregilo S.p.A.*

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Referanseprosjekt Kárahnjúkar HEPP, Island 2005 - 2009

- Vann påtruffet i betydelig omfang,
- Punktlekkasjer på opptil 50 l/s
- Entreprenør ikke insentivert til å utføre effektiv forinjeksjon
- Uenighet mellom byggherren Landsvirkjún og hovedentreprenøren Impregilo om håndtering av vann
- Entreprenør prioriterte fremdrift, og drev gjennom lekkasjene uten å injisere tilstrekkelig

Foto: Impregilo S.p.A.

Referanseprosjekt Kárahnjúkar HEPP, Island 2005 - 2009

- Betydelig etterinjeksjonsjobb med PU
- Lekkasjer kun delvis redusert
- Byggherren fikk merkostnaden

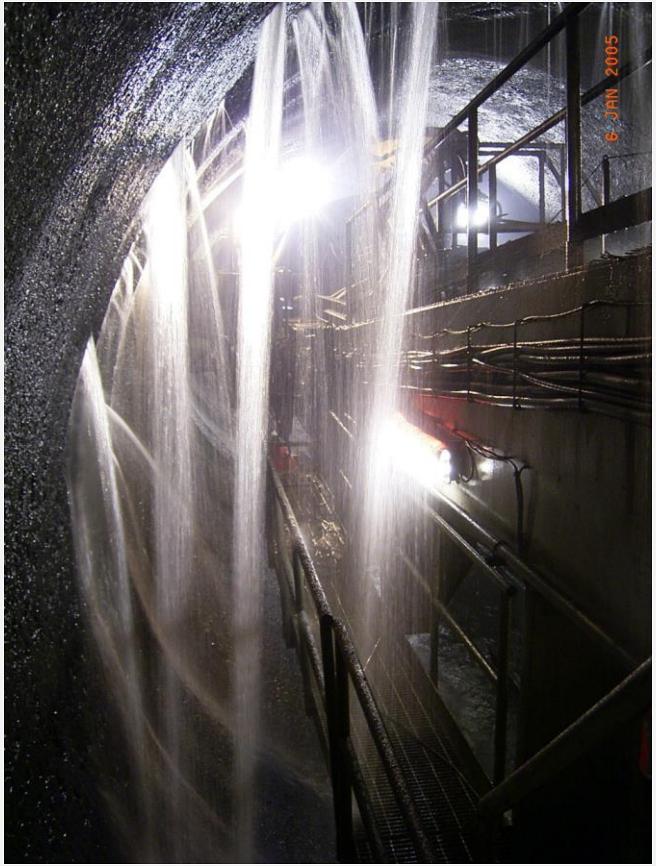
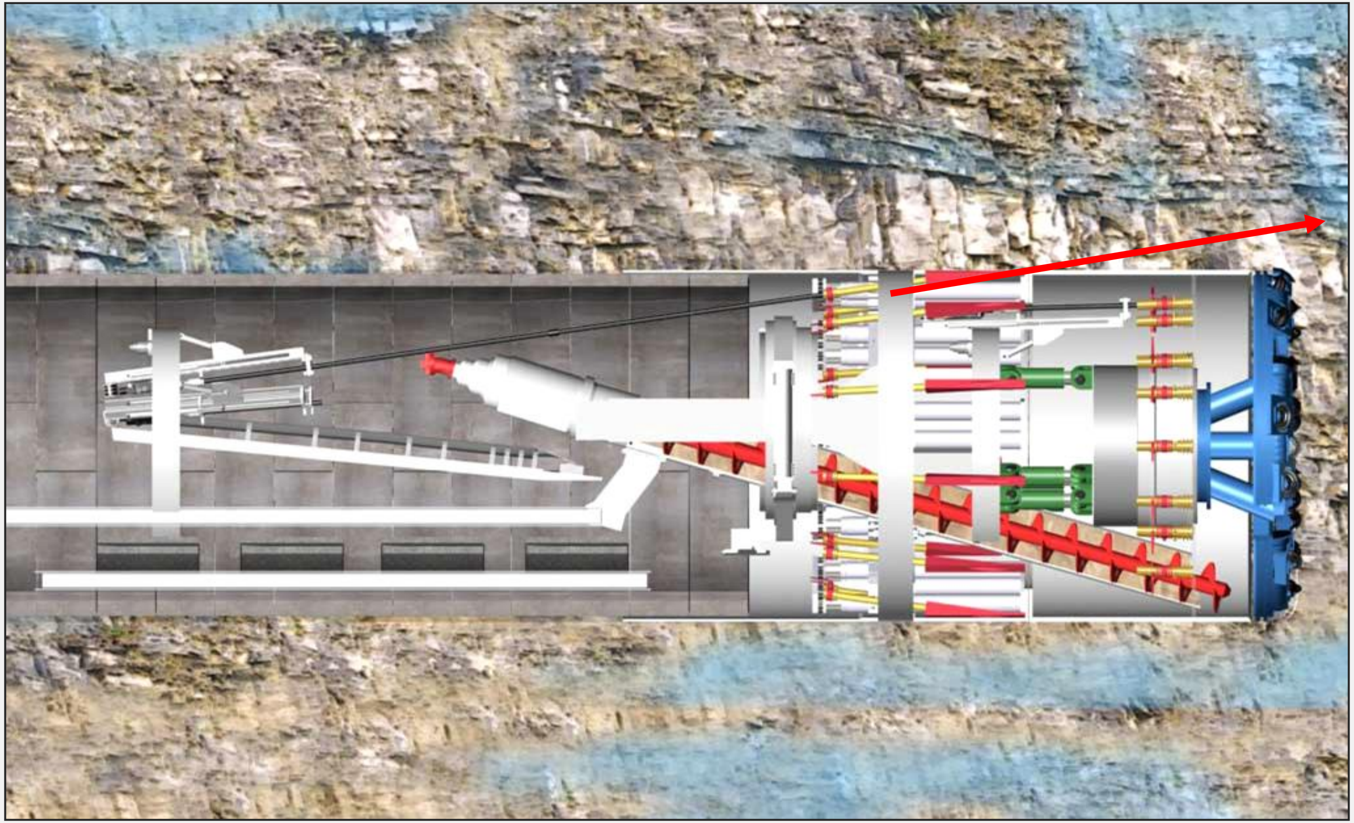


Foto: Impregilo S.p.A.

Arrowhead water tunnel, San Bernardino, CA

- Vann i bergmassen forventet i stort omfang
- Sedimentære bergarter med horisonter av permeabel sandstein
- "Running ground" i sandstein med hydraulisk grunnbrudd
- Inj opplegget måtte tilpasses
- Suksessfaktor: samarbeid entreprenør - byggherre



K. Garshol

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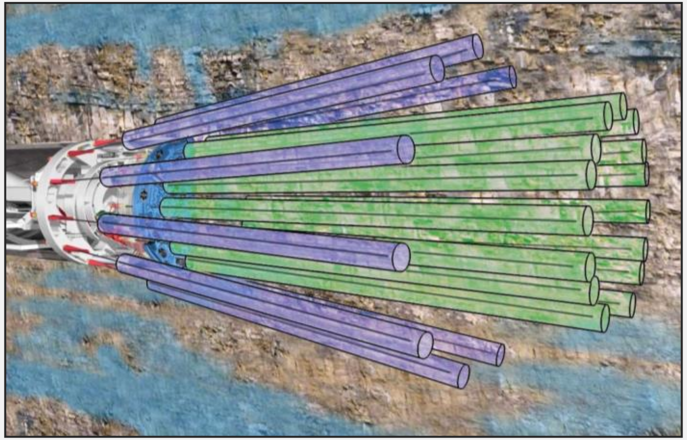
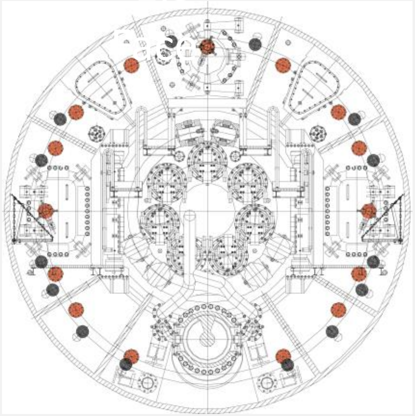
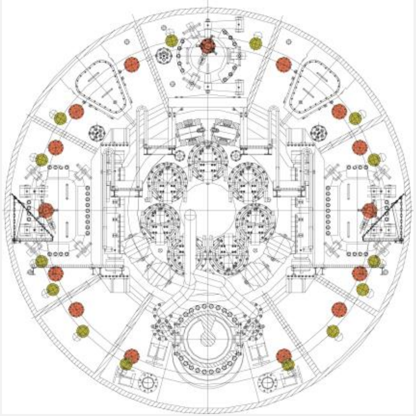
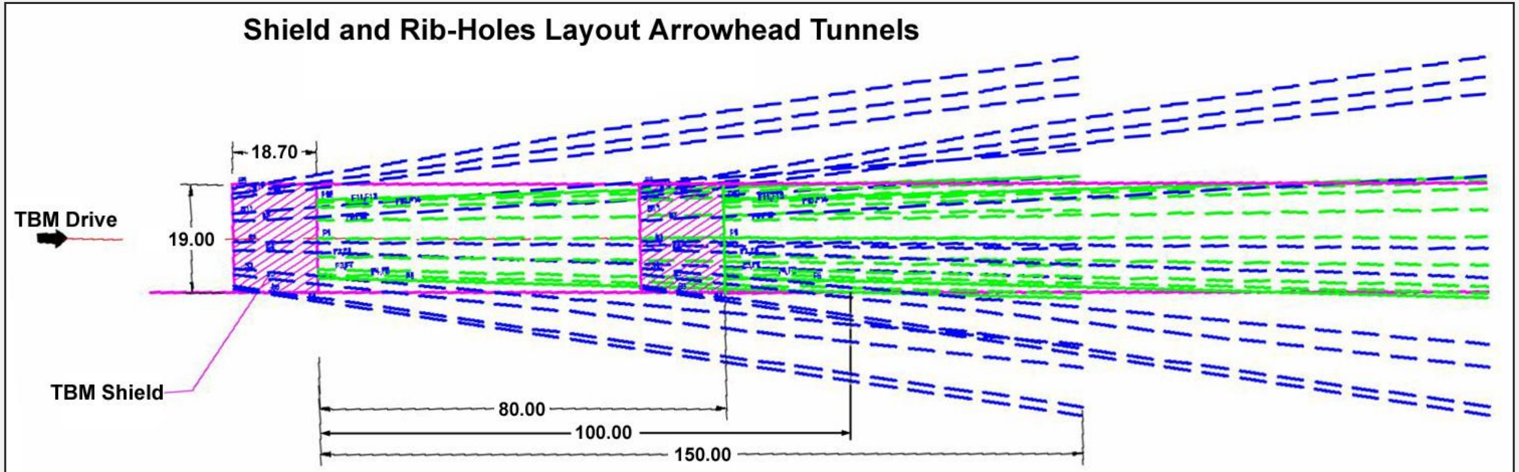
Arrowhead water tunnel, San Bernardino, CA









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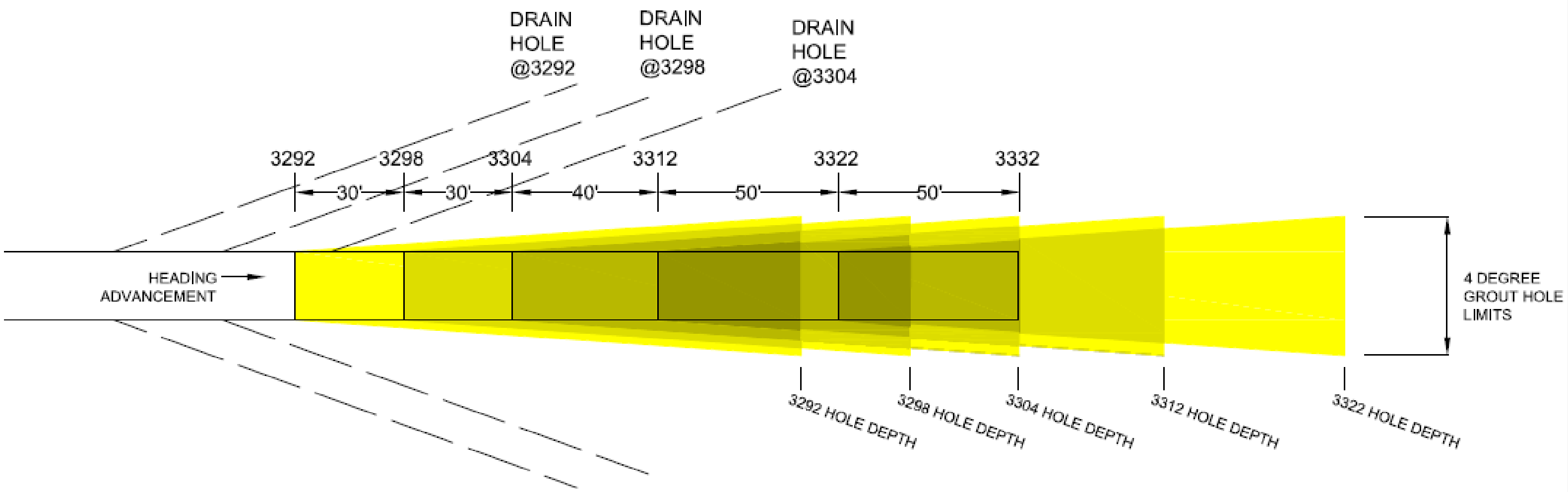
Arrowhead water tunnel, San Bernardino, CA

ARROWHEAD EAST TUNNEL PRE-EXCAVATION GROUTING
RINGS 3292 TO 3322



Ring	3292	3298	3304	3312	3322
Max. Hole Inflow (gpm)	220	20	38	32	42
Max. Backpressure (psi)	275	200	160	120	140
No. of grout holes	17	6	14	8	11
Hole Depth (ft)	140-150	140	140	140	140
Footage Drilled (incl. re-drill)	11,158	1,055	2,360	1,120	2,076
Cement Grout (lb)	358,979	5,746	26,051	2,735	4,777
Colloidal Silicate (gal)	19,125	24,759	14,663	11,255	12,565
Number of Drain Holes	2	2	1	0	0
Time (days)	22 (4 cs only)	6	5.5	4	3

1 x GROUT COVERAGE
2 x GROUT COVERAGE
3 x GROUT COVERAGE
4 x GROUT COVERAGE

K. Garshol

Arrowhead water tunnel, San Bernardino, CA

- Kreativ praktisk løsning for instøpte foringsrør av PVC i svak ustabil bergmasse
- “Bagpacker” foringsrør
- Entreprenørens praktiske kreativitet

K. Garshol

NGI

Oppsummering

- Konseptet for midlertidig og permanent vannkontroll må defineres nøye
- Forinjeksjonsarbeider er mer kompliserte og betydelig dyrere i TBM-sammenheng enn sammenliknet med B&S
- Fokus på behovsprøving og effektiv metodikk for å bruke minst mulig tid og ressurser på injeksjon
- Samarbeid og konstruktiv dialog mellom byggherre og entreprenør helt vesentlig for å lykkes

NGI

NORSK BERGMEKANIKKGRUPPE

Time, tunnel length, geology – therefore Q_{tbm}

Nick Barton

Nick Barton & Associates Rock Engineering
www.nickbarton.com

1. **PARAMETERS:** ***PR, AR, U, T and links to Q***

2. **CUTTER FORCE VERSUS ROCK MASS STRENGTH**

3. **CASE-RECORD SURVEY for (mostly) OPEN-GRIPPER**

4. **WORLD-RECORD TBM PERFORMANCES**

5. **TBM DELAYS IN FAULT ZONES**

6. **DECELERATION (-m) ACCENTUATED IN FAULT ZONES**

7. **IS IT CORRECT TO USE TBM: *'BECAUSE the TUNNEL IS SO LONG'?***

8. **IS IT CORRECT TO USE TBM: *'BECAUSE CONDITIONS WILL BE BAD'?***

9. **Q_{TBM} PROGNOSIS DEVELOPMENT: Q WITH MACHINE-ROCK INTERACTION**

10. **APPLICATION OF Q_{TBM} AT FOLLOBANEN (2009) and 2018**

1. PARAMETERS: *PR, AR, U, T and links to Q*

***PR** m/hr, **P**ENETRATION **R**ATE with continuous boring*

***AR** is actual TBM **A**DVANCE **R**ATE*
e.g. m/week, m/month, m/year). (24hours not so interesting)

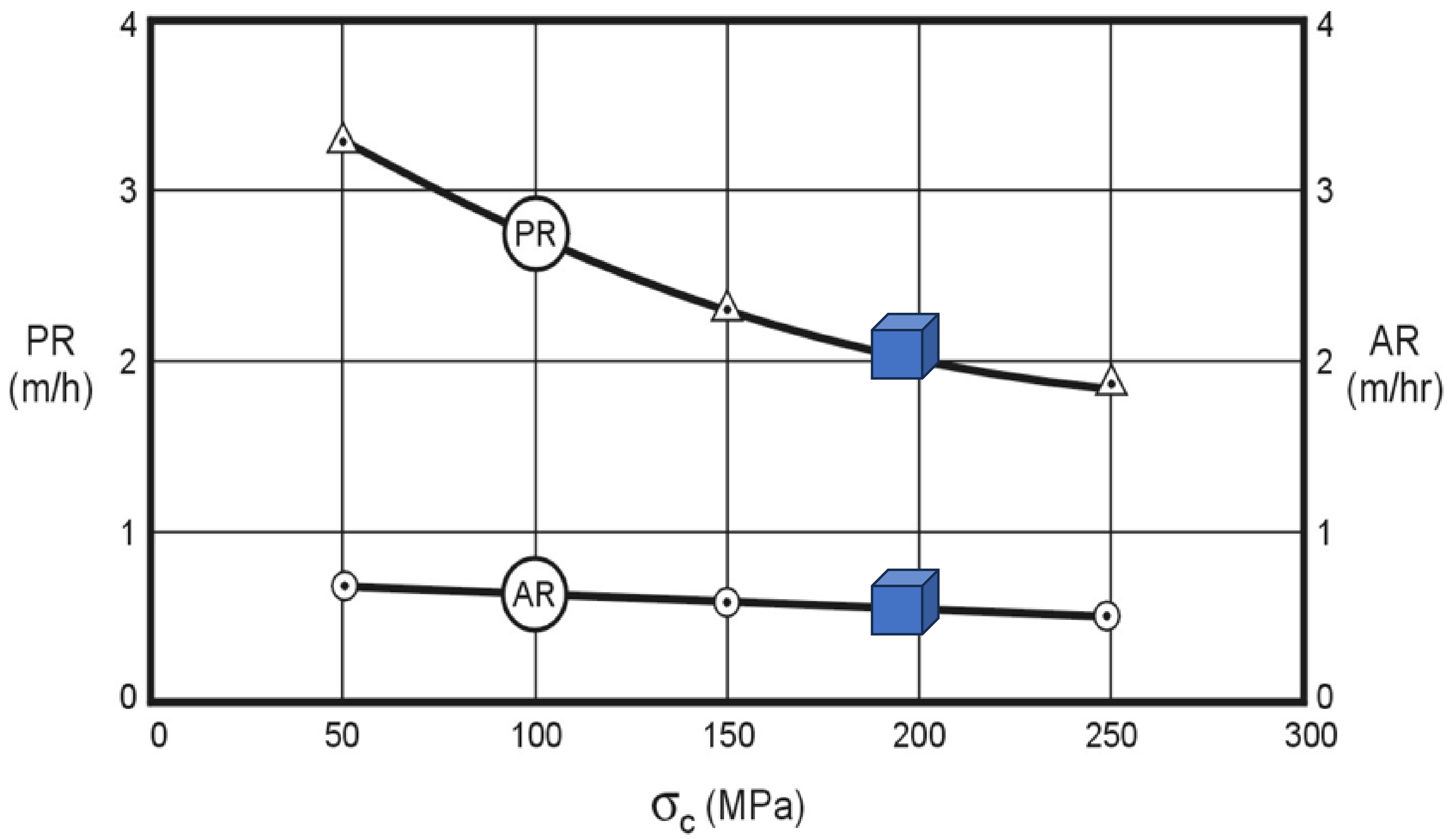
U is utilization (depends on machine-type, diameter, geological conditions and on TIME)

***T** is total time: 24hrs, 168hrs, 730hrs, 8730 hrs, etc*

*HINT: if each **AR** period is given in **m/hr** the influence of **TIME and TUNNEL LENGTH can be better** understand*

Shale, tillite, sandstone: σ_c = 50, 150, 250 MPa

(Fawcett, 1993 data: plotted as here in Barton, 2000 book)

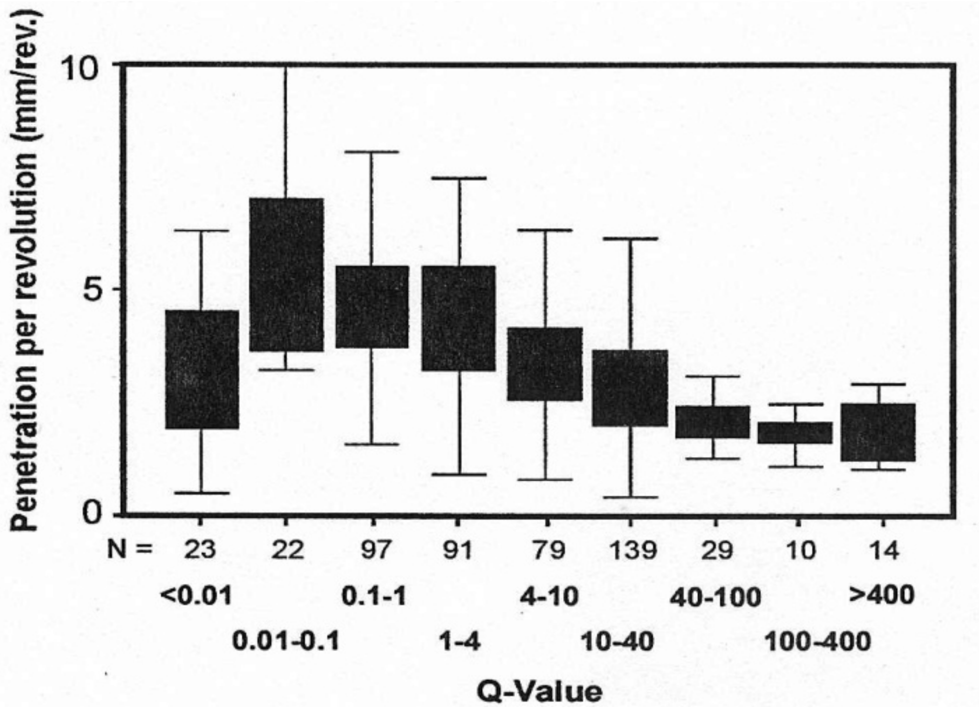


AR = PR x U (?)

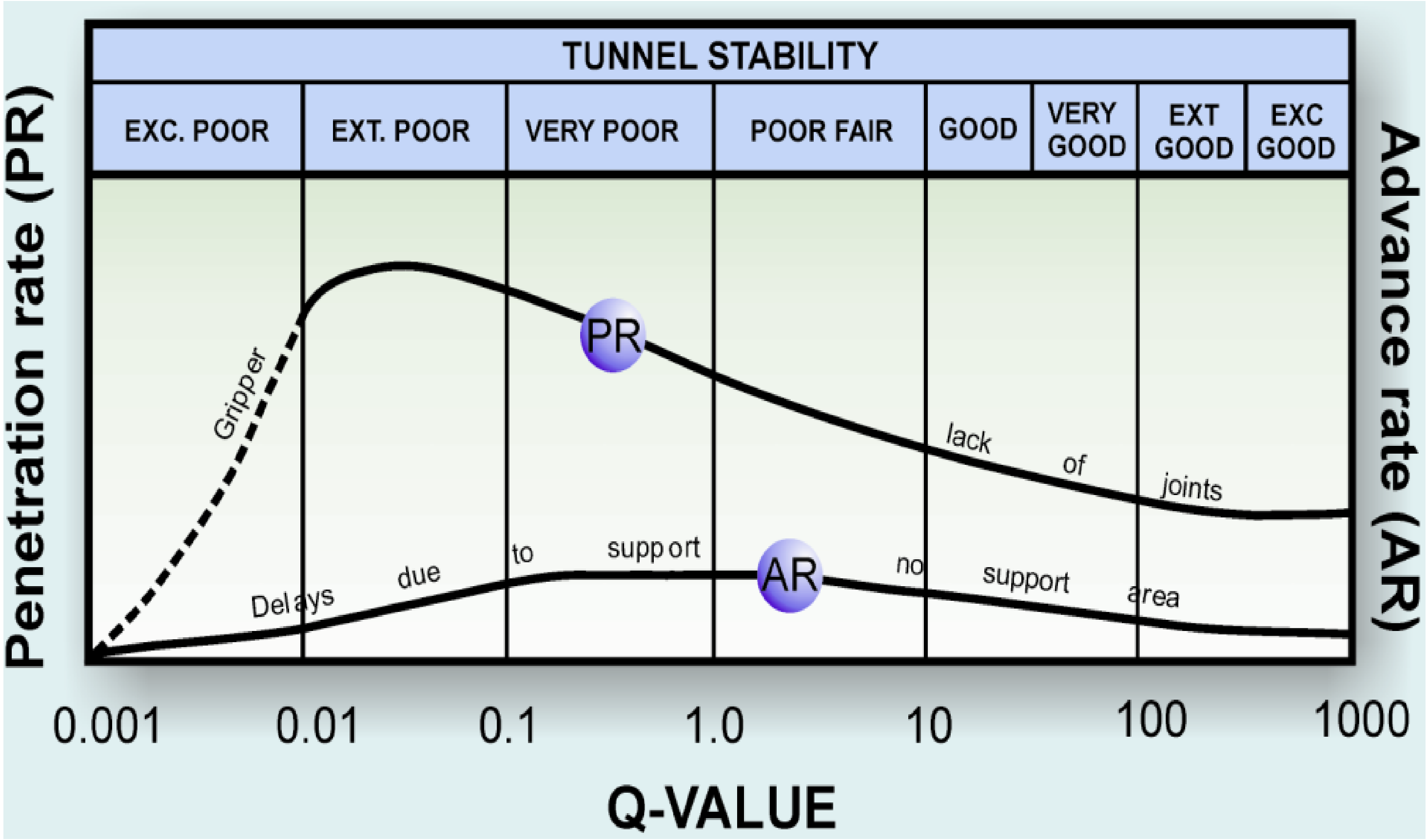
≈ Follo trend also!
But AR only m/week here.

EVIDENCE LINKING (almost) BASIC Q-VALUES WITH PR:

2.85 km in granites, Malaysia.

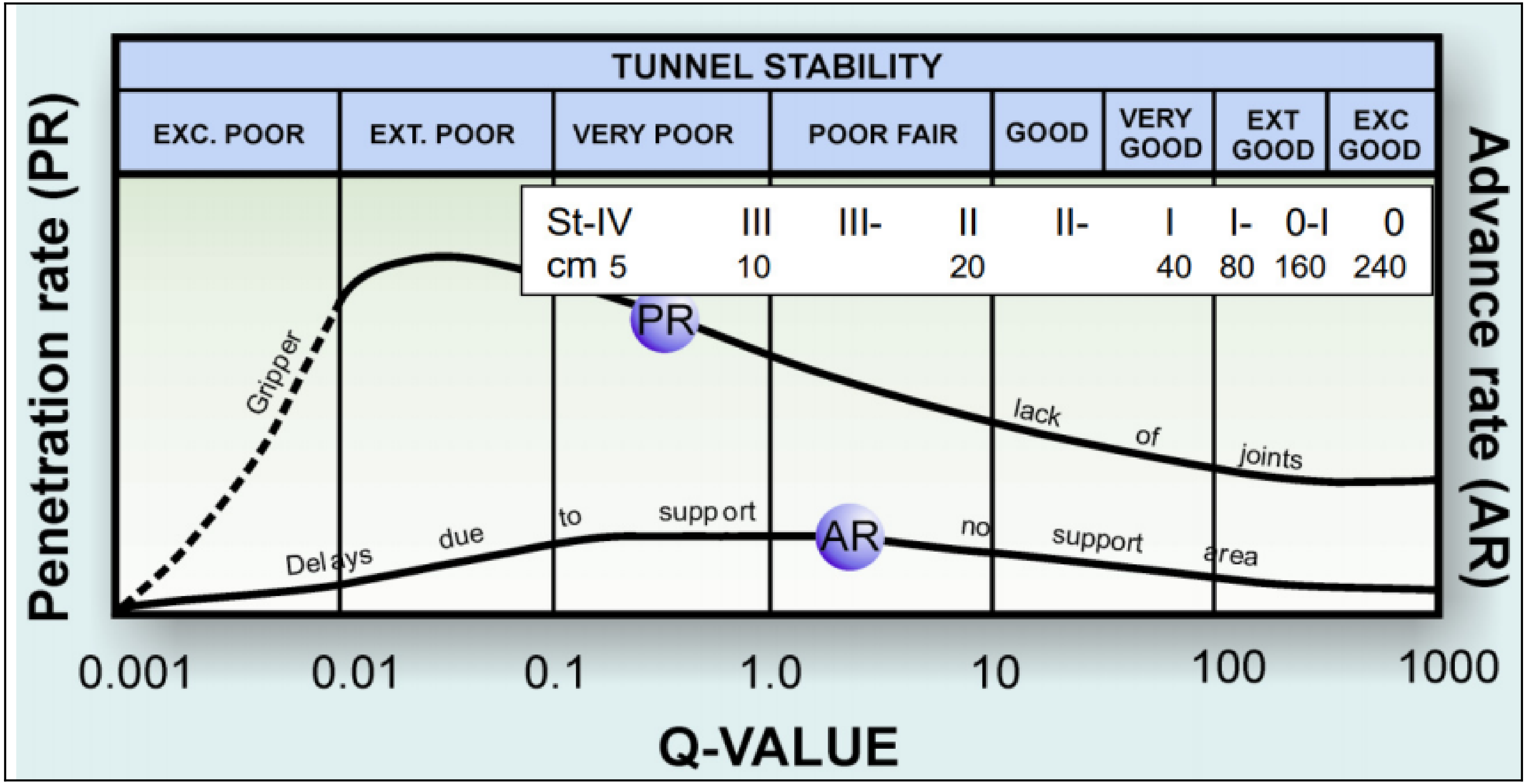


'Q-ADJECTIVES' BELOW DIFFERENT WITH TBM DUE TO *PR* and *AR*!



Q-values with all joints included *(not just least favourable Jr/Ja)*

(Sundaram and Rafek, 1998)



Q-VALUE SCALE FOR DESCRIBING ROCK MASS QUALITY.

THE NORMAL 'Q-ADJECTIVES' GOOD, VERY GOOD ETC. NEED MODIFYING FOR TBM.

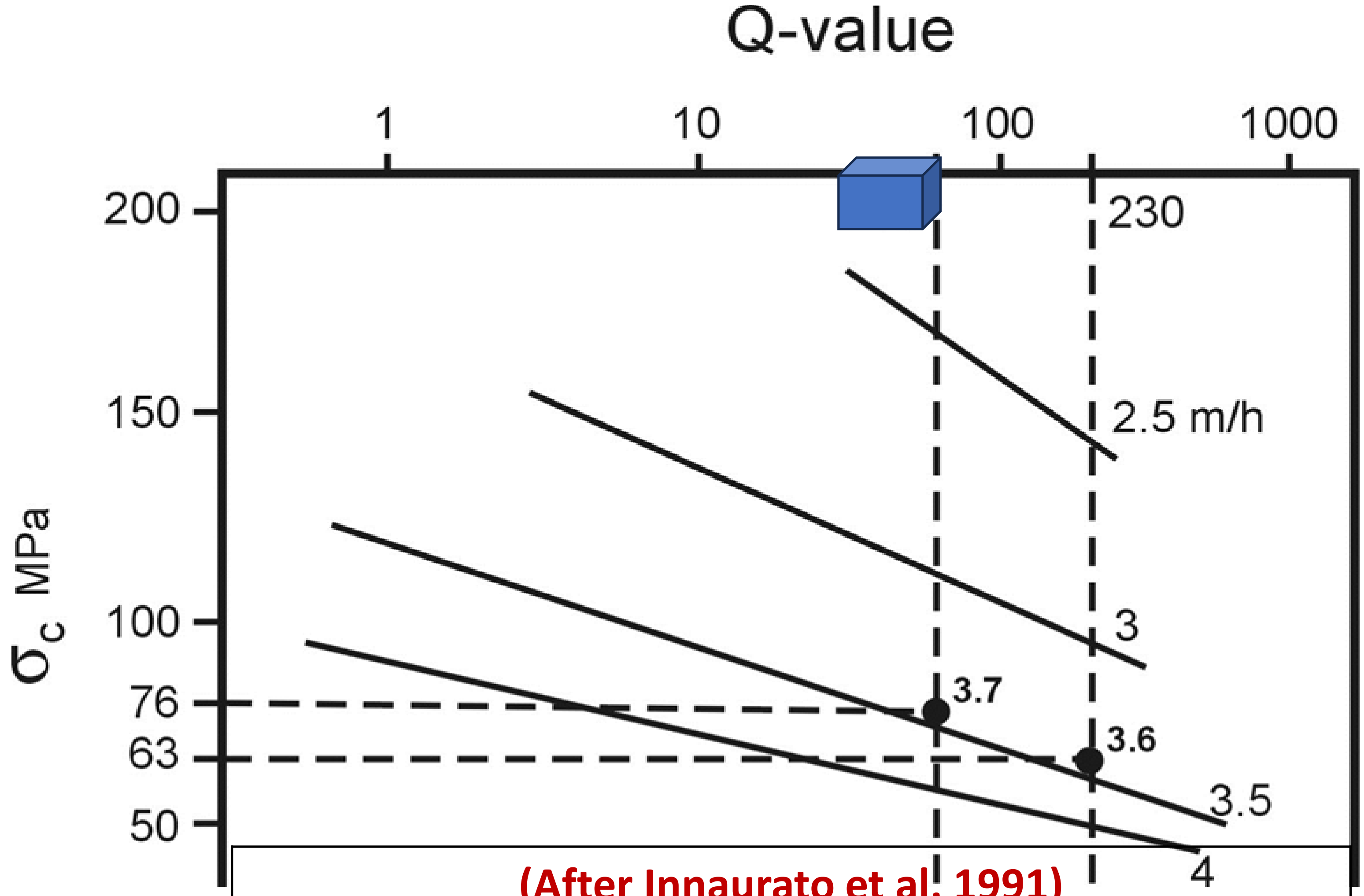
INSET SHOWS VERY APPROXIMATE NTNU FRACTURING CLASSES (AND SPACINGS).

Maybe shift inset more to the left?

THIS ‘ICE-AGE’ PHOTO EMPHASISES THAT THE NUMBER OF JOINT SETS (NOT JUST THE ADDITION OF ALL FRACTURE SETS) PROBABLY ALSO MATTERS IN A ***PR-PROGNOSIS*** METHOD. (FRICTIONAL PROPERTIES LIKE Jr ALSO IMPORTANT?).

LOGICAL TRENDS: high Q, high σ_c, lower PR

Typ. Follobanen

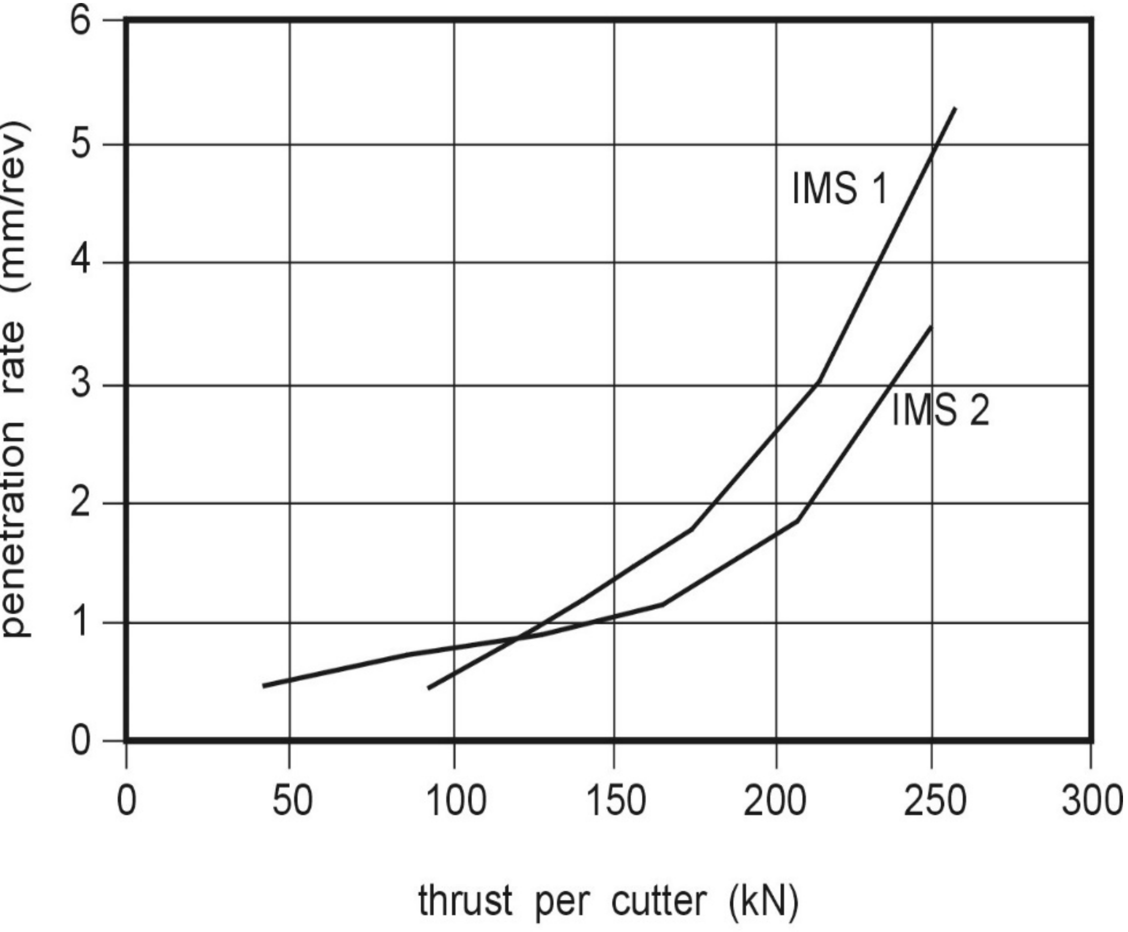


(After Innaurato et al. 1991)

2. CUTTER FORCE VERSUS ROCK MASS STRENGTH

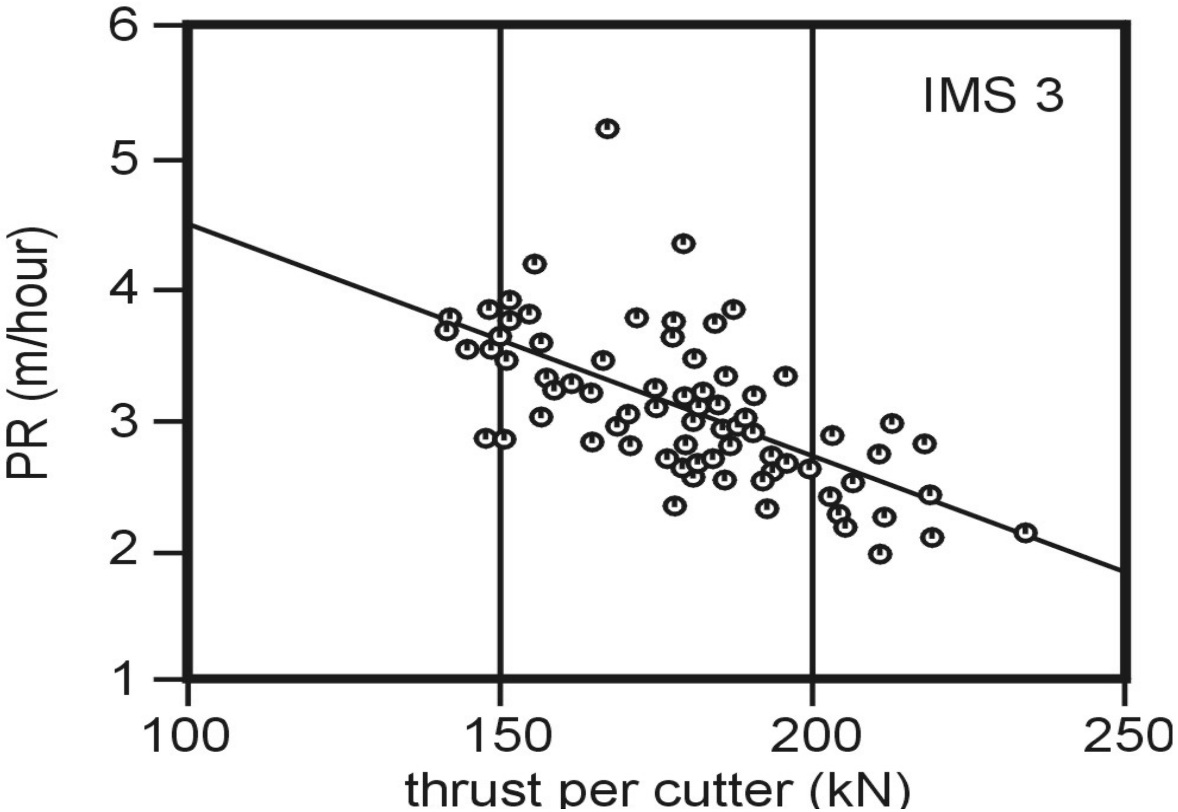
CUTTER THRUST COMPARED TO ROCK MASS STRENGTH

(Figures from Grandori et al. 1995)

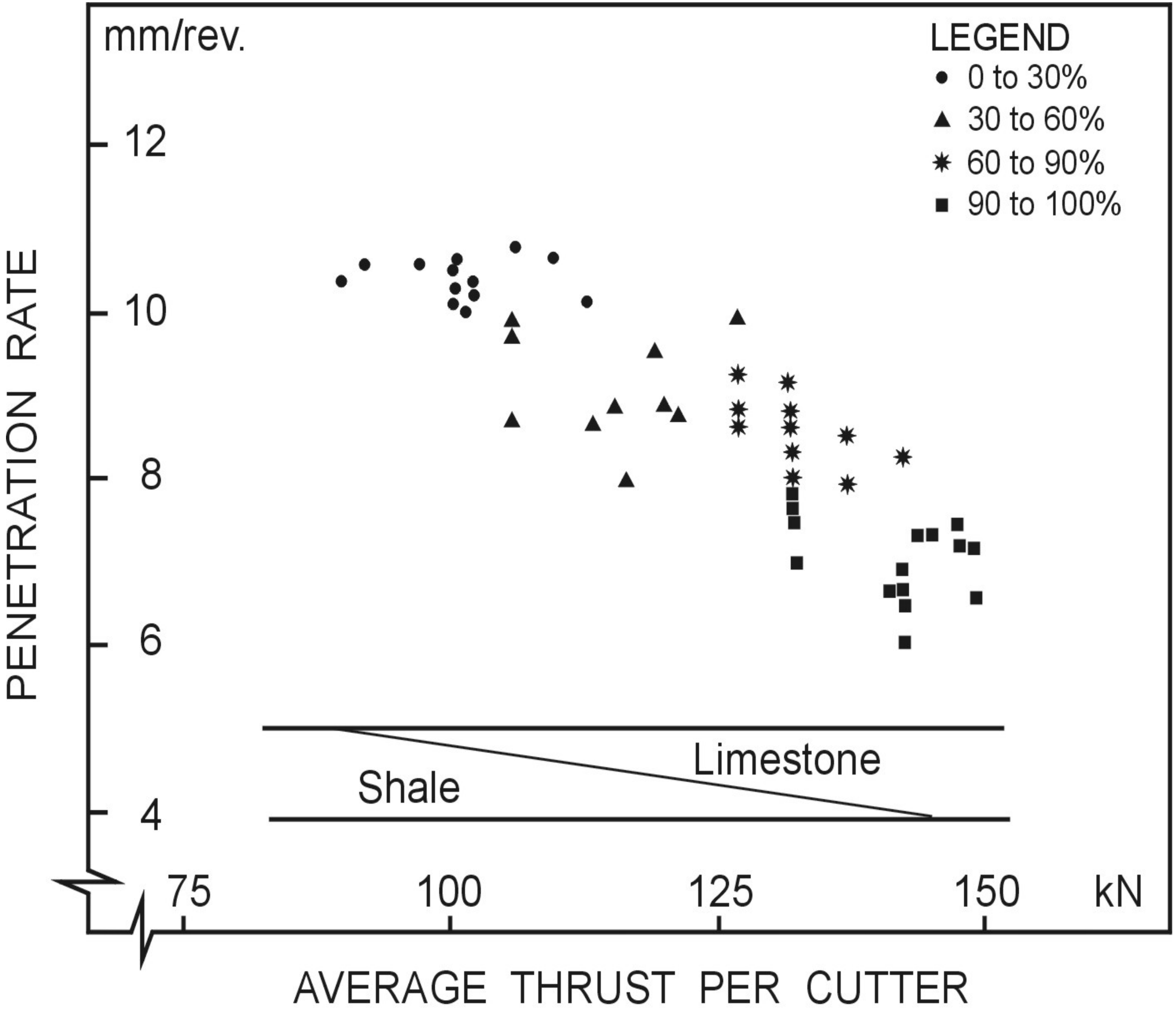


LEFT: WHAT TO EXPECT IF ENOUGH POWER for HIGH THRUST

BELOW: IF ROCK IS TOO HARD



FOR REALISTIC TBM PROGNOSIS *it is logical to* COMPARE *CUTTER THRUST (F)* WITH ROCK MASS STRENGTH



UNDER-POWERED TBM FROM 1980's.

REDUCED *PR* DESPITE INCREASED THRUST/CUTTER.

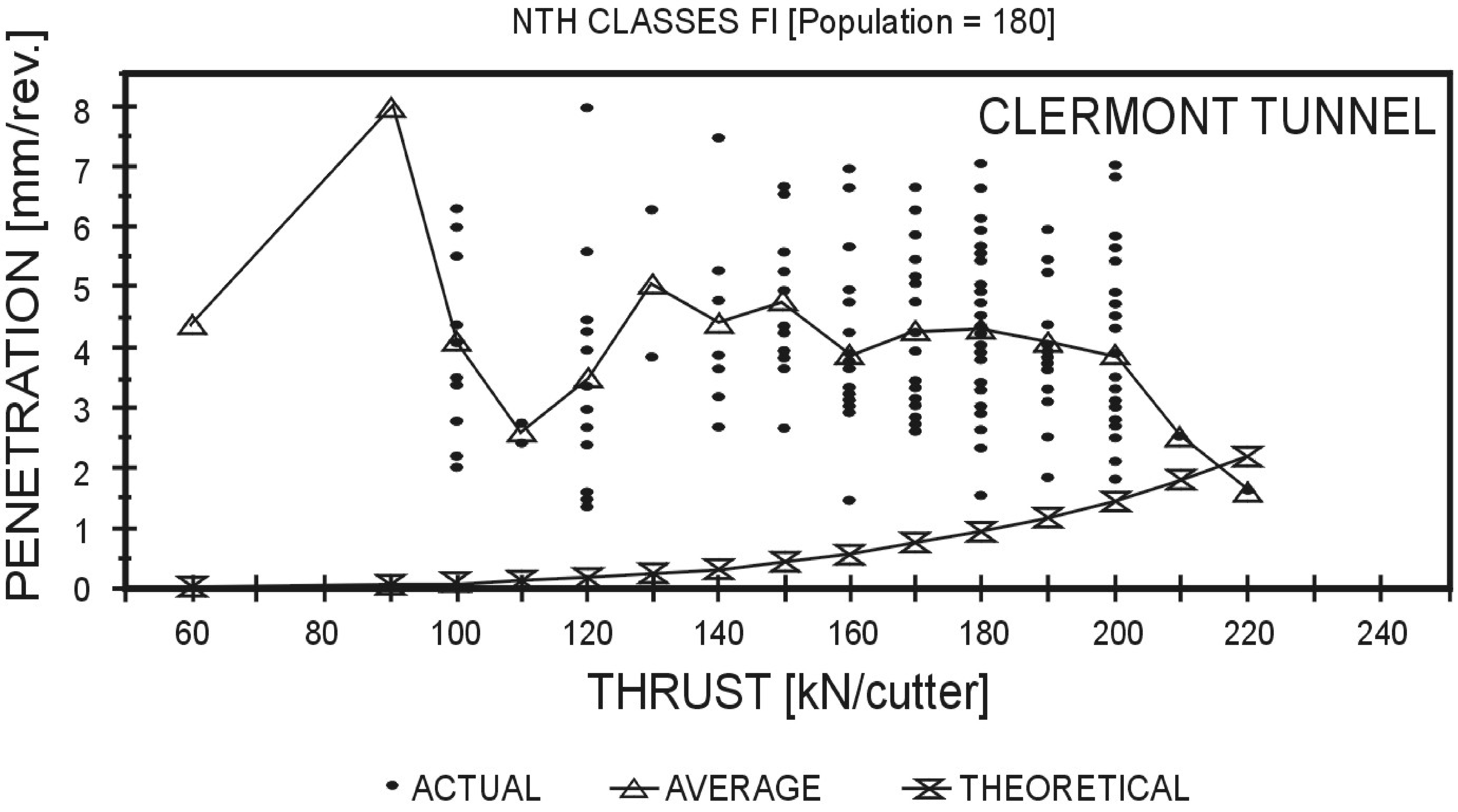
% HARD LIMESTONE SHOWN.

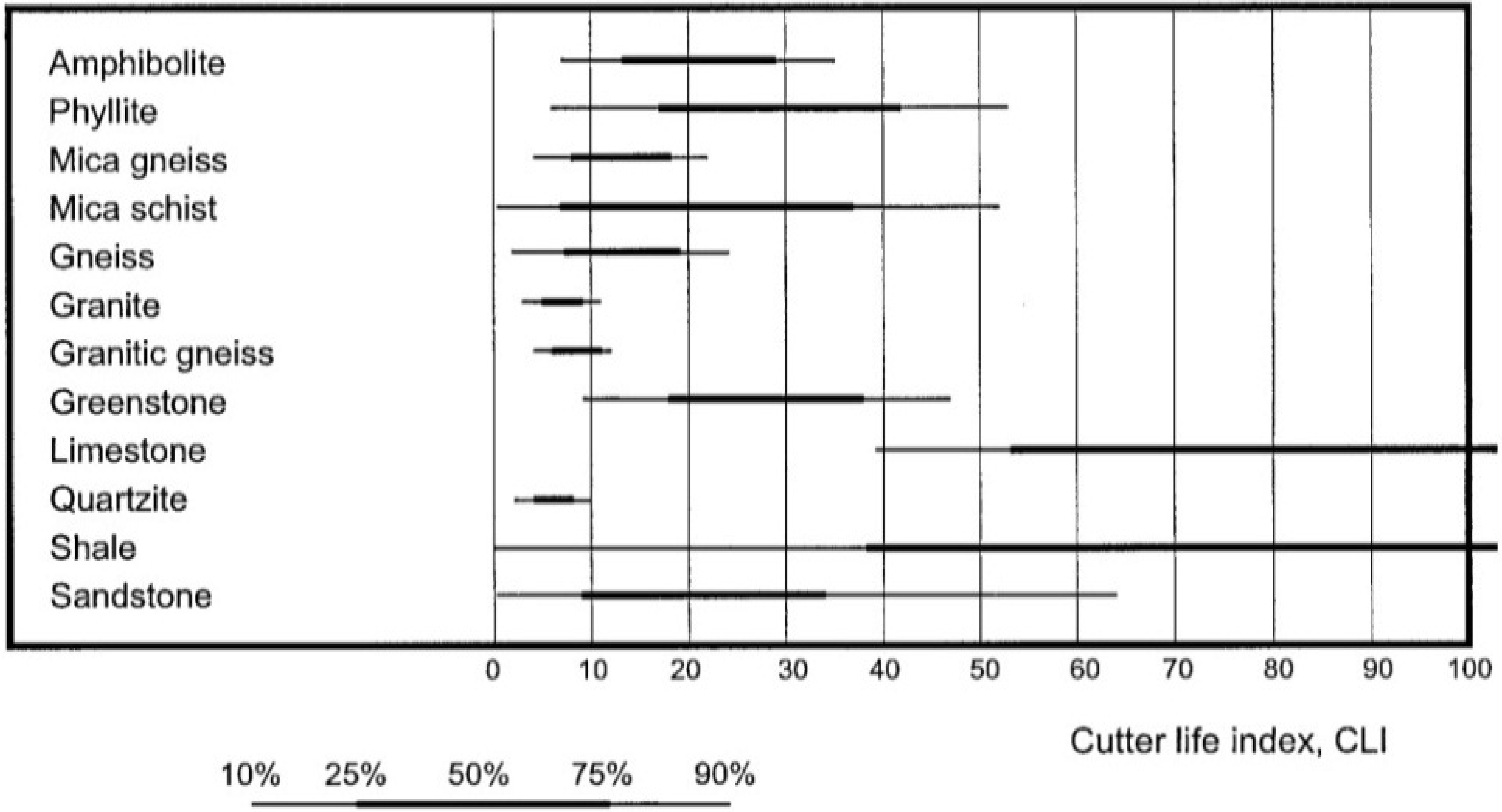
(NELSON ET AL. 1983).

(40 MPa / 130 MPa)

TBM PROGNOSIS FAILS TO PREDICT REDUCED PROGRESS WITH INCREASED CUTTER THRUST. TBM UNDER-POWERED IN RELATION TO VERY HARD META-SANDSTONES. JOINT PROPERTIES / ROCK STRENGTH NEED MODELLING?

(McKelvey, Blindheim et al. 1996). There should be more NTH/NTNU curves for fair comparison.

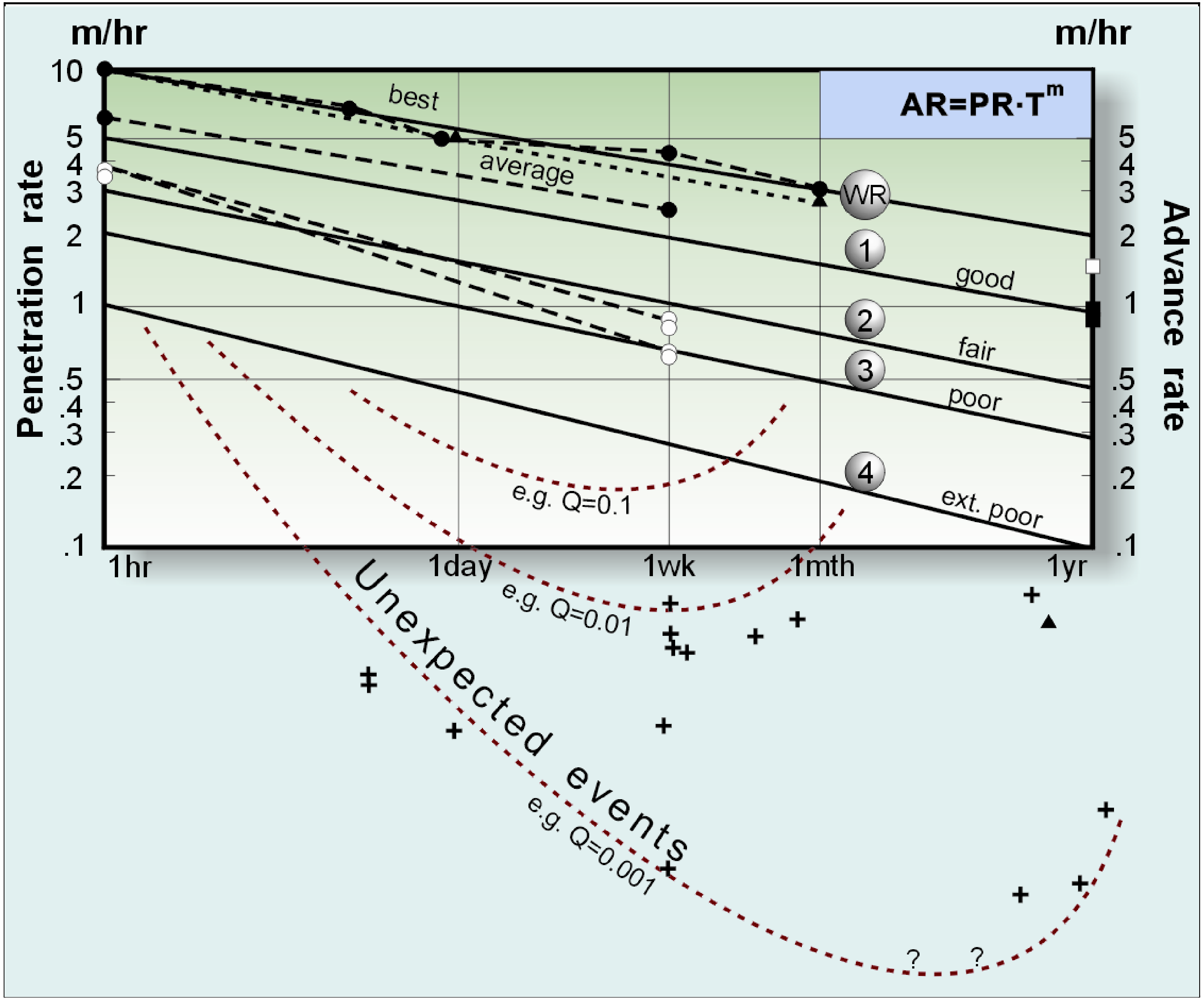




CUTTER LIFE INDEX (CLI)……….NTH/NTNU 1994…..used in two places in Qtbm

3. CASE-RECORD SURVEY for (mostly) OPEN-GRIPPER

4. WORLD-RECORD TBM PERFORMANCES



CASE RECORD EVIDENCE OF DECELERATION from 145 cases representing 1000 km of TBM

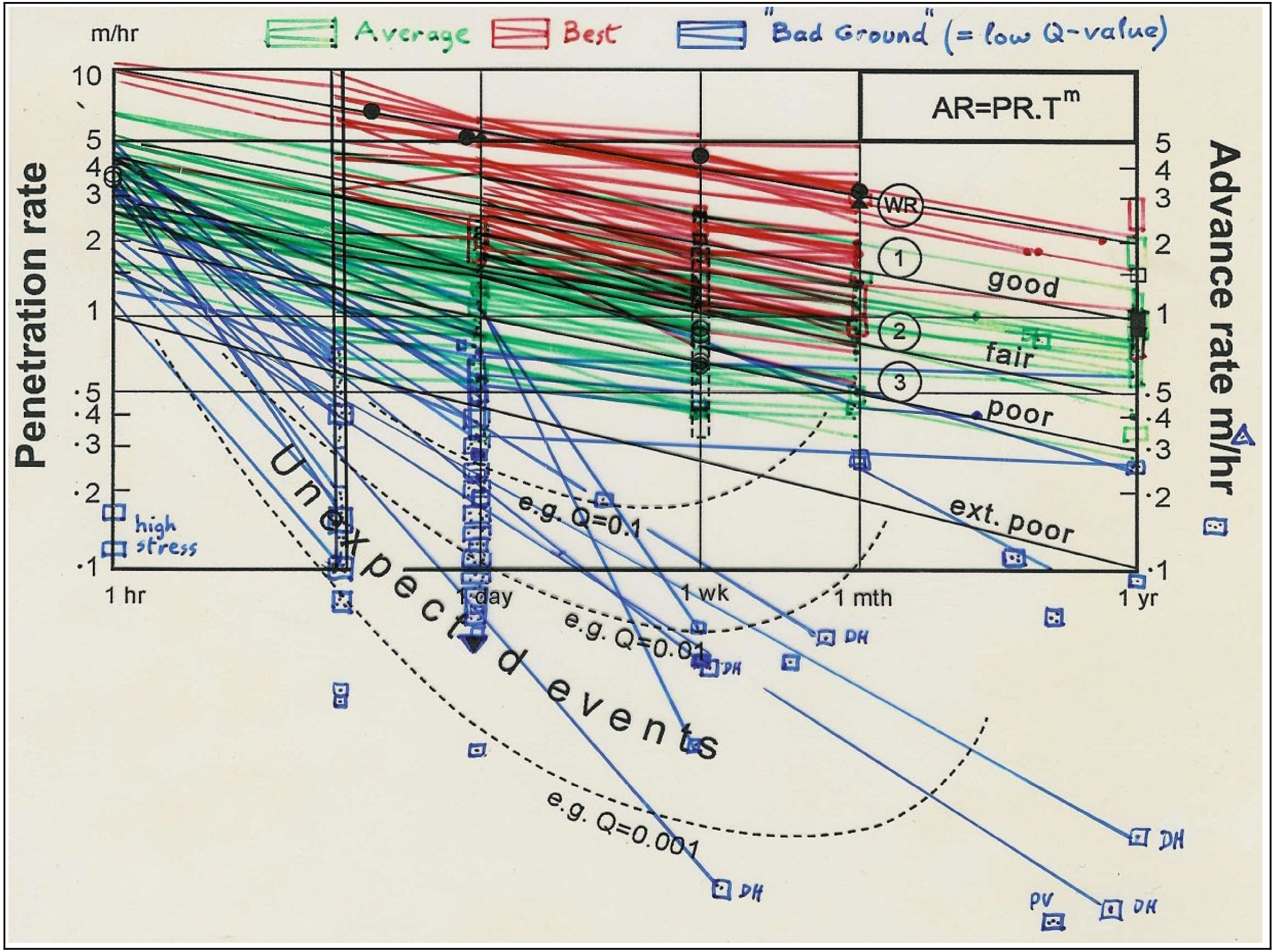
(Mostly open-gripper cases)

Conventional equation:

AR = PR x U

but reality is :

$$AR=PR \cdot T^m$$



BEST

MEAN

WORST

Note: no horizontal lines. Several Norwegian TBM results are included.

(U cannot be constant WITH TIME/LENGTH)

Barton, 2000

WORLD RECORDS FOR HIGH SPEED TUNNEL EXCAVATION

DIAMETER	3 - 4 m	4 - 5 m	5 - 6 m	6 - 7 m
BEST DAY	172 m Robbins Katoomba Australia ★	128 m Robbins SSC No. 4 USA	99 m Robbins Little Calumet USA	114 m Robbins Dallas Metro USA
BEST WEEK	703 m Robbins Katoomba Australia ★	477 m Robbins SSC No. 4 USA	562 m Robbins Little Calumet USA	500 m Robbins Dallas Metro USA
BEST MONTH	2066 m Robbins Oso USA	1822 m Robbins Yellow River China	2163 m Robbins Little Calumet USA ★	1690 m Robbins Dallas Metro USA
MONTHLY AVERAGE FOR PROJECT	1189 m Robbins Katoomba Australia	1352 m Robbins Yellow River China ★	1095 m Robbins Yindaruqin China	1187 m Robbins Dallas Metro USA

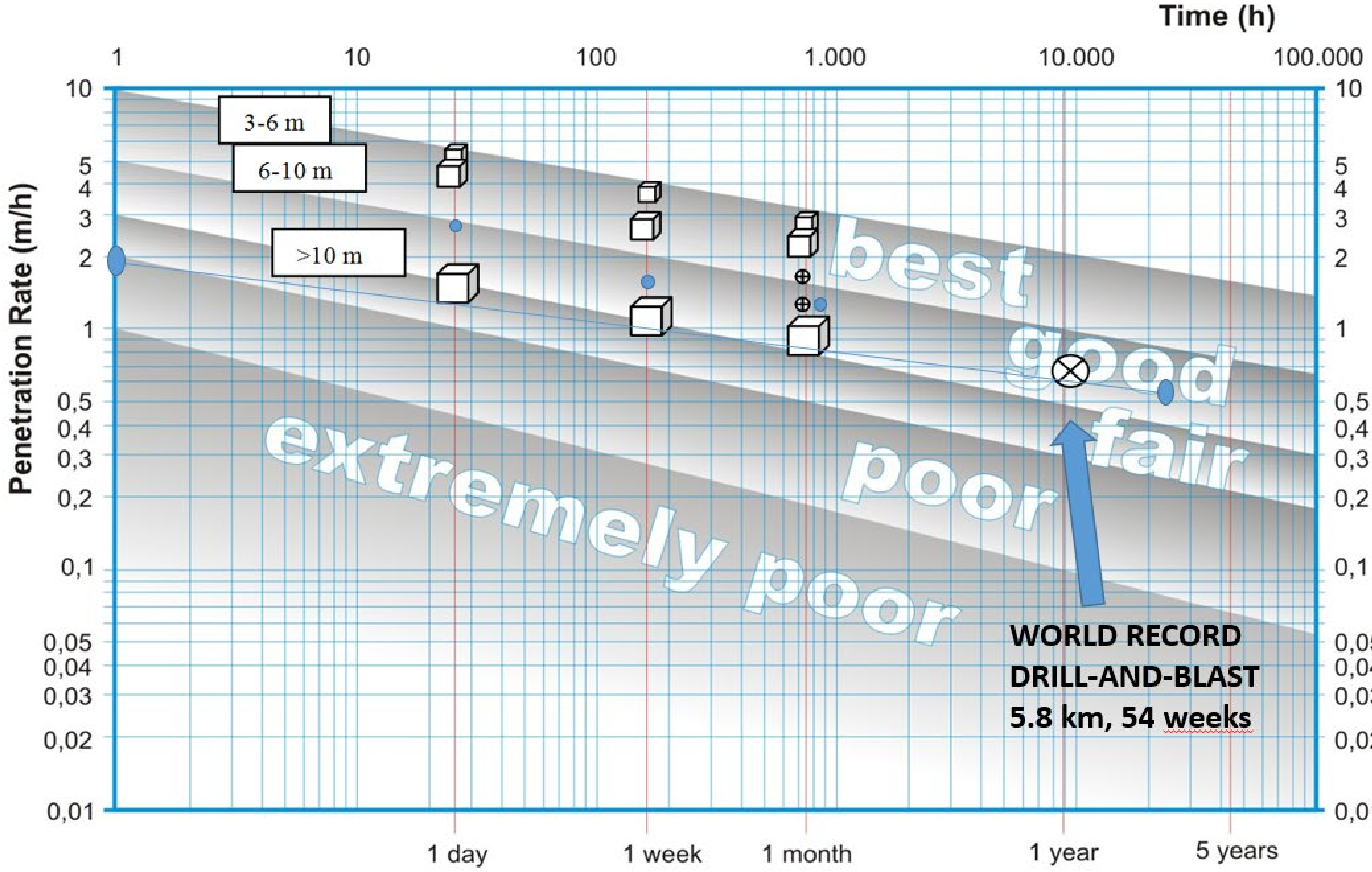
DIAMETER	7 - 8 m	8 - 9 m	9 - 10 m	10 - 11 m	11 - 12 m
BEST DAY	115 m Robbins Karahnjukar Iceland	75 m Robbins Channel Tunnel UK	74 m Robbins TARP Chicago USA	48 m Robbins TARP Chicago USA	30 m Herrenknecht Murgenthal Switzerland
BEST WEEK	428 m Robbins Karahnjukar Iceland	428 m Robbins Channel Tunnel UK	324 m Robbins TARP Chicago USA	185 m Robbins TARP Chicago USA	100 m Robbins Bozberg Switzerland
BEST MONTH	1482 m Robbins TARP Chicago USA	1719 m Robbins Channel Tunnel UK	982 m Wirth Guadarrama Spain	685 m Robbins TARP Chicago USA	385 m Robbins Bozberg Switzerland
MONTHLY AVERAGE FOR PROJECT	770 m Robbins TARP Chicago USA	873 m Robbins Channel Tunnel UK	715 m Robbins TARP Chicago USA	none reported	none reported

★ **172m one day !**
★ **703m one week !**
★ **2163 m one month !**
(16 km one year !)

★ **BEST MONTH = 2163m, BUT BEST MONTHLY AVERAGE *'ONLY'* 1352m.**

UK chalk marl: UCS 5-9 MPa

NOTE: *BUT* BIG DELAYS WHERE 3 JOINT SETS AND SEA WATER:
90/9 X 1/2 X 0.66/1
(over-break effected ring-building, water damaged electronics) 18m problem!



WORLD RECORDS COLLECTED IN SIZE BRACKETS:

(3-6m, 6-10m, > 10m).

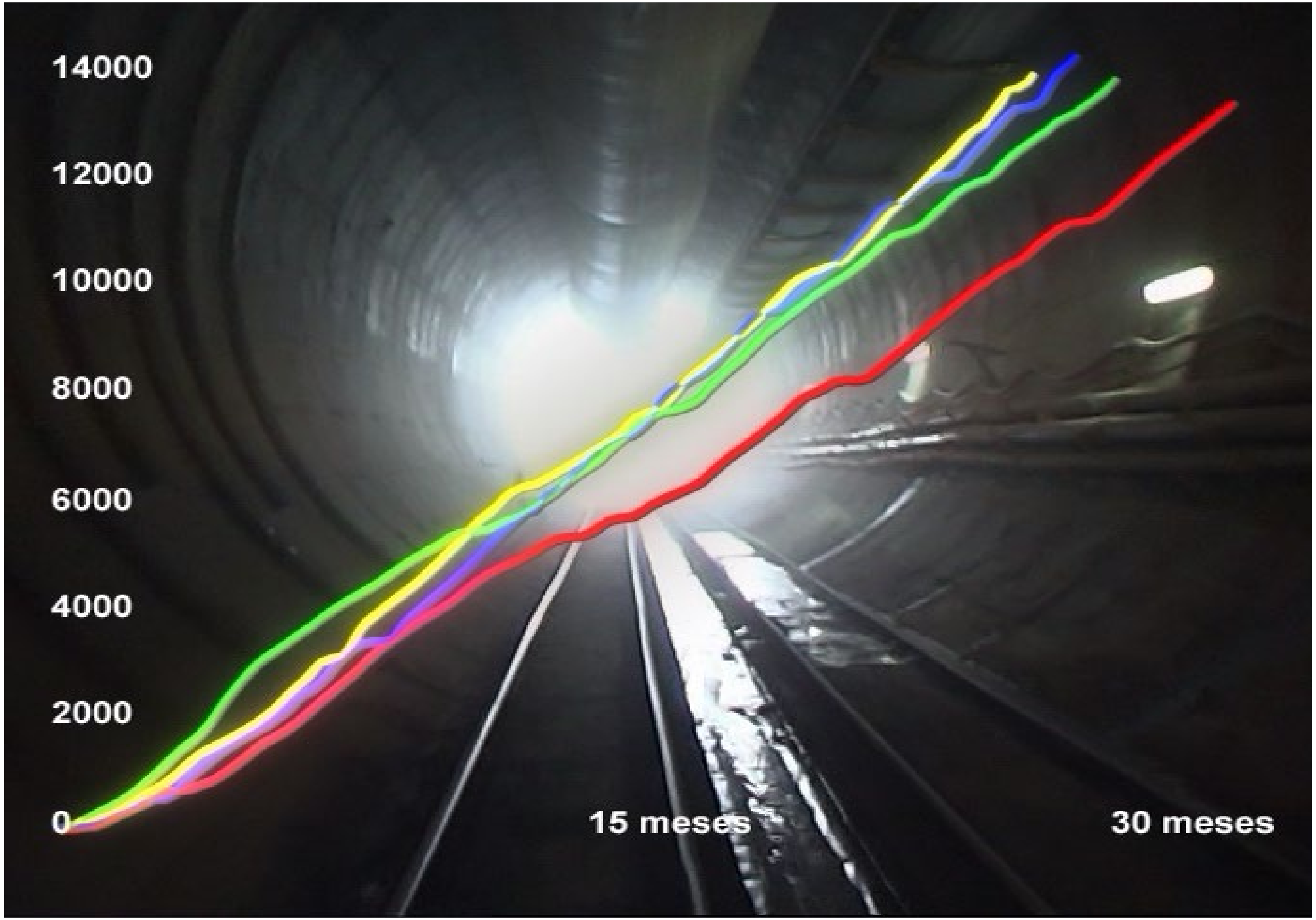
MOSTLY ROBBINS WORLD RECORDS)

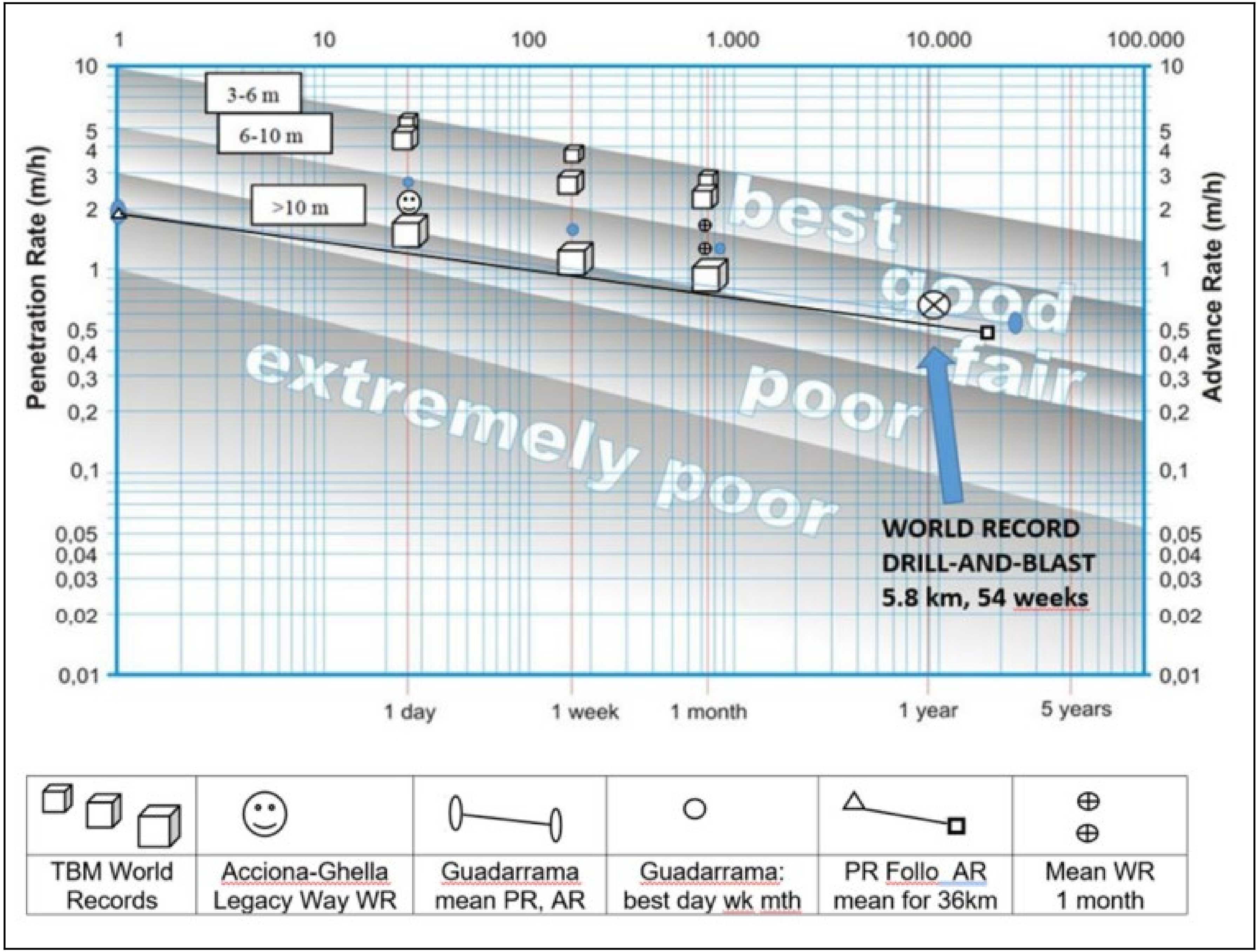
4x14km best

mean 56km Guadarrama 9m

(Barton, 2013)

GUADARRAMA 4 x DOUBLE-SHIELD TBM, 14 km EACH, 30-33 MONTHS.





WORLD RECORD TBM PERFORMANCES ARRANGED BY SIZE (Barton, 2013).

ADDITIONAL DATA EXPLAINED IN THE TABULATION.

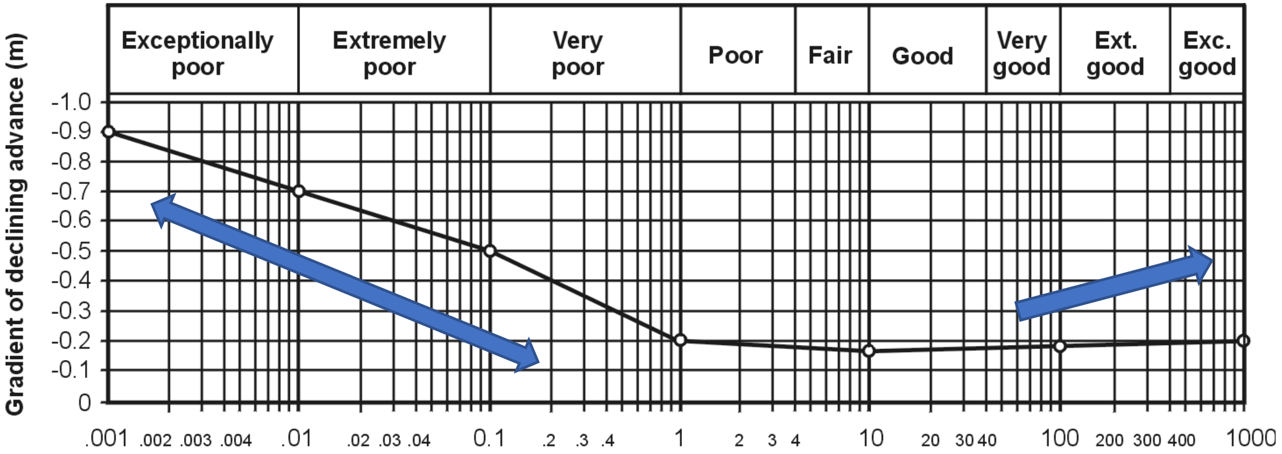
THE STRONGLY SIZE-RELATED RESULTS SUGGEST AN ADDITIONAL CORRECTION FOR PR BEYOND THAT ALREADY INCLUDED IN QTBM.

PR X 5/D IMPROVES PROGNOSIS. 'TODAY'S' TBM DIAMETERS INCREASING BEYOND THE EARLIER SMALLER DIAM. DATA BASE.

PERFORMANCE Line # (refer to Figure)	DECELERATION Gradient (-) *m* *(units of LT⁻²)*
WR (world records) 1, 2, (good, fair) 3, 4 (poor, extremely poor) Q ≈ 0.1 (delays) Q ≈ 0.01 (big delays) Q ≈ 0.001 (stuck TBM) *(trends from 145 cases)*	-0.13 to -0.17 -0.17, -0.19 -0.21, -0.25 -0.5 -0.7 -0.9 *(Σ ≈ 1000 km, mostly open-gripper)*
DOUBLE-SHIELD at Guadarrama tunnels (2x Wirth, 2x Herrenknecht)	*-0.08 to -0.12 (best ≈ 50% of open-gripper) (4 x 14 km)*

DELAYS IN FAULT ZONES ARE RELATED WITH LOW Q-VALUES.

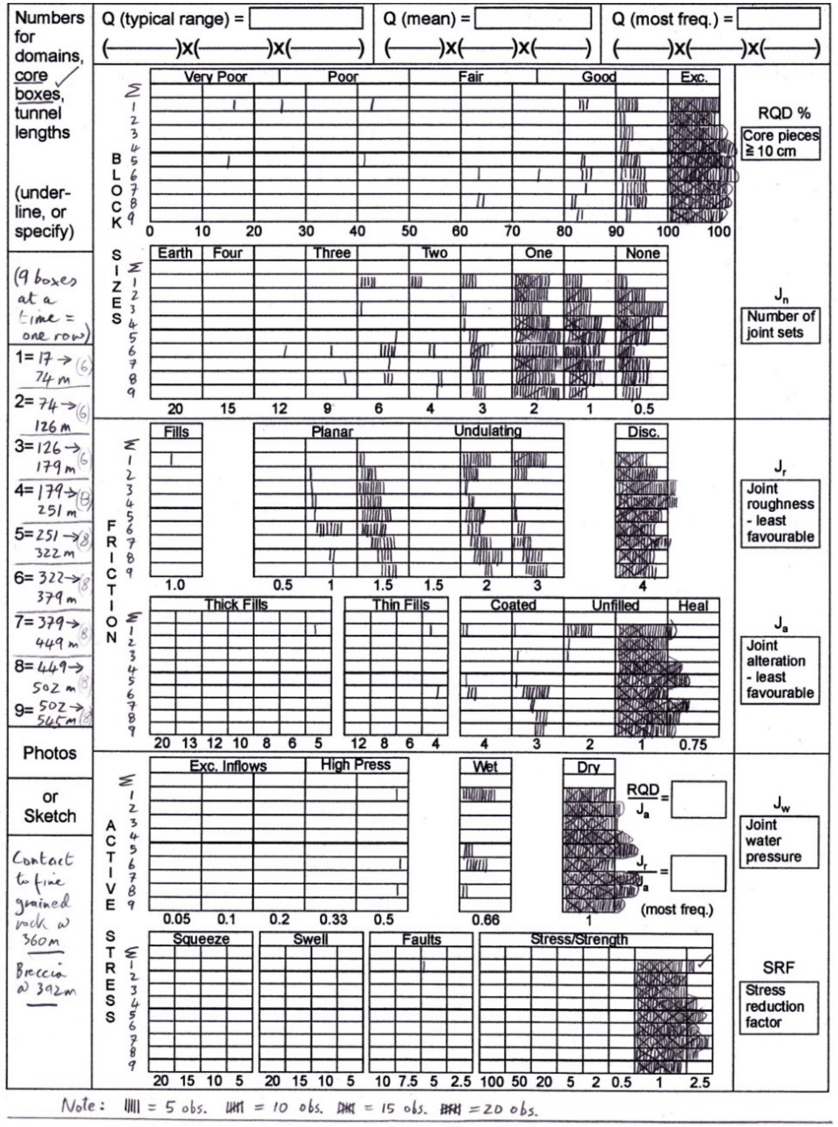
Q LESS IMPORTANT WHEN Q>1 (but new set of problems when Q>50)



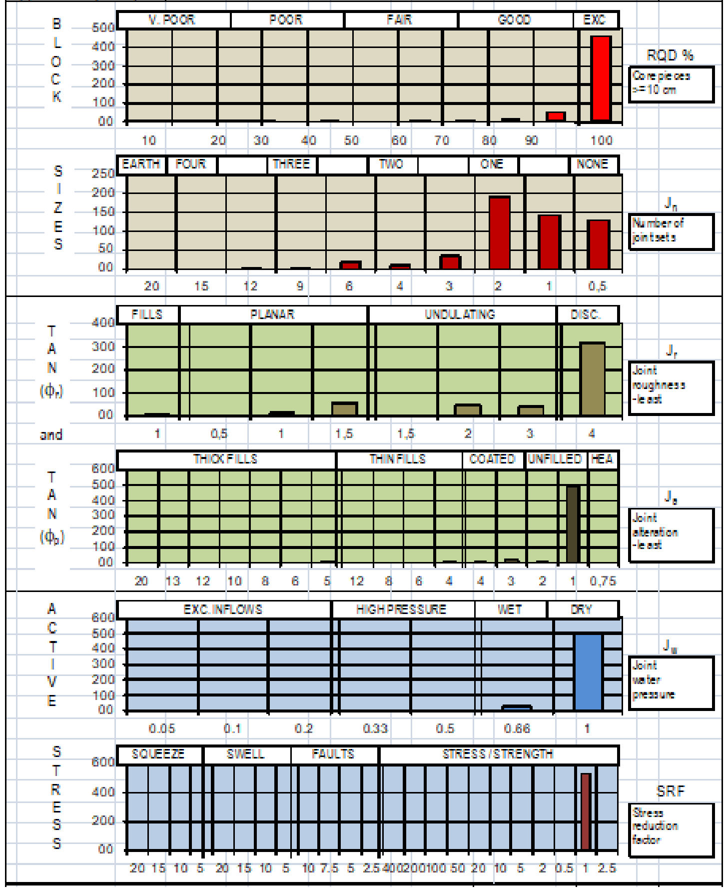
Rock mass quality $Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$

DELAYS WITH LOW Q ARE EXPERIENCED IN MANY TBM PROJECTS. ALSO DELAYS WITH VERY HIGH Q!

BAD NEWS FOR TBM….few joints, VERY HIGH Q, RMR

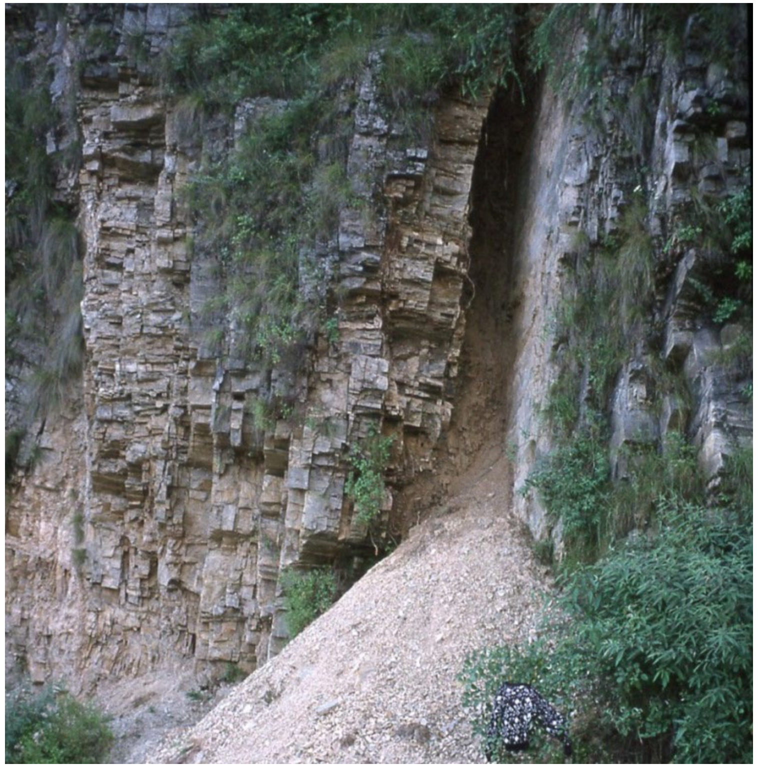


Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	95	/	3.0	*	1.5	/	3.0	*	0.66	/	1.0	=	10.450
Q (typical max)=	100	/	0.5	*	4.0	/	1.0	*	1.00	/	1.0	=	800.0
Q (mean value)=	98	/	1.6	*	3.3	/	1.2	*	0.98	/	1.0	=	169.07
Q (most frequent)=	100	/	2.0	*	4.0	/	1.0	*	1.00	/	1.0	=	200.00



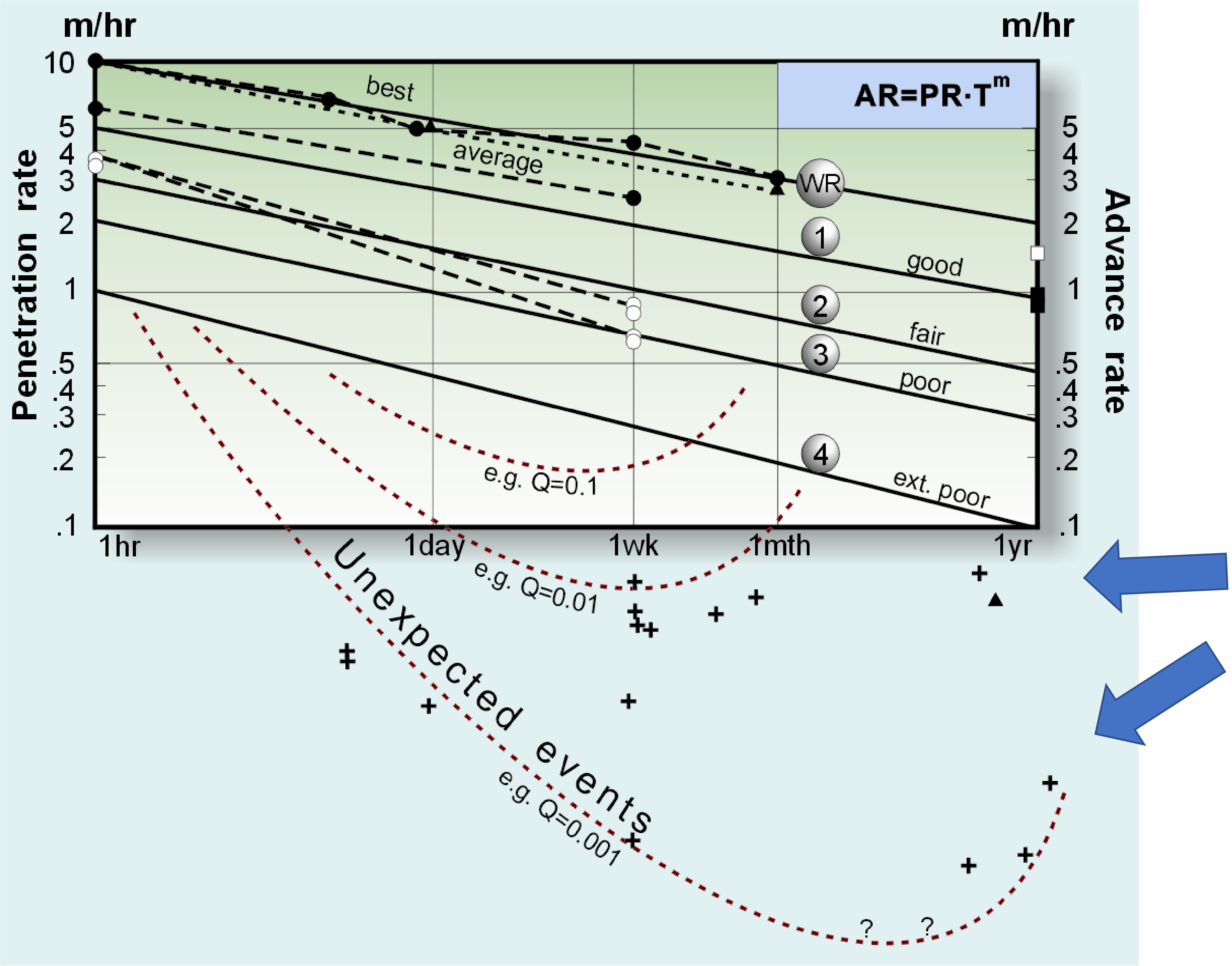
5. TBM DELAYS IN FAULT ZONES

FAULT ZONES ARE UNIQUE CHALLENGES FOR TUNNELLERS IN GENERAL *(and for TBM in particular)* BECAUSE…….



RQD, Jn, Jr, Ja, Jw, SRF……..

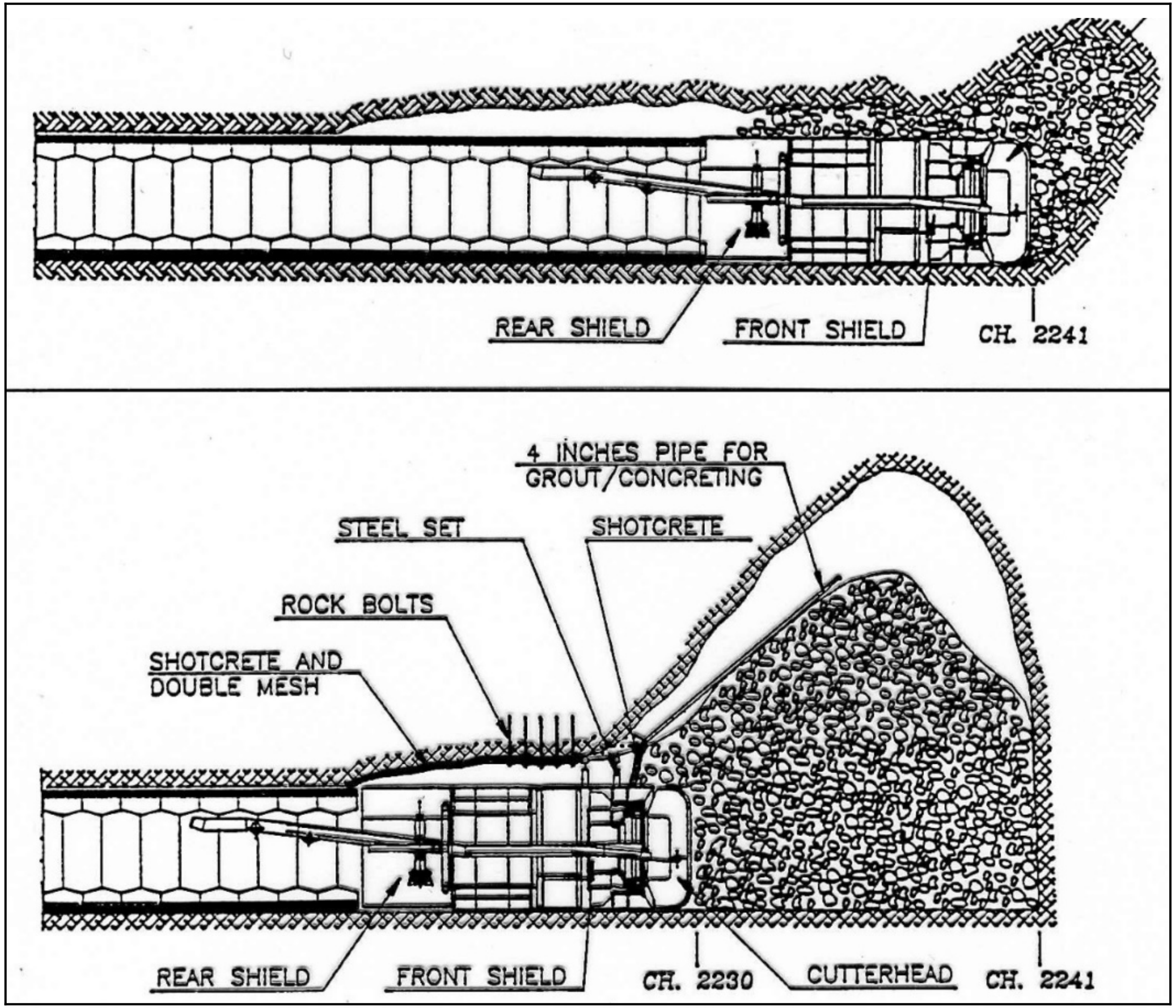
all the Q-parameters *(and everybody else's parameters!)* may be adverse, also TIME + COST



FAULT ZONES *(WITH LOW Q-VALUES)* ARE NOT SUPPOSED TO BE 'UNEXPECTED EVENTS'

……………………….

BUT OFTEN ARE BECAUSE NO PROBE DRILLING, DUE TO THE 'TEMPTATION' OF HIGH-SPEED TBM TUNNELLING



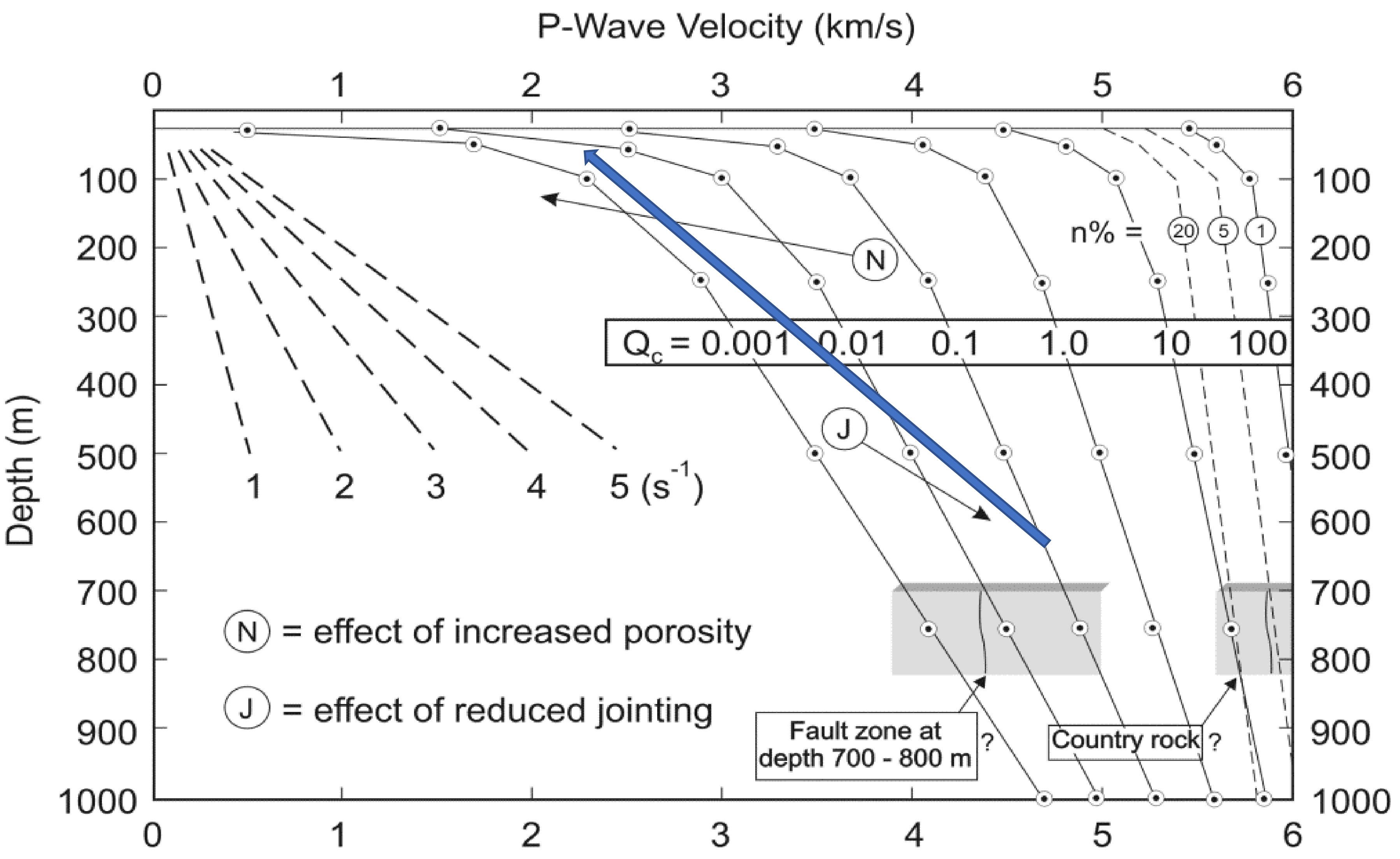
EVINOS-MORNOS WATER TUNNEL, GREECE

FAULT ZONES ALSO CREATE *PROBLEMS FOR DOUBLE-SHIELD* TBM

– IF ZONE IS NOT PRE-TREATED (FOLLOWING PROBE-DRILLING DISCOVERY)

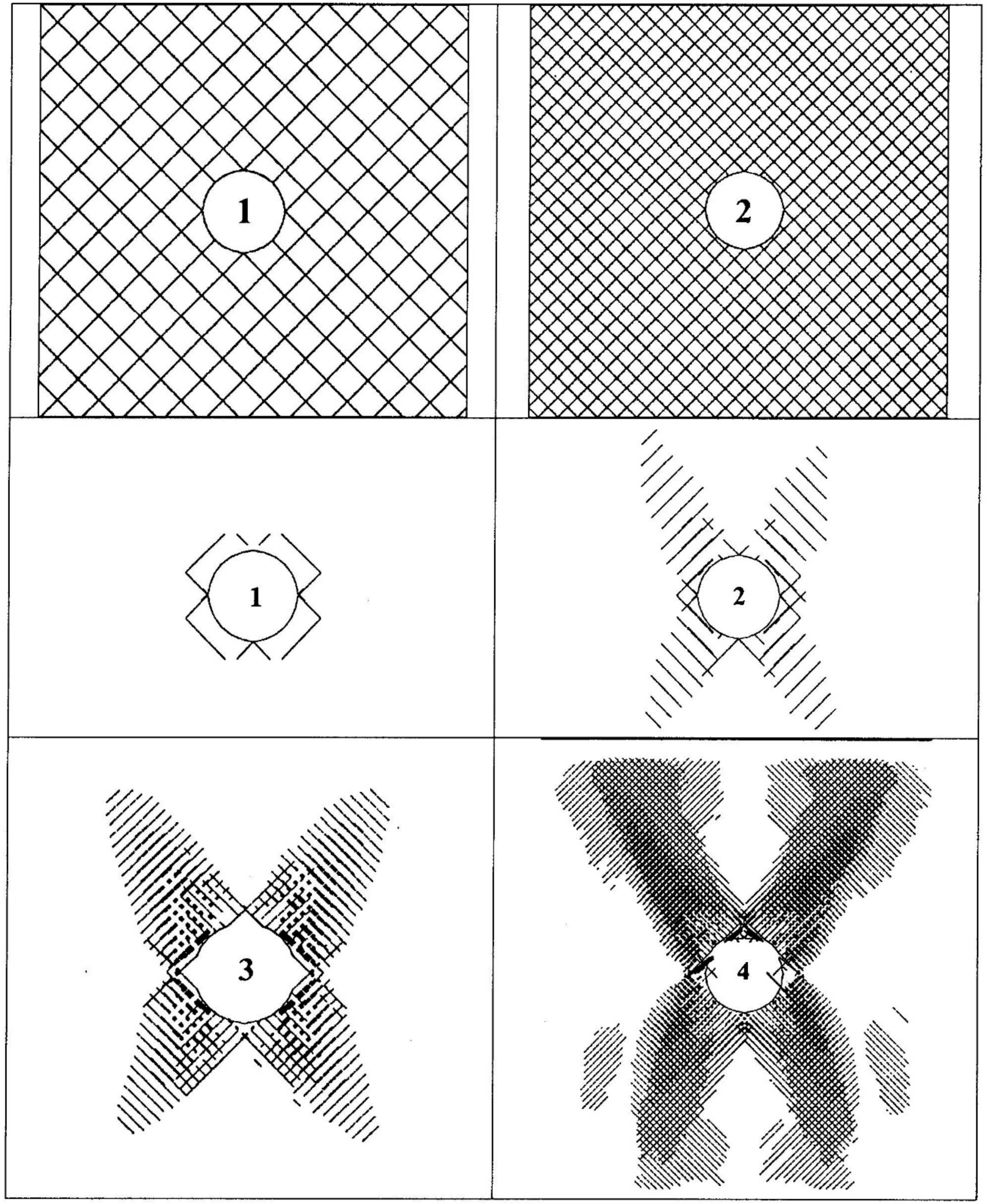
(Grandori et al., 1995).

LESSON: AVOID TBM WITHDRAWL



BECAUSE VELOCITY Vp IS STRESS-DEPENDENT, STRESS RELEASE (BY WITH-DRAWING A TBM) HAS AN ADVERSE EFFECT ON PROPERTIES AND STAND-UP TIME

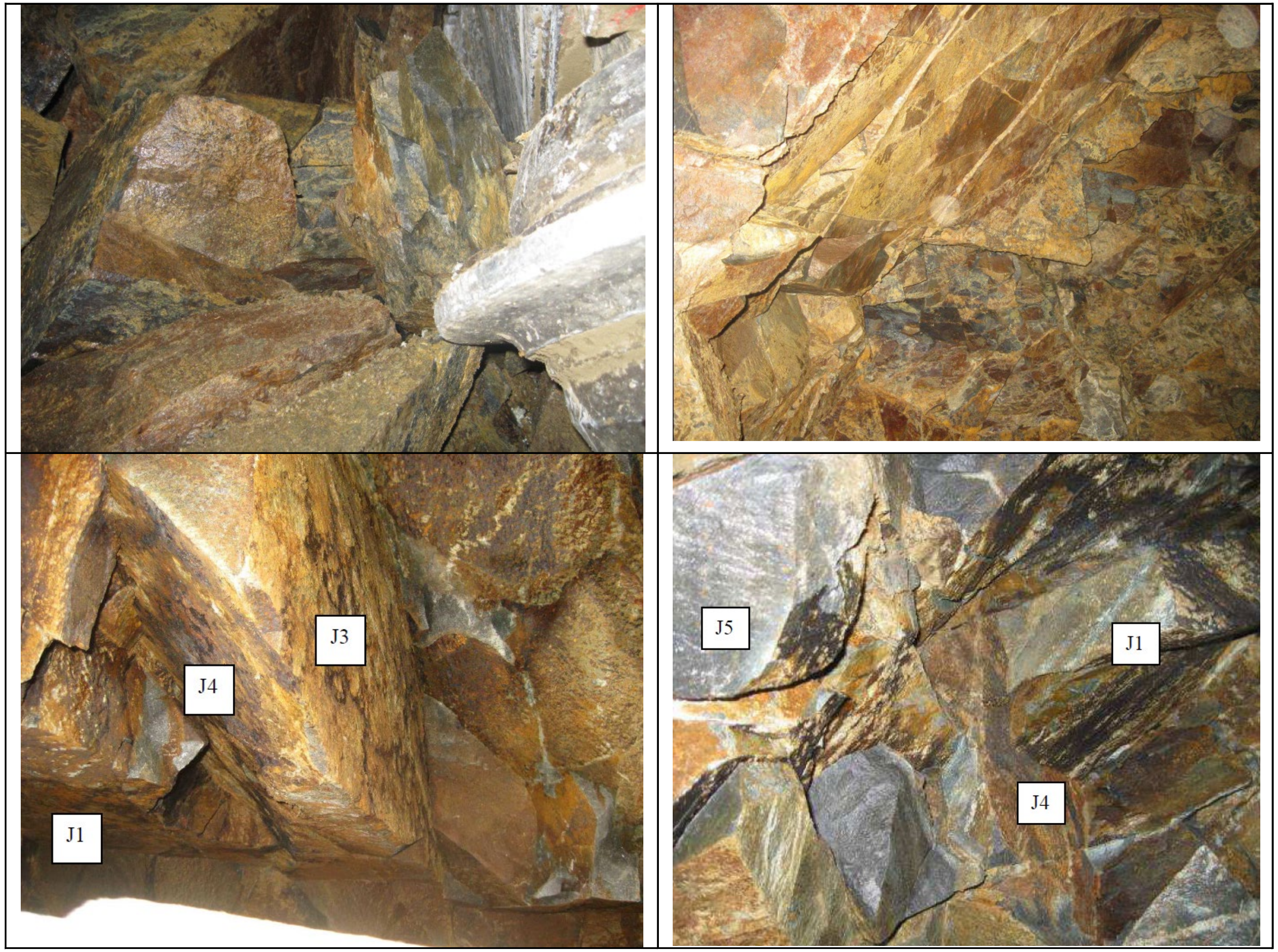
(Barton, 2006)



DISTINCT ELEMENT
UDEC MODELS
SUGGEST POTENTIAL
'TRAUMA' IN
(heavily fractured)
FAULT ZONES

i.e. **DEEP EDZ.**

(Shen and Barton, 1997)



CHILE MINE TUNNEL

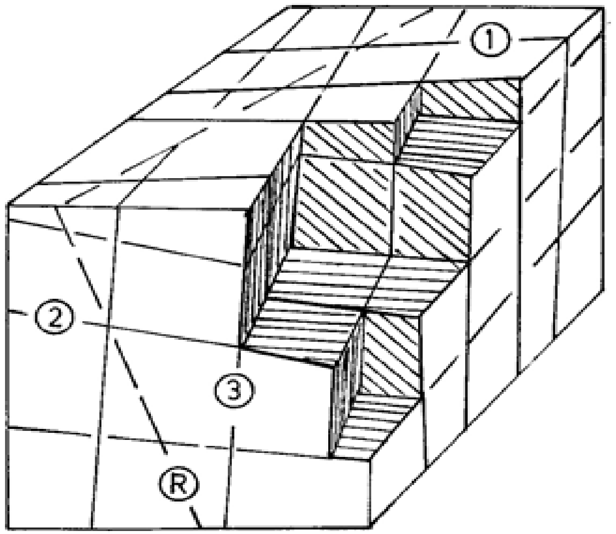
DOUBLE-SHIELD MACHINE 'OVER-EXCAVATED' IN THIS FAULTED ZONE.

WHEN Jn/Jr ≥ 6, OVER-BREAK OR OVER-BORING IS LIKELY

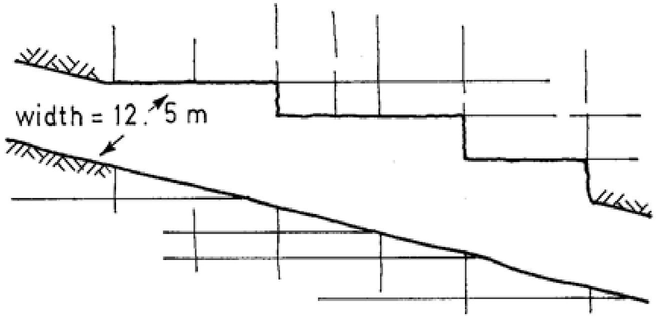
$Q \approx 40/15 \times 1.5/4 \times 1.0/2.5 = 0.4$ 'very poor'

..............(i.e. Jn/Jr ≥ 6)

(see next screen for 'overbreak' rule from Q)



OVERBREAK
(and easier chip/ block formation) with Jn/Jr ≥ 6



Jn = number of sets

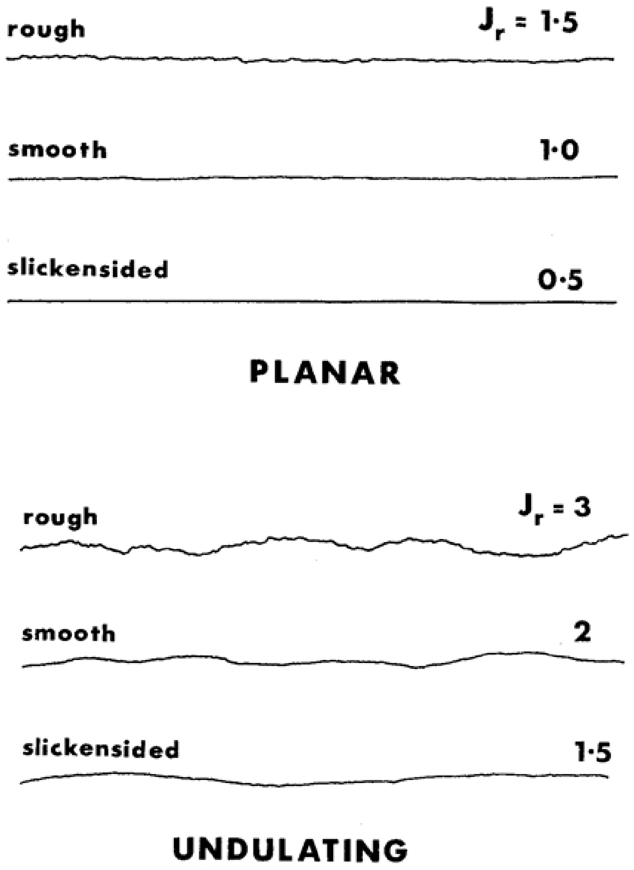
Jr = roughness

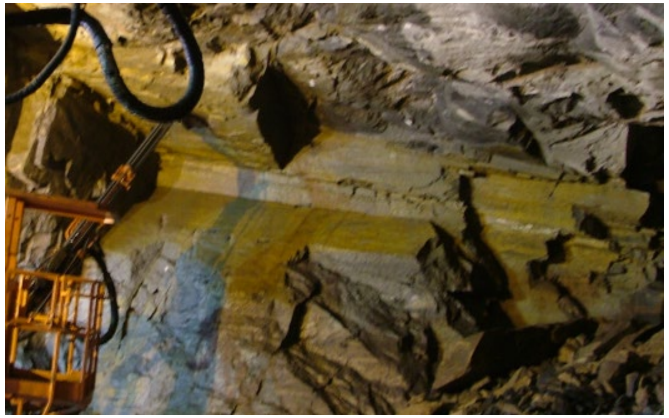
6/1.0	9/1.5
12/2	15/3

(DESPITE FOUR JOINT SETS, TOO MUCH ROUGHNESS AND DILATION)

In photos:

Jn/Jr = 9/(1-1.5)



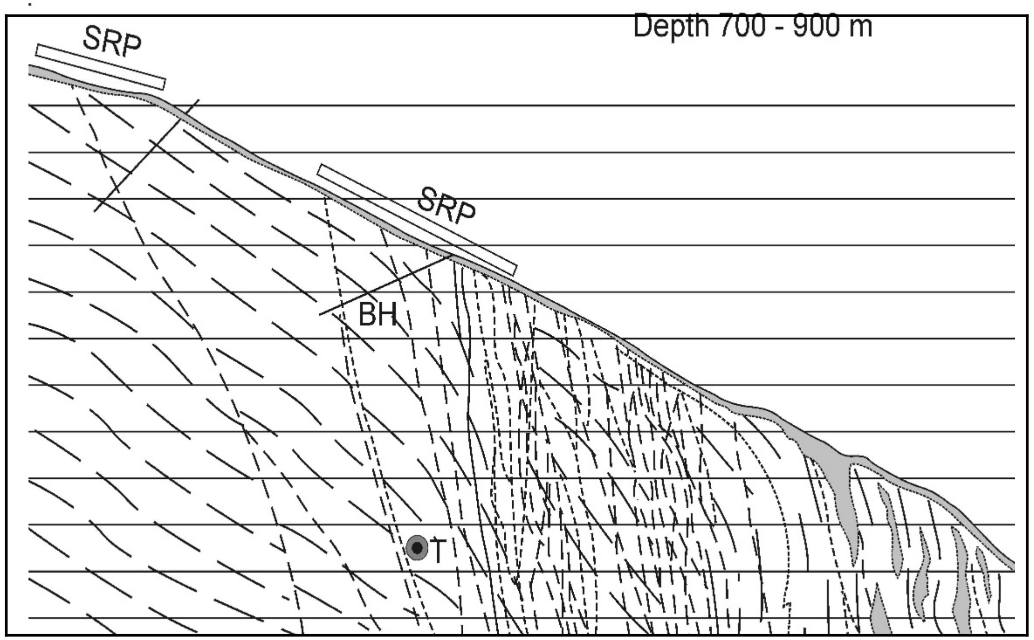


PONT VENTOUX, N.W. ITALY

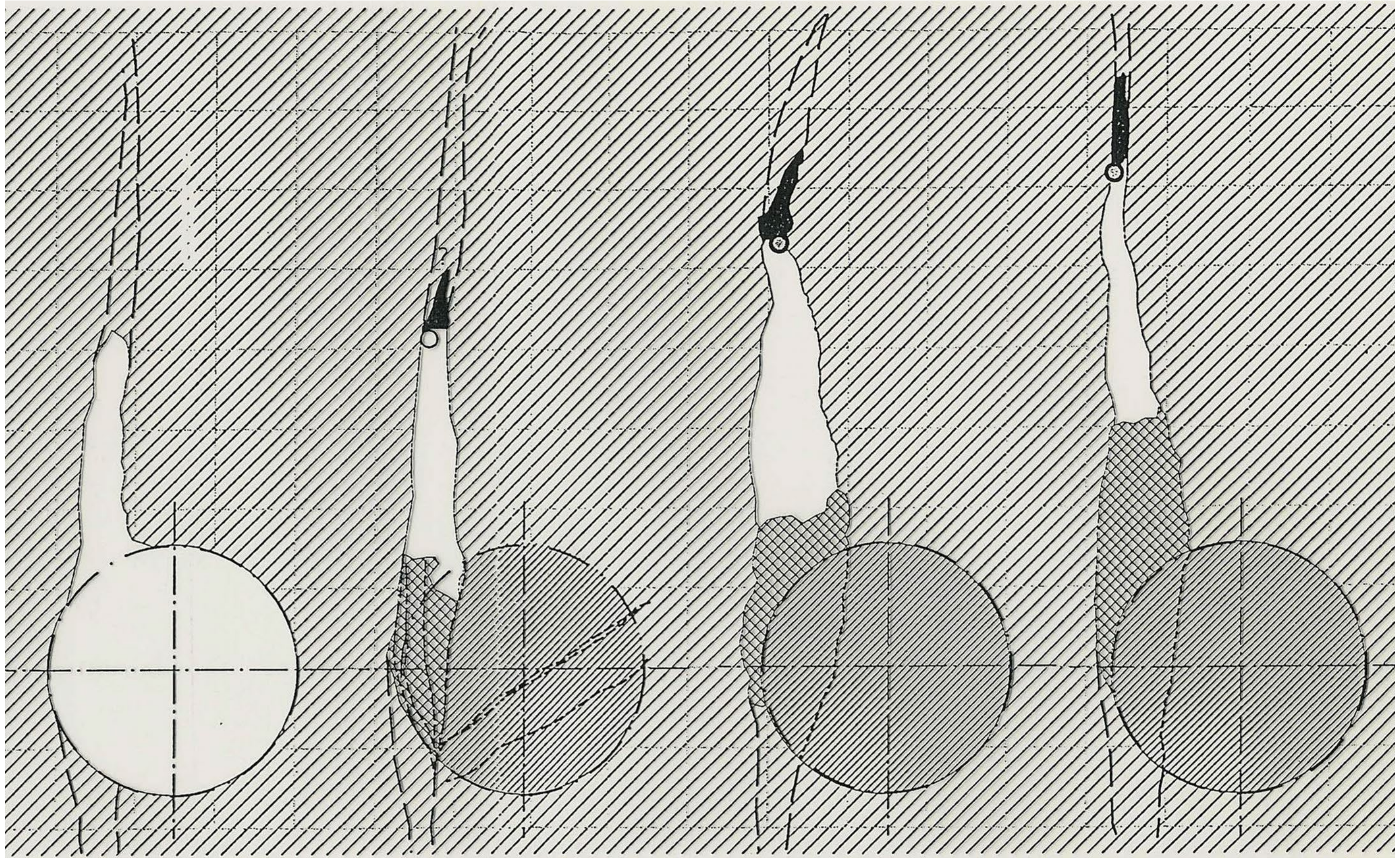
TBM STOPPED BY

MULTIPLE-FAULTS IN WATER-BEARING SCHISTS.

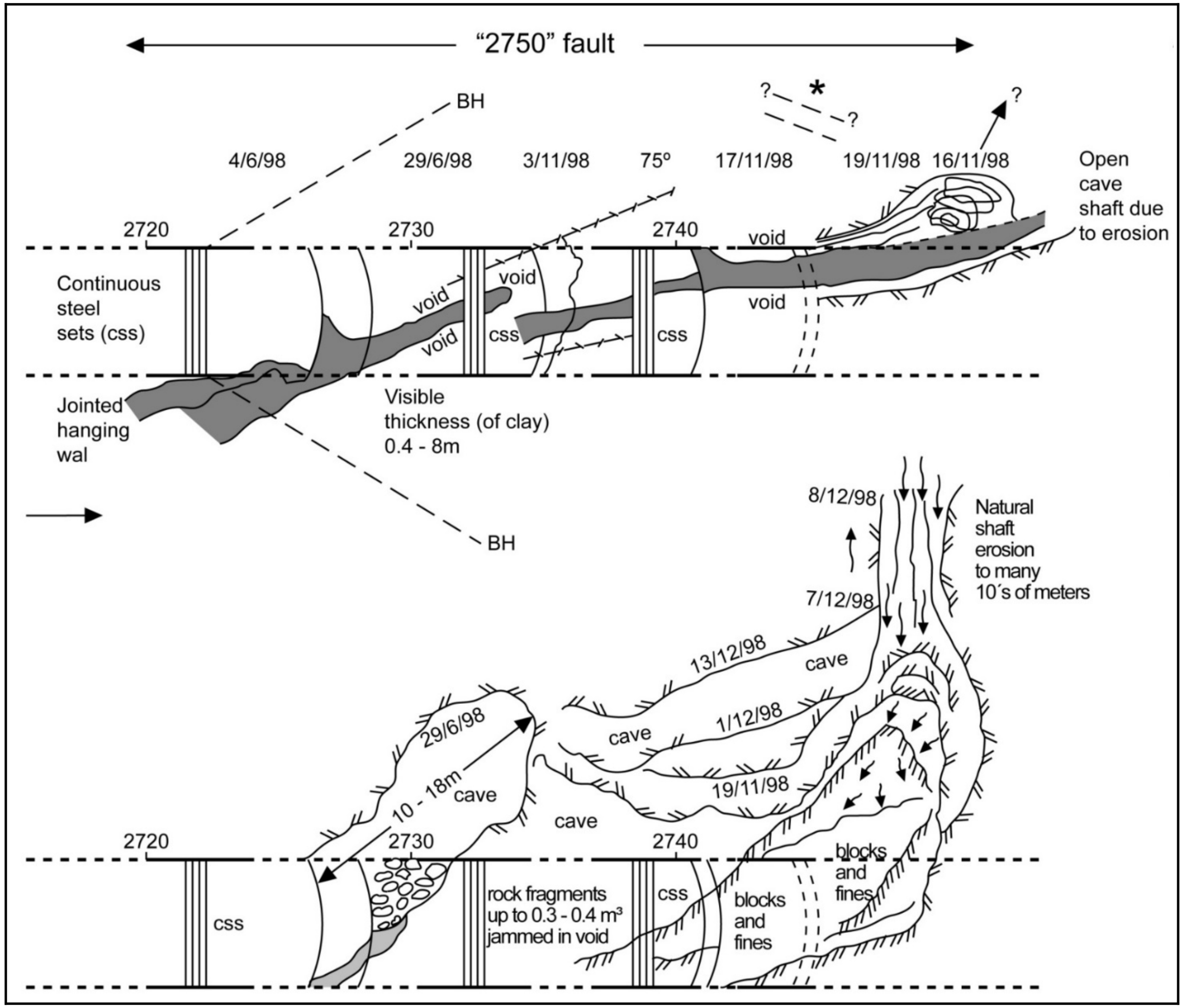
GEOLOGIC SECTION DRAWN AFTER TBM STUCK!

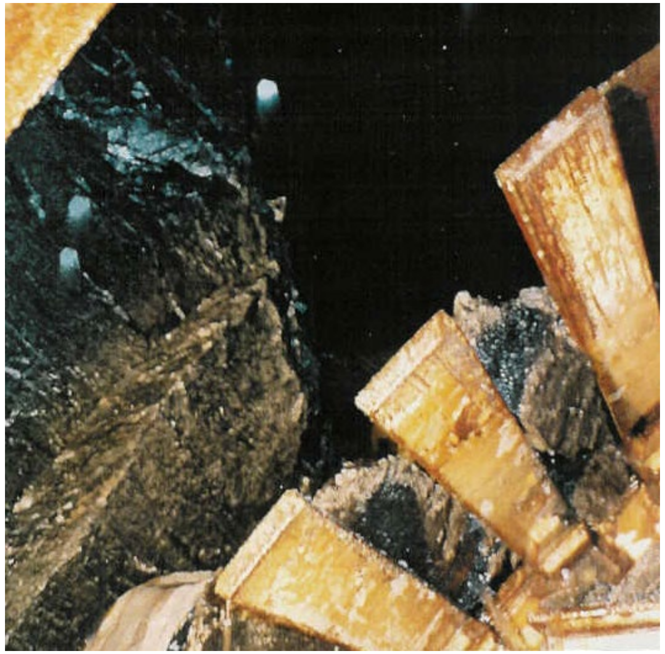


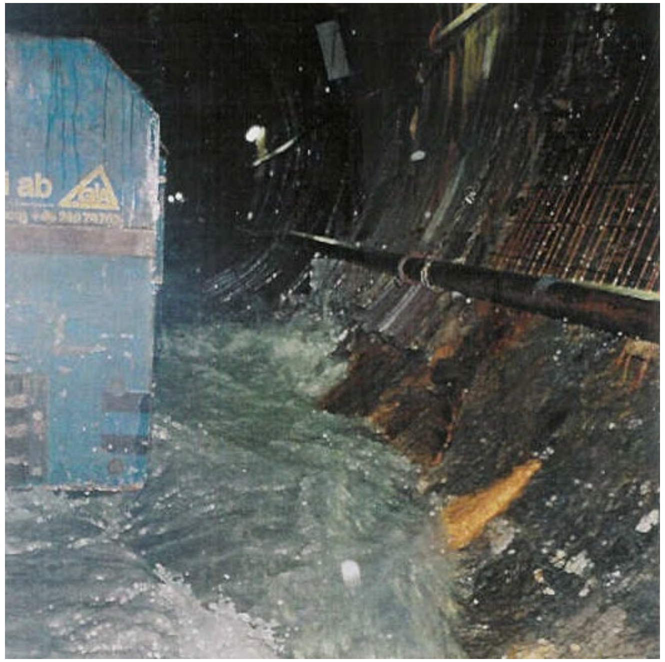
AN EXAMPLE of PROBLEMS : Fault at 2498-2517m



1. CLAY COMPROMISES GRIPPERS
2. WATER ERODES SHAFT AND LOOSENS BLOCKS
3.TUNNEL STABILITY REDUCES
4. CUTTER-HEAD REPEATEDLY BLOCKED







THIS SUB-PARALLEL FAULT DELAYED THE PROJECT 30m/5 months. SHAFT ERODED BY WATER AND FALLING BLOCKS. FINALLY D+B TO COMPLETE.

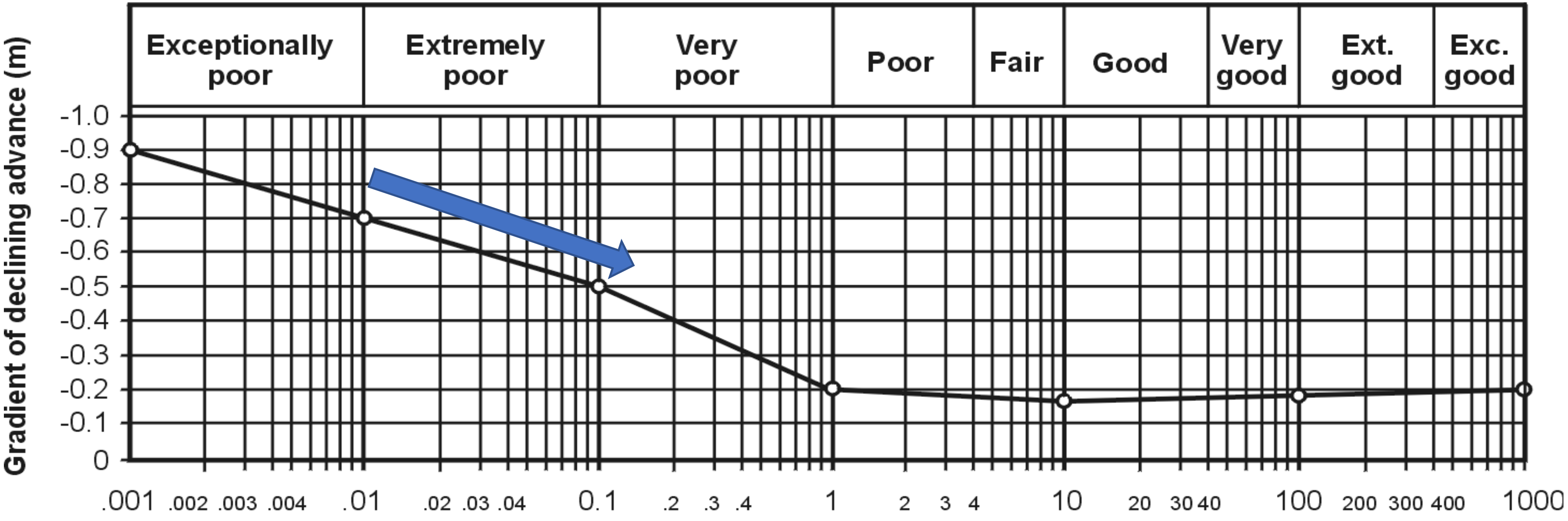
(Figures, photos, Karl G.Holter, NB) ....EXTREME –m VALUE

6. DECELERATION (-m) ACCENTUATED IN FAULT ZONES

DECELERATION GRADIENTS (-m) ARE *Q-VALUE RELATED: WHEN* Q < 1.

BUT MANY Q parameters CAN BE IMPROVED BY PRE-GROUTING !

(improves many Q-parameters, reduces negative –m)



Rock mass quality $\mathbf{Q} = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$

‘THEO – EMPIRICAL’ REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM.

We need three basic equations:

1. ***AR = PR x U*** **(all TBM must follow this)**

2. $U = T^m$ **(*decelerating advance rate* means time-dependent U)**

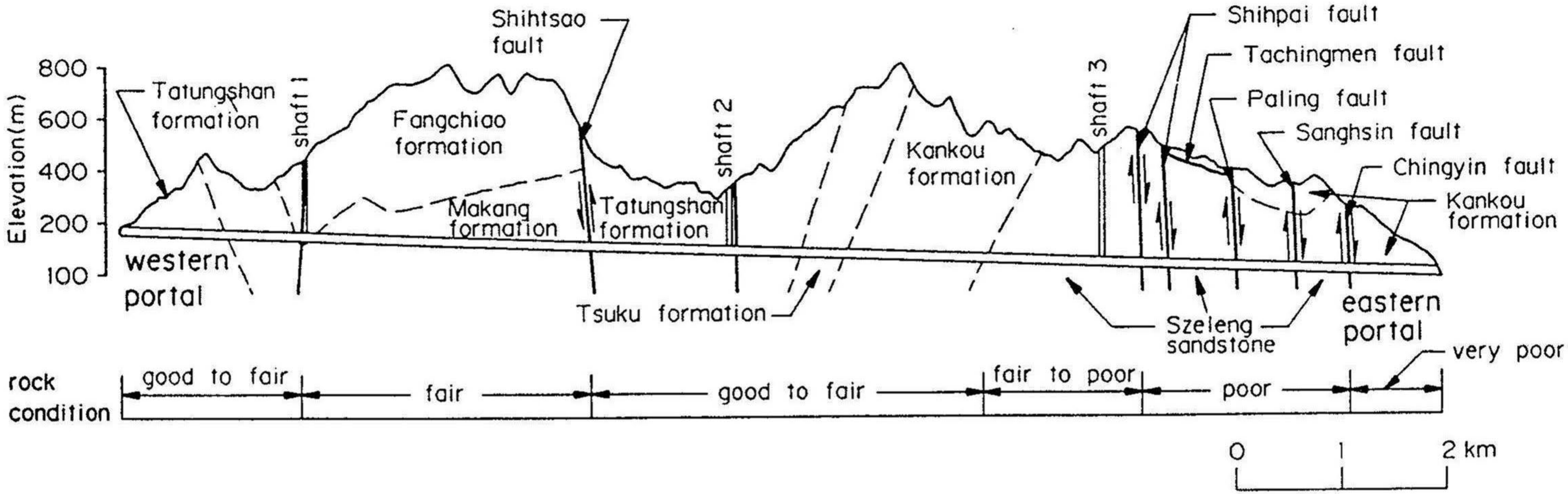
3. ***T = L / AR*** **(time for length L depends on AR……as when walking)**

Therefore we have the following:

4. $T = L / (PR \times T^m)$ **(from #1, #2 and #3)**

5. $T = (L / PR)^{(1/(1+m))}$

VERY important for TBM……because very *negative* (-)m values make the 1/(1+m) *component* TOO LARGE……time T gets too long (months or years)!

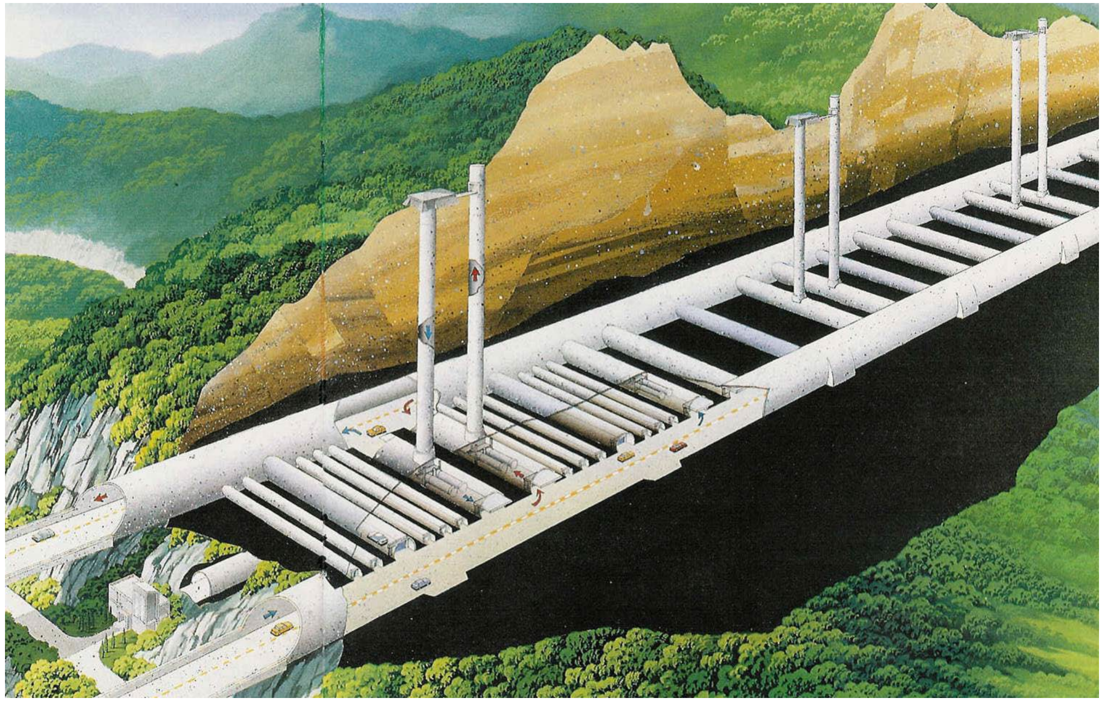


PINGLIN,TAIWAN

FAULT ZONE CHALLENGES.

INITIALLY THREE TBM FROM EASTERN PORTAL.

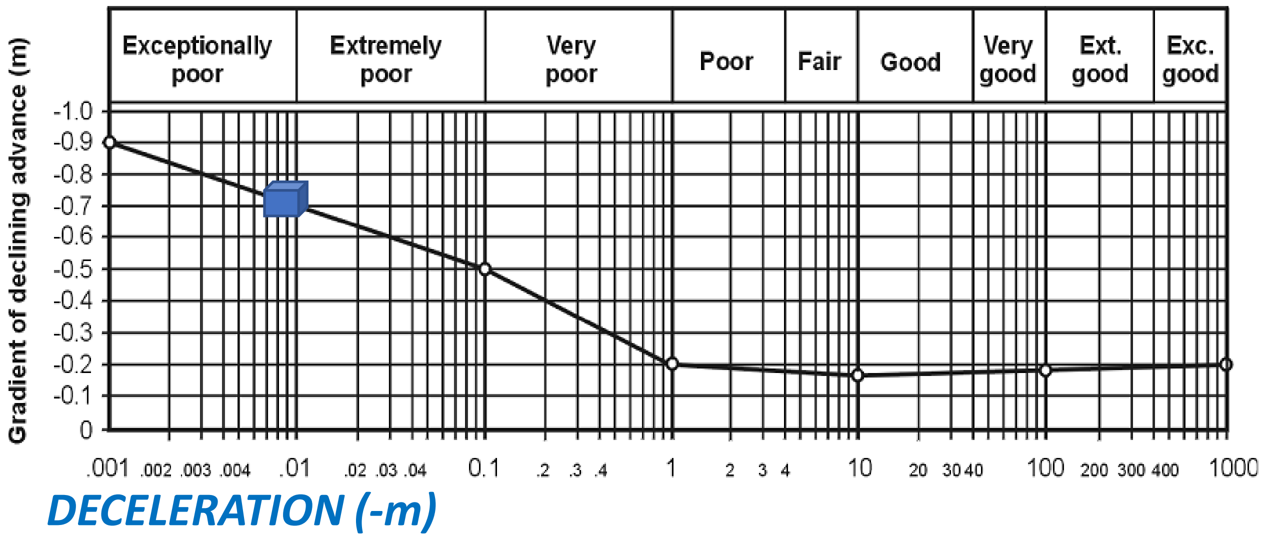
FINALLY all drill-and-blast.



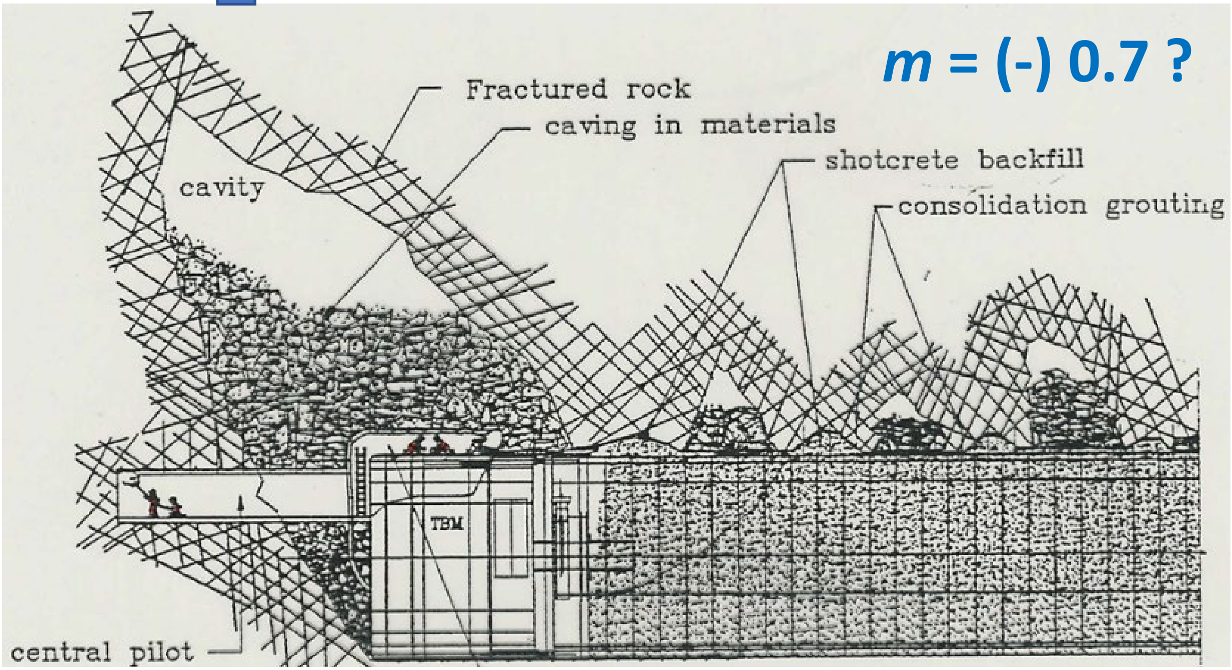
PILOT TBM IN CENTRE. BY-PASSED TO FREE CUTTER-HEAD > 13 TIMES.

OFTEN IN FAULTED ROCK MASS: META-SANDSTONES, CLAY-COATINGS, WATER.

DIFFICULTIES TO DRILL (AND INSERT PACKERS) INTO PRE-INJECTION HOLES.



Rock mass quality $Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$



Shen et al. 1999

1. AR = PR x U

(All TBM must follow this).

2. U = T^m

(*Reducing utilization with time,*

<u>time T must always be quoted</u>!

3. T = L / AR

Time T for advancing length L.

(Also applies to walking!)

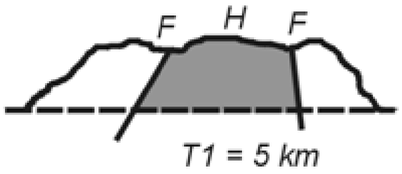
4. $T = (L/PR)^{1/(1+m)}$

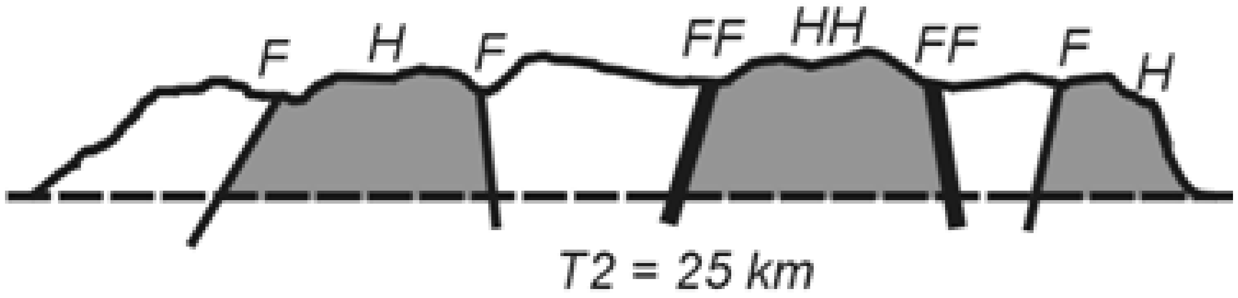
THIS IS (-ve) !!

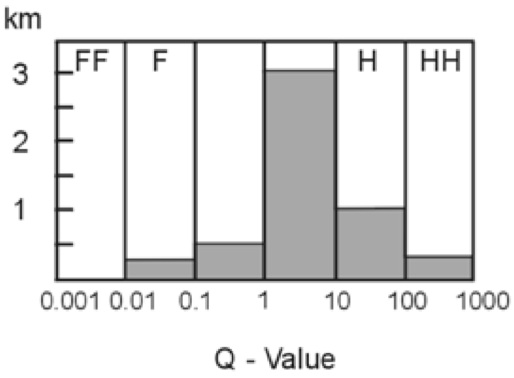
➢ $1/(1+m) = 1/(1-0.7) = 1 / 0.3$ **= 3.3!**

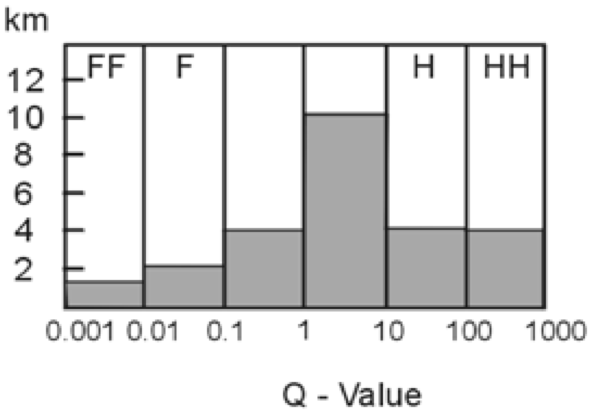
7. IS IT CORRECT TO USE TBM: *'BECAUSE THE TUNNEL IS SO LONG'?*

8. IS IT CORRECT TO USE TBM: '*BECAUSE ROCK CONDITIONS WILL BE SO BAD*'?





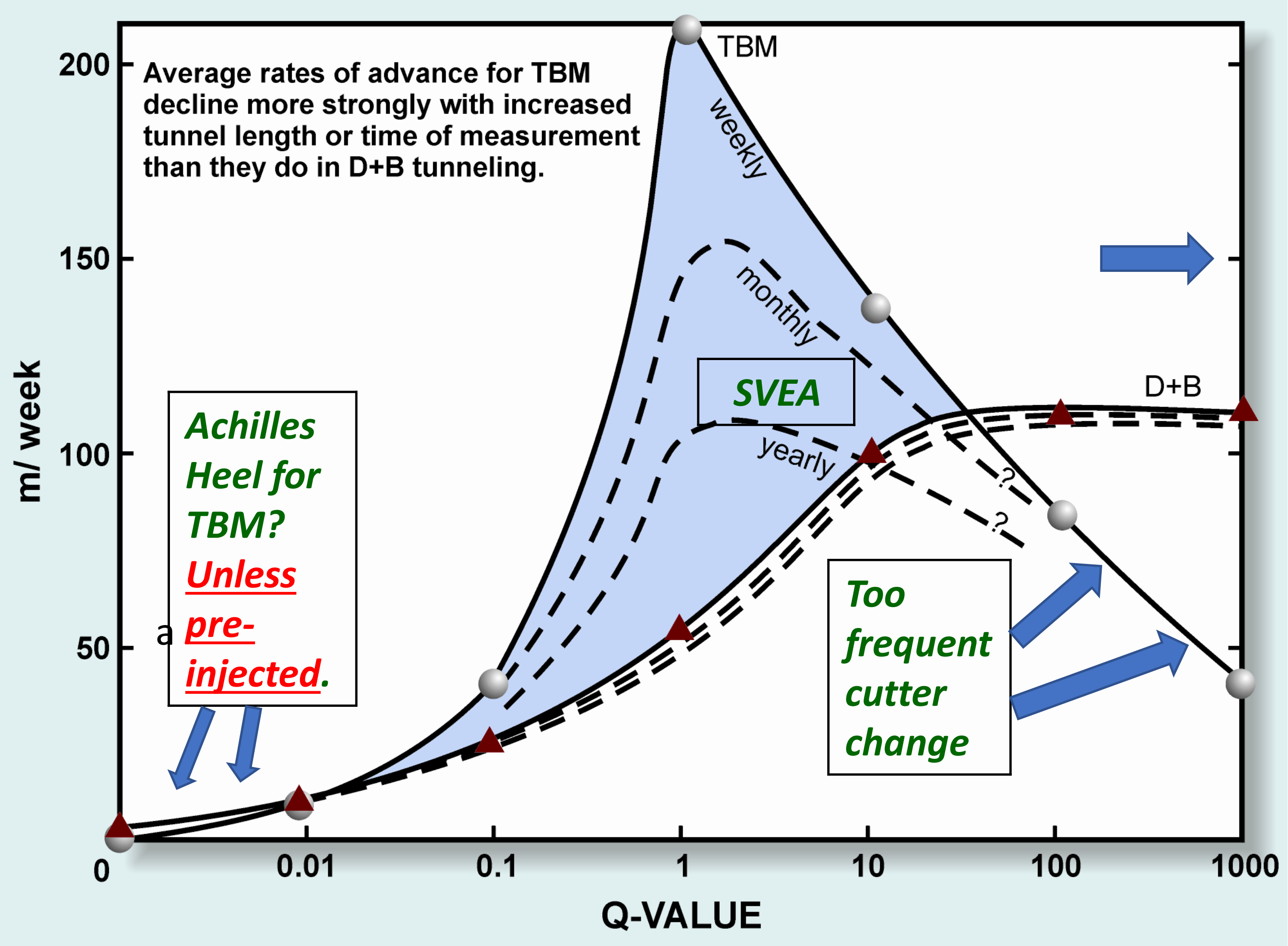




5 km, better investigated, fewer 'extremes', lower cover – probably.

25 km, much less investigated, maybe many 'extremes'

CENTRAL Q-VALUES *AND* Q_{TBM} VALUES BEST FOR TBM.
TAIL-DISTRIBUTIONS (of Q) ARE 'faster' WITH D+B !



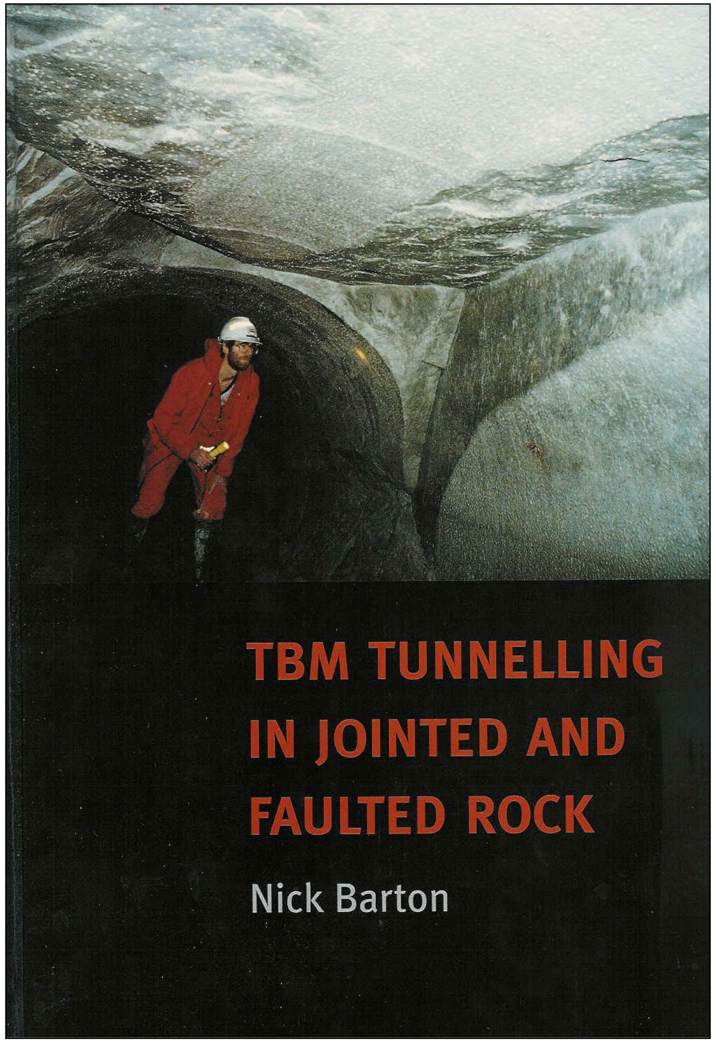
Record for drill-and-blast:

150m/BEST week (SVEA)

Whole project 104 m/week average, 5.8 km

9. Q_{TBM} PROGNOSIS DEVELOPMENT: Q WITH MACHINE-ROCK INTERACTION

DEVELOPMENT of ***Q**TBM* (extra parameters appended to Q). Analysis of case records TOOK SIX MONTHS, WHILE WRITING THIS BOOK AND THE FIRST ARTICLE, both in 1999.



TBM performance estimation in rock using Q_{TBM}

Nick Barton, Technical Adviser, NGI, Norway, Visiting Professor at the University of São Paulo, Brazil, has developed a new method for predicting penetration rate (PR) and advance rate (AR) for TBM tunnelling. This method is based on an expanded Q-system of rock mass classification and average cutter force in relation to the appropriate rock mass strength. Orientation of fabric or joint structure is accounted for, together with the compressive or point load (tensile) strength of the rock. The abrasive or non-abrasive nature of the rock is incorporated via the University of Trondheim cutter life index (CLI). Rock stress level is also considered. The new parameter Q_{TBM} can be estimated during feasibility studies, and can also be back calculated from TBM performance during tunnelling.

Fig 1. The challenge of faulted rock is still causing big delays in TBM tunnelling and needs quantifying?

TBM tunnelling may give extremes of 15km/year and 15m/year, sometimes even less. The expectation of fast tunnelling places great responsibility on those evaluating the geology and hydrogeolgy along a planned tunnel route. When rock conditions are reasonably good, a TBM may be two to four times faster than drill+blast. The problems lie in the extremes of rock mass quality, which can be both too bad, as in Fig 1, and too good (no joints), where alternatives to TBM methods may be faster.

There has been a long-standing challenge to develop a link between rock mass characterisation and essential machine characteristics such as cutter load and cutter wear, so that surprising rates of advance (or slowness) become the expected rates. Even from a 1967 TBM tunnel Robbins[7] could report 7.5km of advance in shale during four record breaking months. Yet, earlier in the same project, 270m of unexpected glacial debris had taken nearly seven months. Advance rates (AR) of 2.5m/h that can decline to 0.05m/h in the same project need to be explained by a quantitative rock mass classification.

A penetration rate (PR) pushing 10m/h for short periods is so different from an advance rate through a major regional fault zone as slow as 0.005 m/h that a large range of quality seems to be required. The new parameter Q_{TBM} can range over 12 orders of magnitude but each end of the scale is exceptionally unfavourable for progress and project economy.

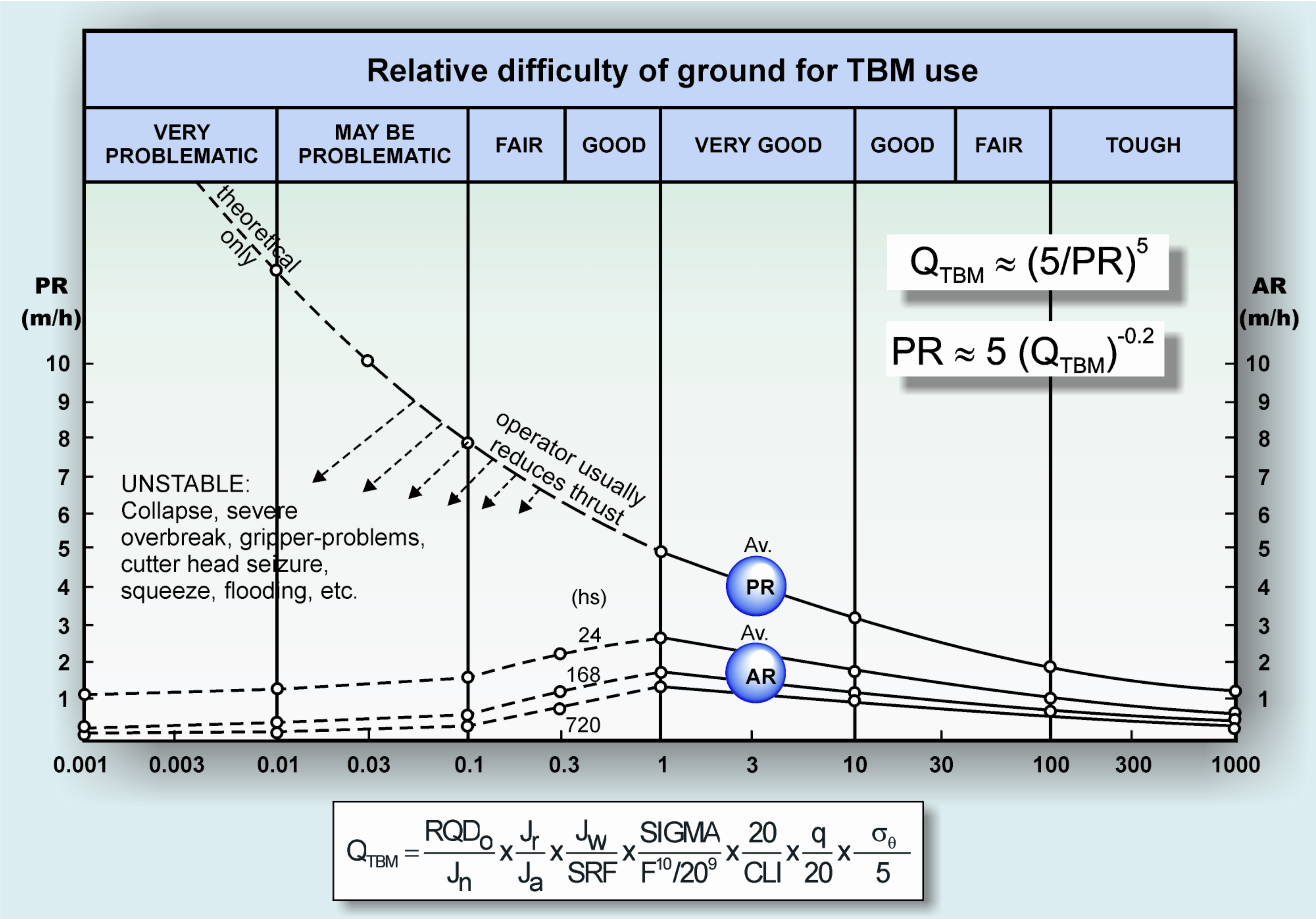
THE Q_{TBM} MODEL FOR TBM PROGNOSIS

involves Q , and machine/rock interaction ‘normalizations’

$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{\left(F^{10}/20^9\right)} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

$$SIGMA \approx 5\,\gamma\,Q_c^{1/3}$$

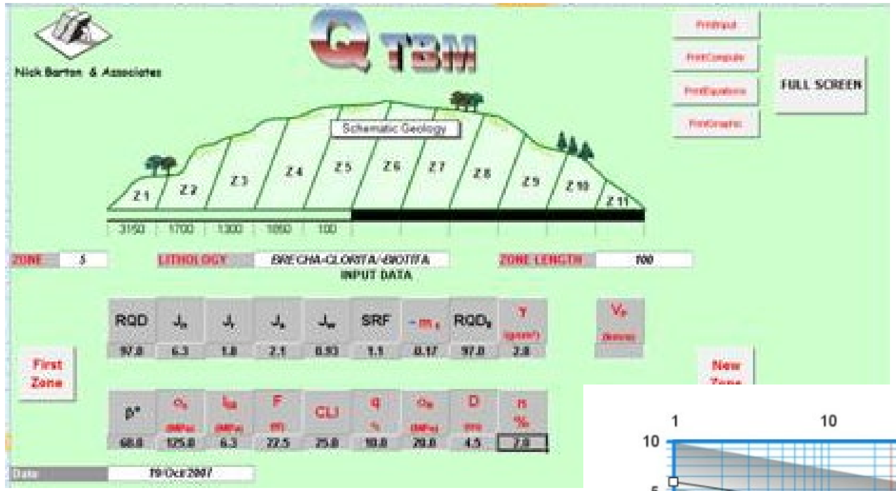
$$PR \approx 5\,Q_{TBM}^{-1/5}$$

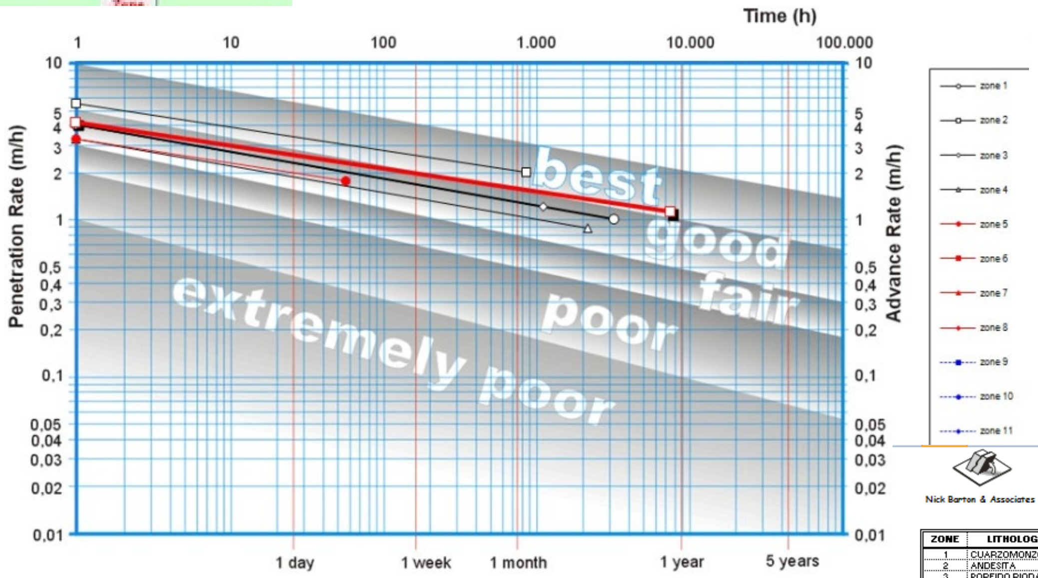


THE QTBM EQUATION WAS DEVELOPED BY TRIAL AND ERROR.

MOST ‘ADDITIONS’ TO Q-PARAMETERS ARE *‘NORMALIZED BY CENTRAL VALUES’*

THE THREE QTBM SCREENS
(DETAILS SHOWN NEXT)
DEVELOPED FROM NB EQUATIONS
BY Ricardo Abrahão, RAGeociencias





Nick Barton & Associates

Q TBM

Contract *SRK / ANGLO AMERICAN - CHILE*
Site *LOS BRONCES*
Date *19-Oct-07*

INPUT DATA

ZONE	LITHOLOGY	RQD	J_n	J_r	J_a	J_w	SRF	m_1	RQD_0	γ	β°	σ_c	I_{50}	F	CLI	q	σ_θ	D	n	L	Vp
1	CUARZOMONZONITA	92.00	6.10	1.70	2.10	0.92	0.90	-0.17	92.00	2.80	60.00	200.00	10.00	27.50	10.00	10.00	15.00	4.50	2.00	3,150.00	0.00
2	ANDESITA	71.00	11.60	1.60	2.60	0.78	1.30	-0.19	71.00	2.80	60.00	150.00	7.70	22.50	55.00	10.00	25.00	4.50	2.00	1,700.00	0.00
3	PORFIDO RIODACITIC	97.00	6.80	1.50	2.30	0.92	1.00	-0.17	97.00	2.80	60.00	200.00	10.00	27.50	10.00	10.00	25.00	4.50	2.00	1,300.00	0.00
4	BRECHA TURMALINA	88.00	5.30	1.70	2.00	0.96	1.20	-0.17	88.00	2.80	60.00	150.00	7.50	25.00	10.00	10.00	20.00	4.50	2.00	1,850.00	0.00
5	BRECHA-CLORITA/-BI	97.00	6.30	1.80	2.10	0.93	1.10	-0.17	97.00	2.80	60.00	125.00	6.25	22.50	25.00	10.00	20.00	4.50	2.00	100.00	0.00
6																				0.00	0.00
7																				0.00	0.00
8																				0.00	0.00
9																				0.00	0.00
10																				0.00	0.00
11																				0.00	0.00

BASIC CALCULATION

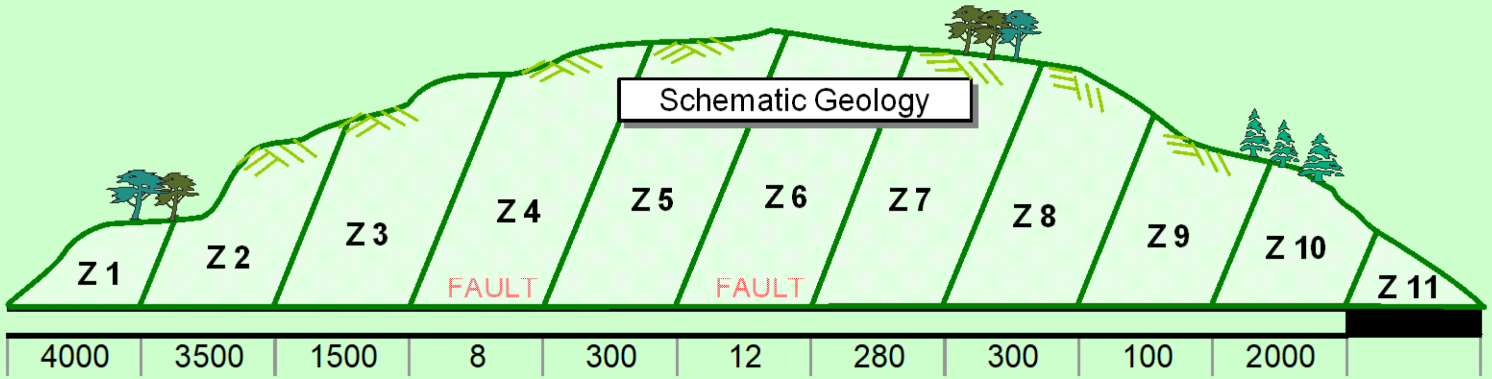
ZONE	LITHOLOGY	STABILITY	ORIENTED	ROCK MASS STRENGTH					Q	GRADIENT
		Q	Q0	Qc	QT	$SIGMA_{CM}$	$SIGMA_{TM}$	SIGMA	TBM	m
1	CUARZOMONZONITA	12.48	12.48	24.96	31.20	40.91	44.07	40.91	**3.17**	-0.17
2	ANDESITA	2.26	2.26	3.39	4.35	21.03	22.85	21.03	**0.67**	-0.15
3	PORFIDO RIODACITIC	8.56	8.56	17.12	21.40	36.08	38.87	36.08	**3.20**	-0.17
4	BRECHA TURMALINA	11.29	11.29	16.94	21.17	35.95	38.73	35.95	**8.72**	-0.17
5	BRECHA-CLORITA/-BI	11.16	11.16	13.95	17.43	33.70	36.30	33.70	**9.26**	-0.15
6									**0.00**	0.00
7									**0.00**	0.00
8									**0.00**	0.00
9									**0.00**	0.00
10									**0.00**	0.00
11									**0.00**	0.00

PERFORMANCE

ZONE	LITHOLOGY	PENETRATION		TIME TO ADVANCE		OVERALL PERFORMANCE		
		PR	AR	T	check	ΣL	ΣT	
1	CUARZOMONZONITA	3.97	0.99	3,186.25	3,150.00	8,100.00 m	7,336.26 h	PRL(av) 4.10
2	ANDESITA	5.42	1.98	858.23	1,700.00			
3	PORFIDO RIODACITIC	3.96	1.19	1,095.75	1,300.00			
4	BRECHA TURMALINA	3.24	0.87	2,138.68	1,850.00			
5	BRECHA-CLORITA/-BI	3.20	1.74	57.35	100.00			
6		0.00	0.00	0.00	0.00	8.10 km	10.19 month	ART(av) 1.10
7		0.00	0.00	0.00	0.00			
8		0.00	0.00	0.00	0.00			
9		0.00	0.00	0.00	0.00			
10		0.00	0.00	0.00	0.00			
11		0.00	0.00	0.00	0.00			

Nick Barton & Associates

Q TBM



ZONE	10	LITHOLOGY	QUARTZ MONZONITE	ZONE LENGTH	2,000

INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)
100.0	4.0	3.0	1.0	1.00	1.0	-0.18	100.0	2.8

V_P (km/s)

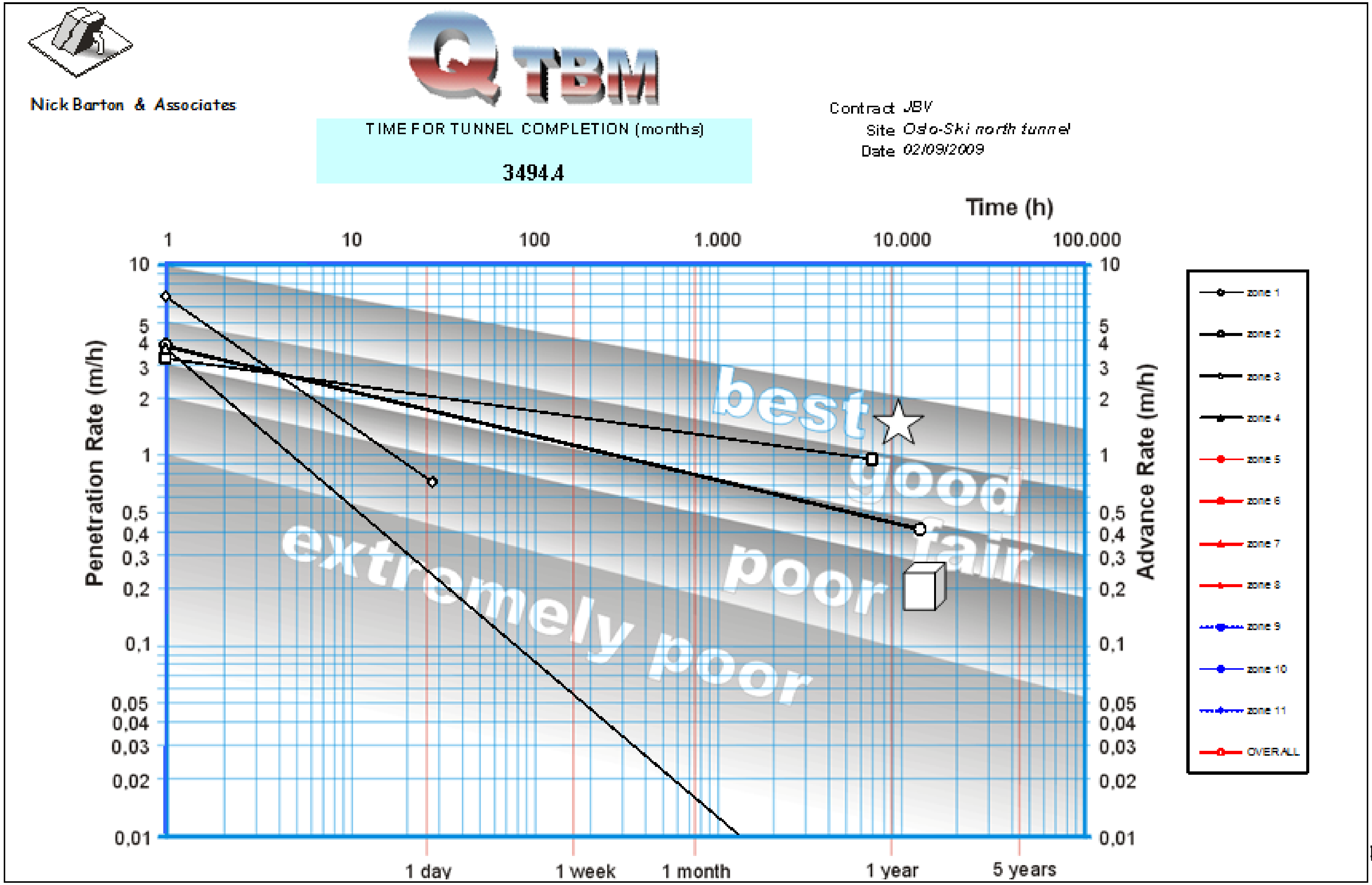
β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
60.0	250.0	15.0	31.0	4.0	24.0	15.0	8.0	1.0

TYPICAL INPUT DATA SCREEN

(assumed Q and Qtbm data is shown for Z10)

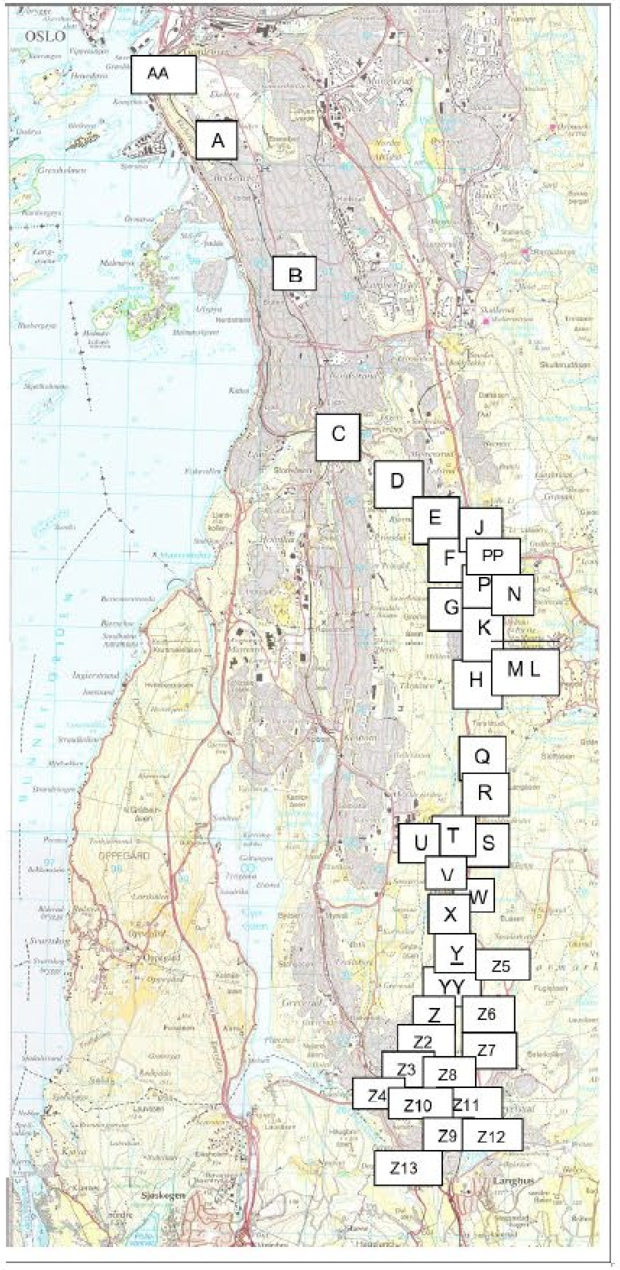
Example of single-shield (▢) and double-shield (★) *(F = 28 or 26 tnf).*

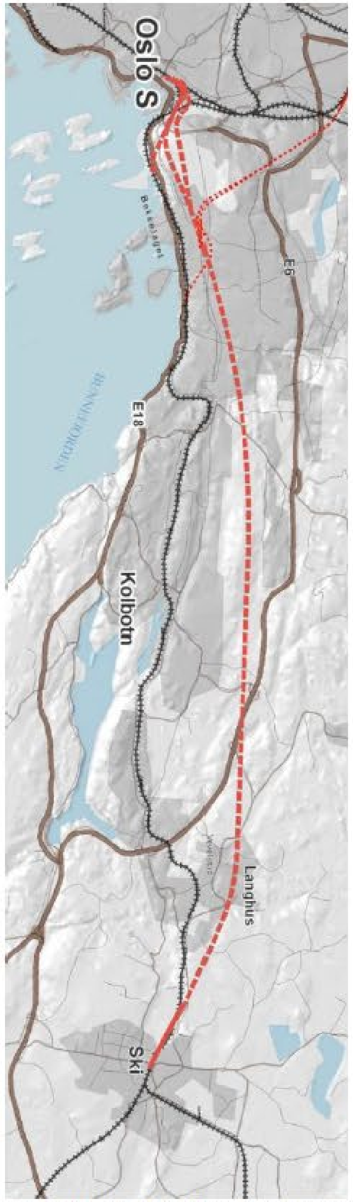
(Note: untreated major fault (LOWEST LINE) stops TBM 'for ever' (290yr in simulation)



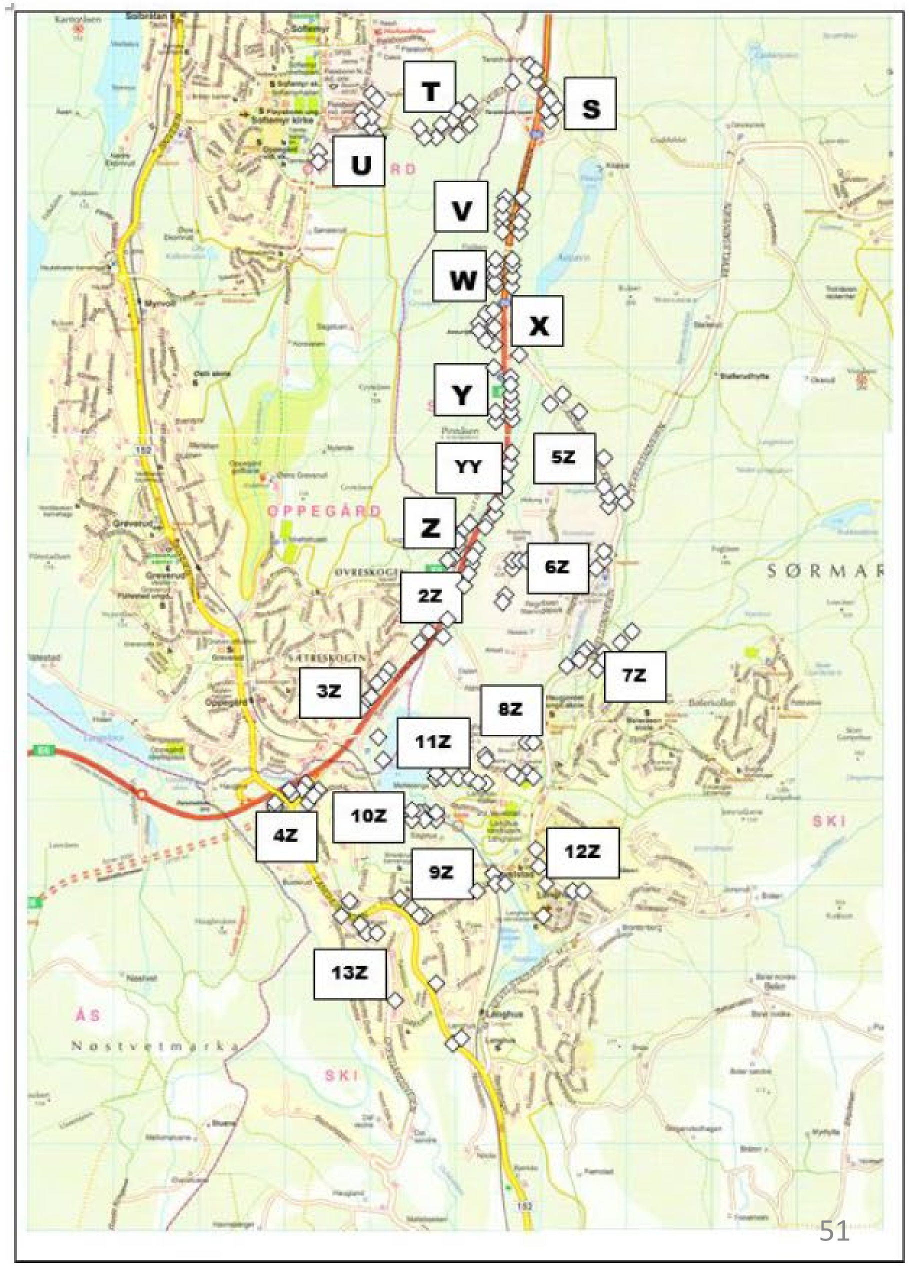
10. APPLICATION OF Q_{tbm} on FOLLOBANEN

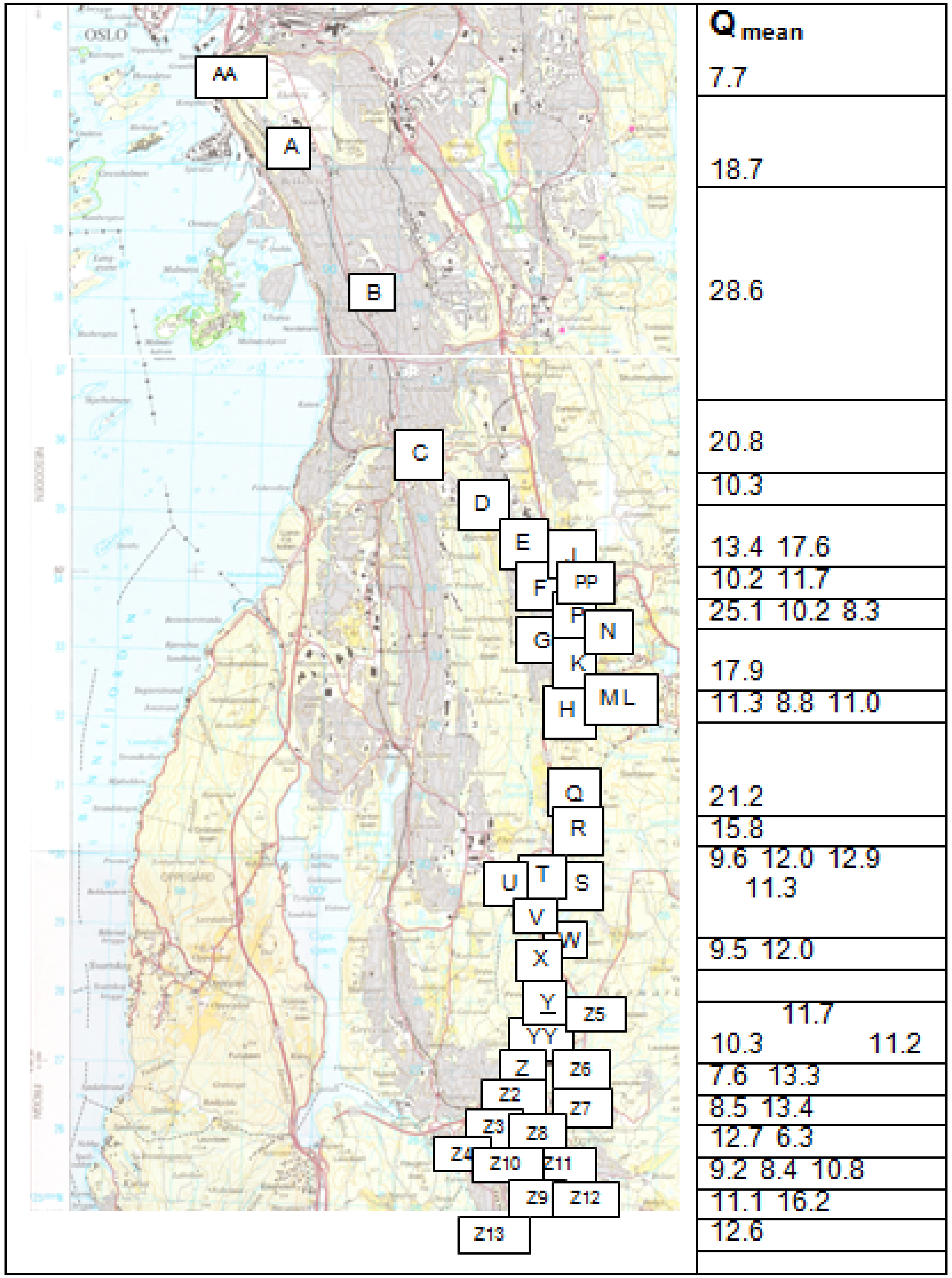
FOLLO.....330 rock cuttings Q-logged in 3 weeks in 2009





MORE EXPOSURES IN SOUTH. SOME VARIABILITY DUE TO 'WIDTH'



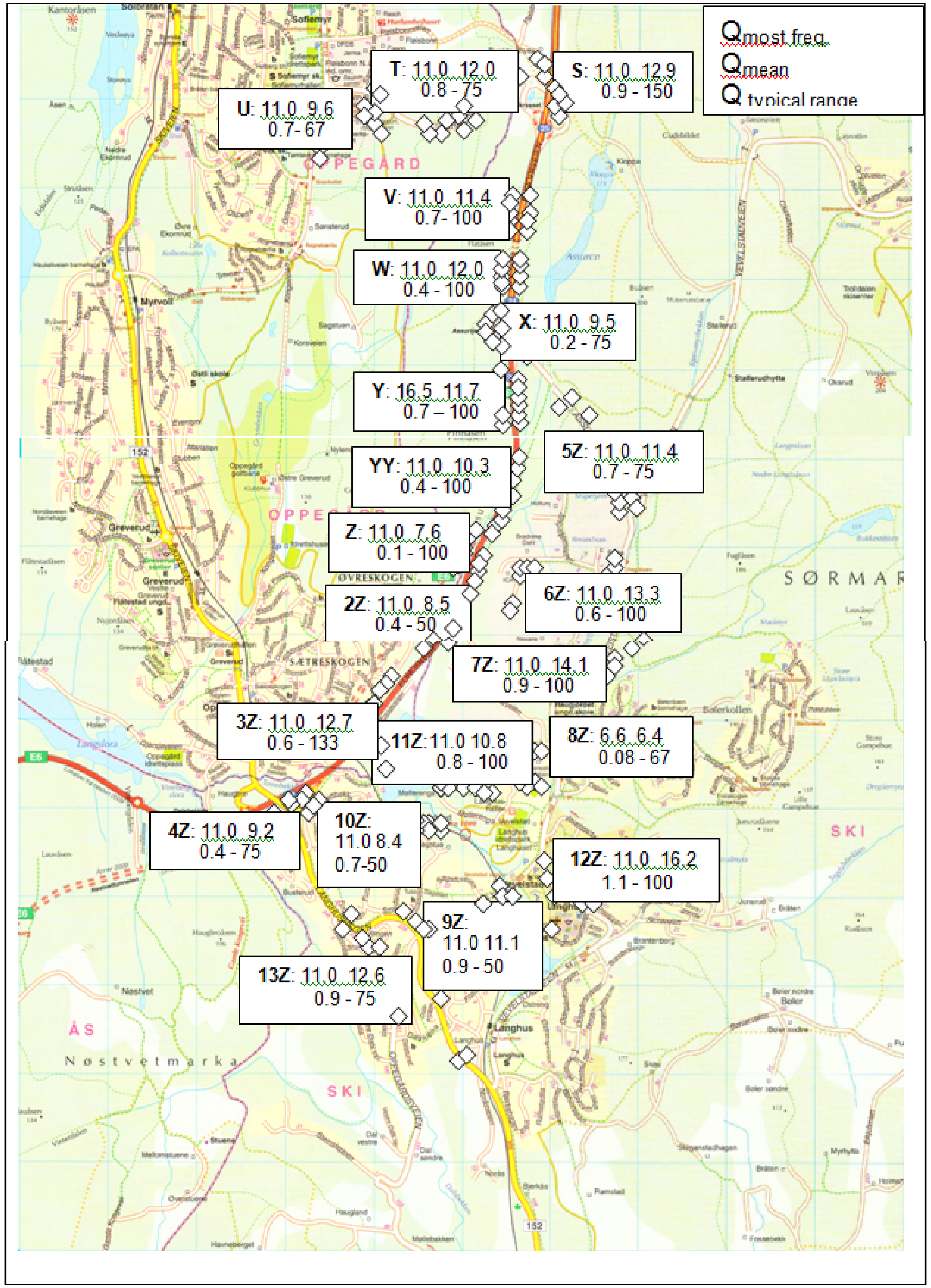


SUMMARY OF mean Q-VALUES FOR 330 ROCK CUTTINGS (nine-per-box) FOR BOTH TUNNELS

NOTE: CUTTINGS (EXPOSURES) GIVE ROCK MASS *Q-CLASSES 1 TO 5*

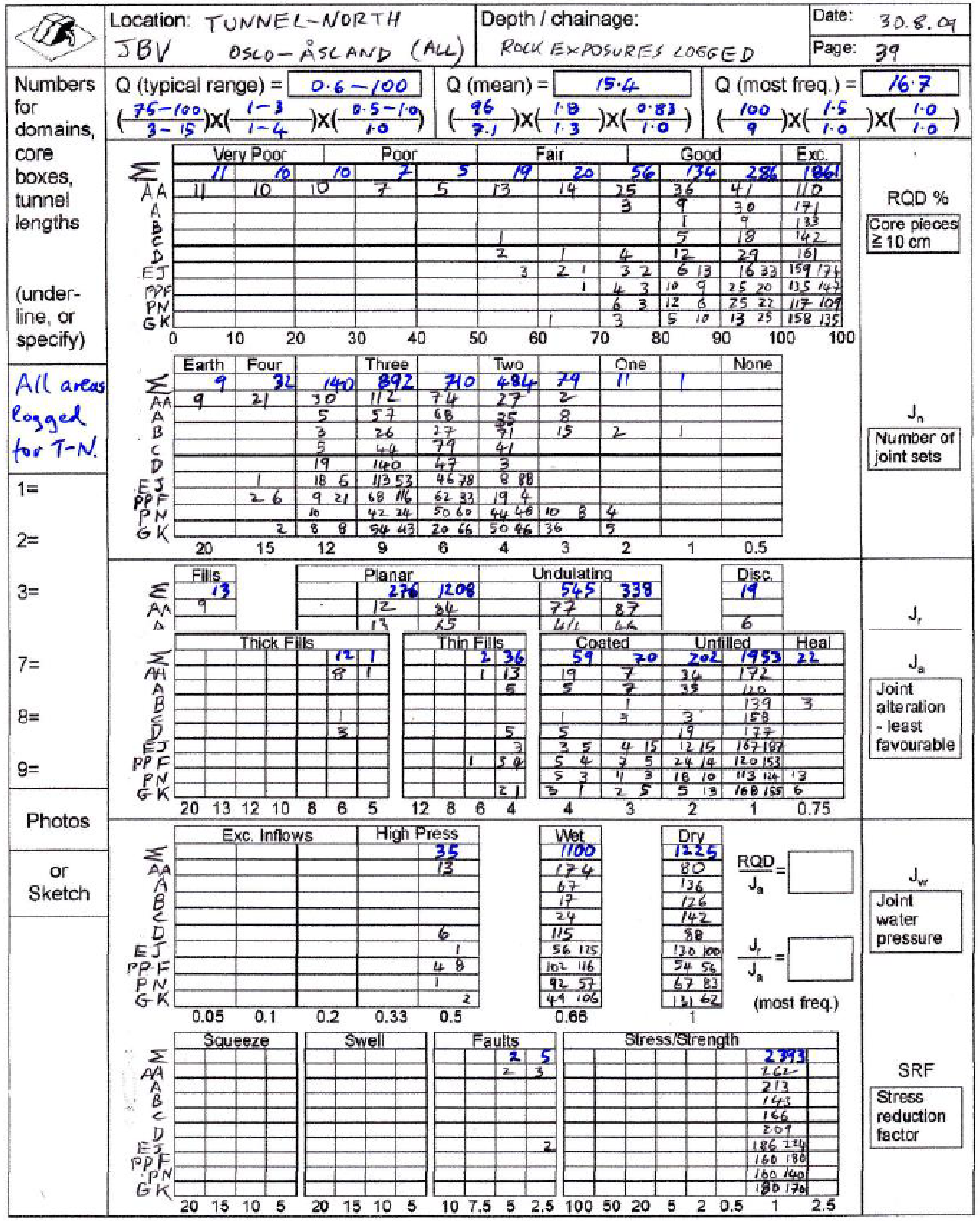
WEAKNESS ZONES / FAULTS GIVE *Q-CLASSES 6 TO 8*

(LOW V_P, LOW Q IN CORE-LOGGING)



SUMMARY OF Q-VALUE STATISTICS (classes 1 to 5) FOR SOUTHERN TUNNELS.

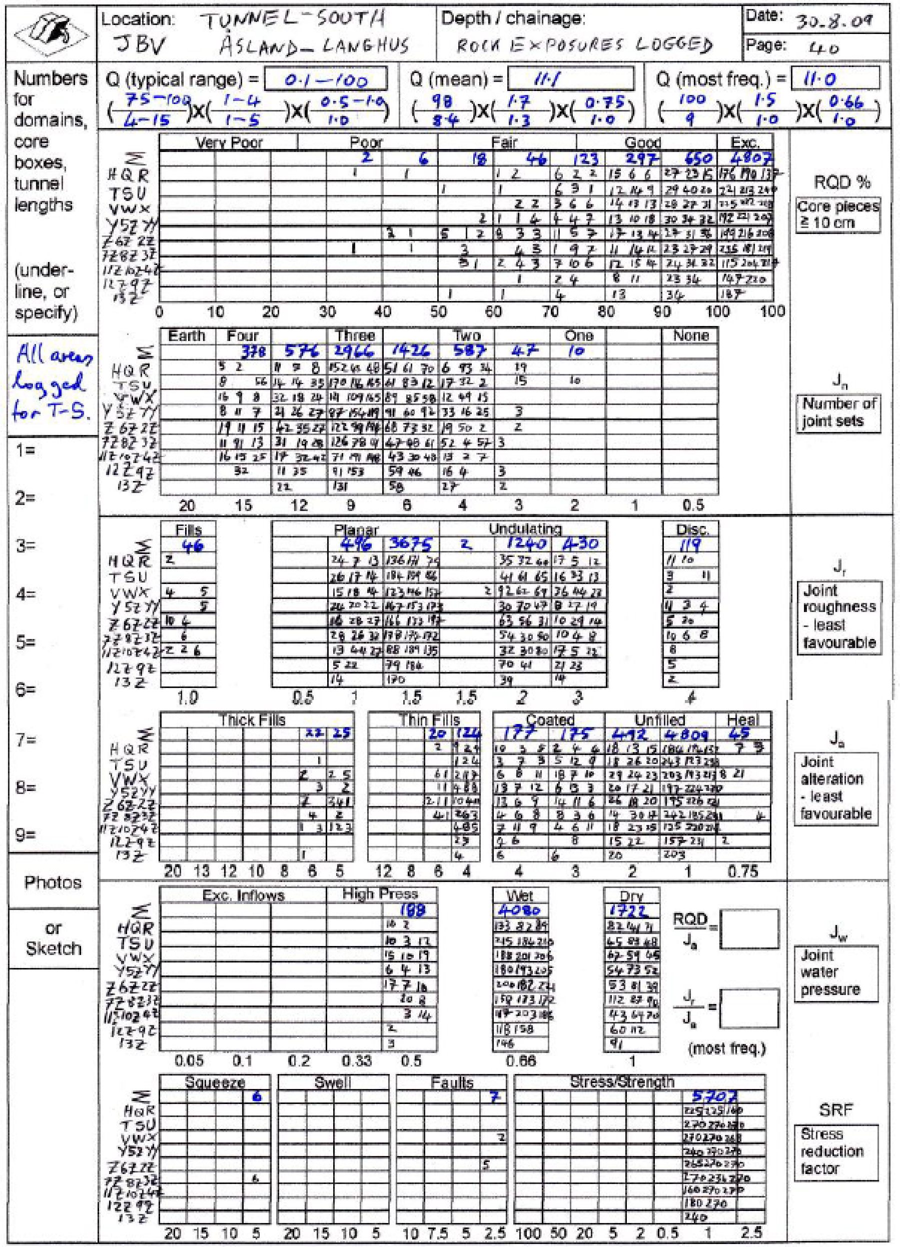
(Fault zones treated separately, using core-logging and seismic refraction)



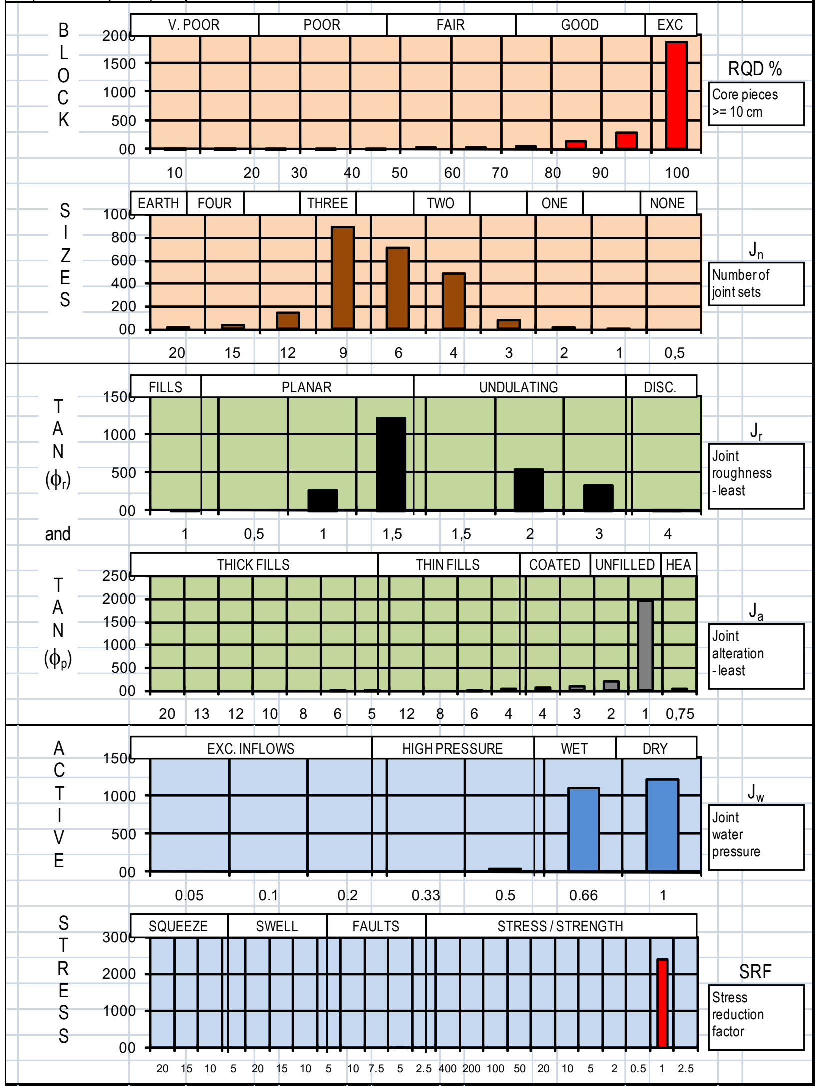
NOT EXACTLY 'ALL-PINK' WITH MINIMAL VARIATION.

LOW Vp FRACTURED ZONES **NOT INCLUDED**

Each letter represents nine locations.



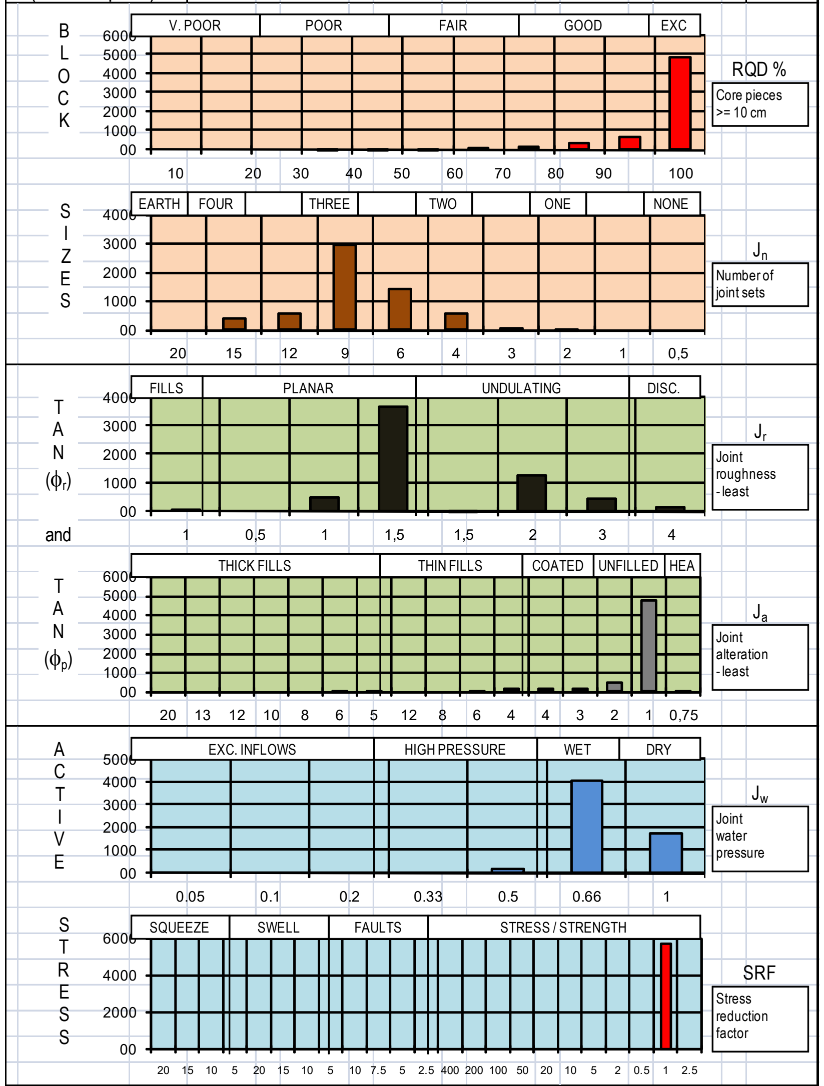
Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	4.0	*	0.50	/	1.0	=	0.625
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	1.0	=	100.0
Q (mean value)=	96	/	7.1	*	1.8	/	1.3	*	0.83	/	1.0	=	15.36
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	1.00	/	1.0	=	16.67



JBV OSLO-SKI	Rev.	Report No. NB&A #1	Figure No. 9
Q-histogram based on compilation of all rock-exposure	Borehole No. : rock exposures	Drawn by NB&A	Date 30.8.09
logging for TUNNEL-NORTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	

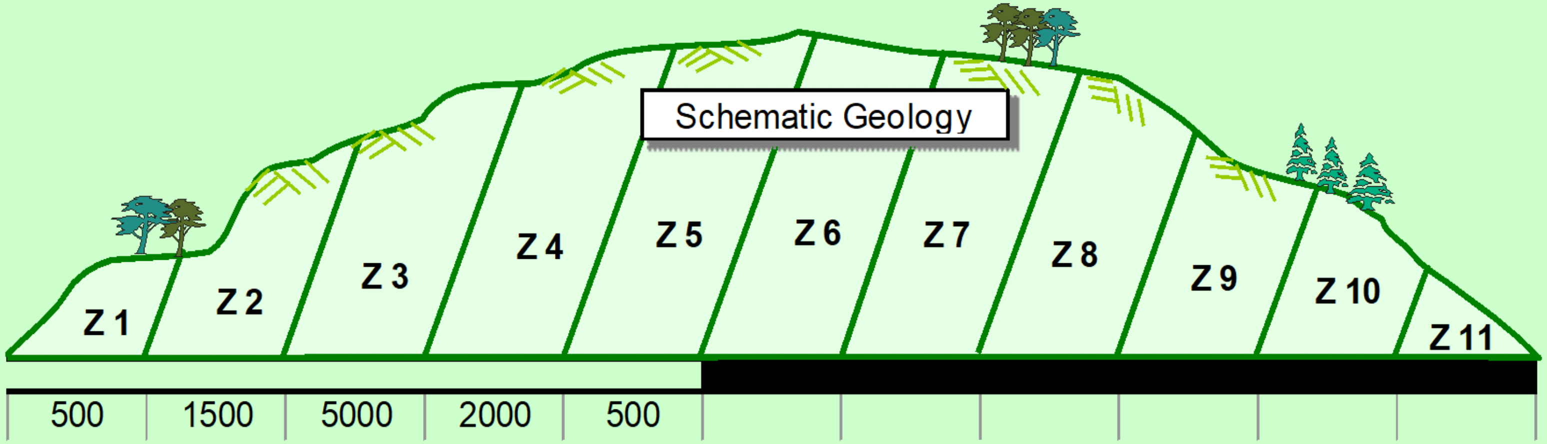
NORTH + SOUTH TUNNELS

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	5.0	*	0.50	/	1.0	=	0.500
Q (typical max)=	100	/	4.0	*	4.0	/	1.0	*	1.00	/	1.0	=	100.0
Q (mean value)=	98	/	8.4	*	1.7	/	1.3	*	0.75	/	1.0	=	11.07
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	0.66	/	1.0	=	11.00



JBV OSLO-SKI	Rev.	Report No. NB&A #1	Figure No. 10
Q-histogram based on compilation of all rock-exposure	Borehole No. : Rock slopes	Drawn by NB&A	Date 31.8.09
logging for TUNNEL-SOUTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	

Values given in Javier Macias lecture.
(JM and NB,2022)



ZONE	5	LITHOLOGY	*Class 1 granitic gneiss*	ZONE LENGTH	*500*

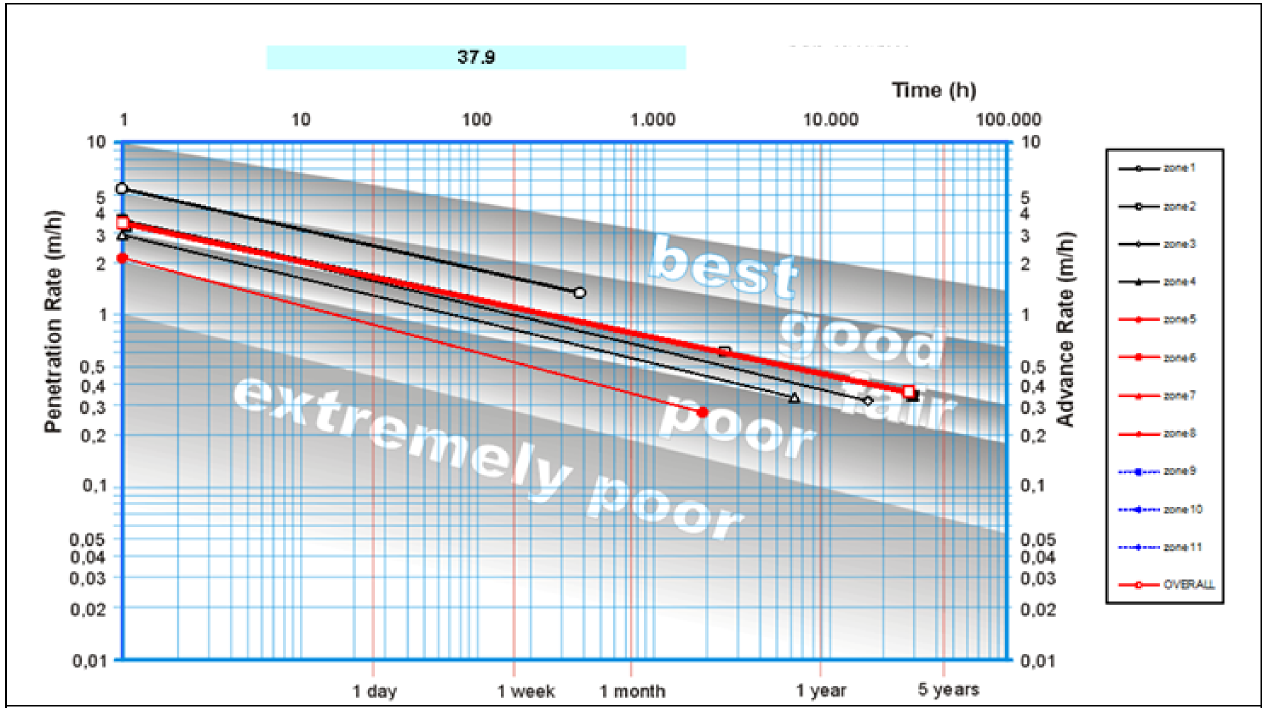
INPUT DATA

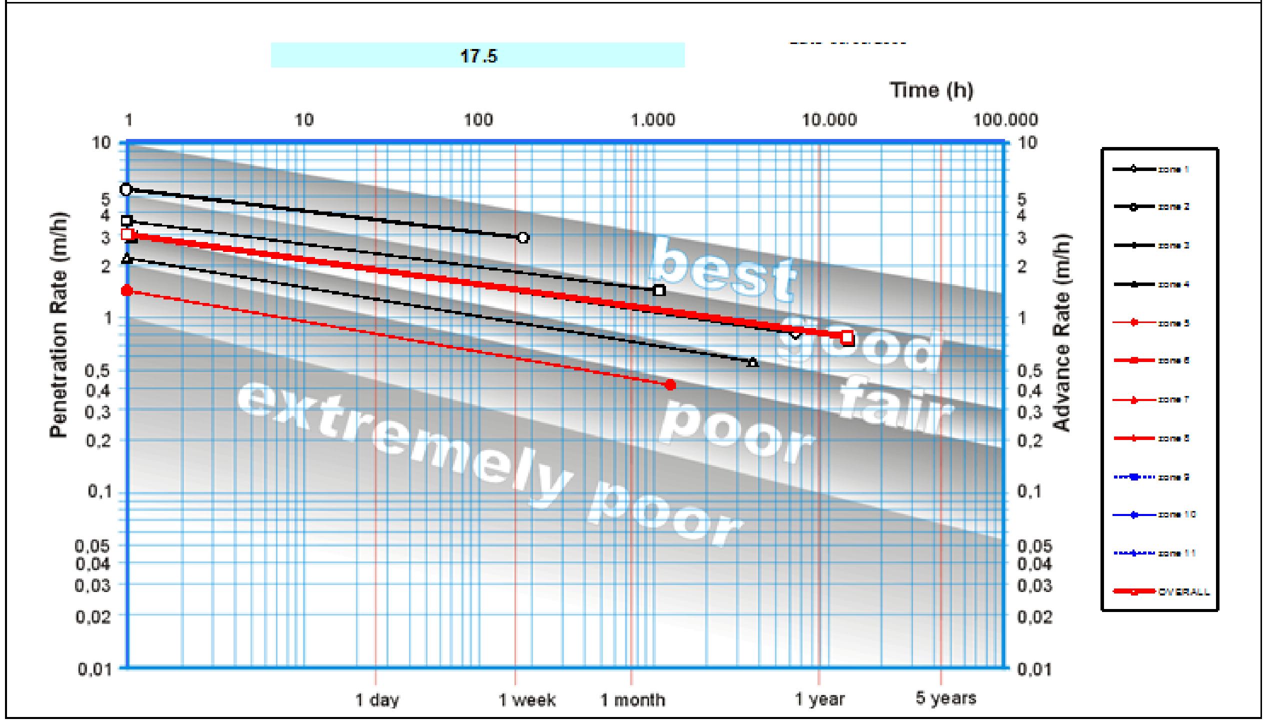
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm^3)	V_P (km/s)
100.0	2.0	3.0	1.0	1.00	1.0	-0.19	100.0	2.8	

β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	250.0		32.0	5.0	35.0	8.0	10.0	1.0

INPUT-DATA SCREEN FOR ASSUMED (in 2009) CLASS 1 ROCK MASS.

MANY ADVERSE CHARACTERISTICS FOR TBM: hard rock, too few joints, LOW PR).





NORTH TUNNELS

Comparing open-gripper TBM (top) and double-shield TBM (bottom).

(37.9 months or optimistic (1/2 x –m) 17.5 months, both without weakness zones).

Assumed distribution of rock classes in the North and South tunnels (in 2009 analyses)

(Representative mean depths are shown in parentheses).

Poorer rock classes Q6, Q7 and Q8 were evaluated by means of V_P from *refraction seismic profiles* in known weakness zones, *and logging of relevant lengths of core.*

Much more Q2, less Q3, less Q4…with benefit of more Vp data

TUNNEL	Q1 Q > 100	Q2 Q 40-100	Q3 Q 10-40	Q4 Q 10-4	Q5 Q 4-1
North L≈ 9.6km	500 *(160)*	2000 *(120)*	5000 *(100)*	1500 *(80)*	500 *(70)*
South L≈ 7.9 km	200 *(130)*	1000 *(110)*	2500 *(80)*	1750 1750 *(60)* *(30)*	500 *(30)*

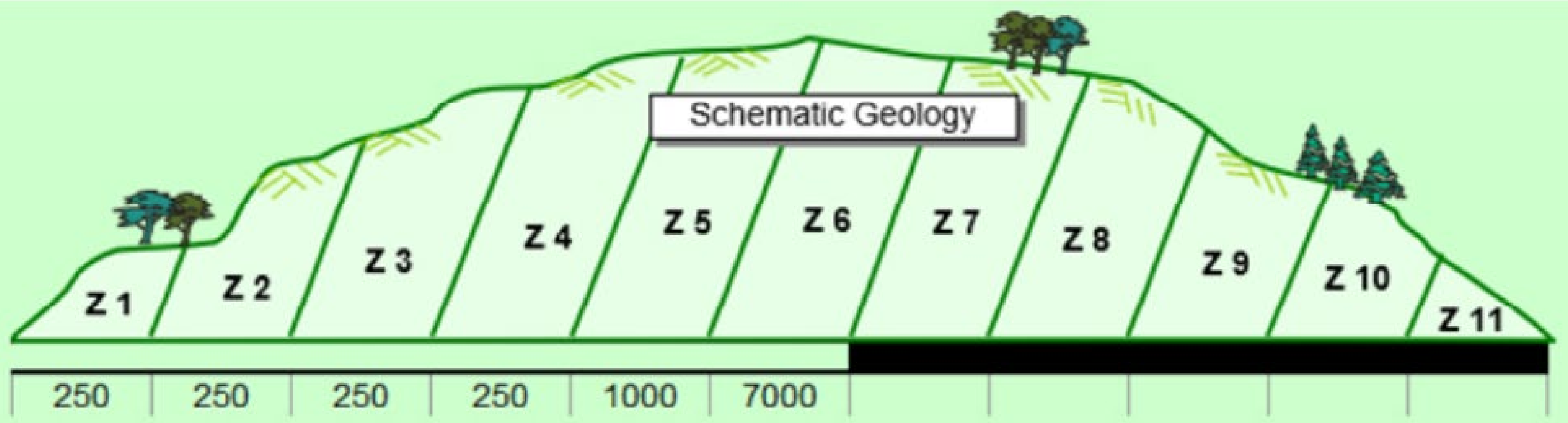
In 2009 this was the seismic data available. Here focussed on low-velocity zones.

Approx. Q-value if 25 m depth	0.01-0.03	0.03-0.1	0.1- 0.3	0.3-1.0	1.0-3.2	3.2- 10	10-32	32-100	100-320
Vp km/s	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0	5.0 – 5.5	5.5 – 6.0
No. of measurements In range	I (1)	III (3)	IIIII IIII (9)	IIIII (5)	IIIII IIIII IIII (14)	IIIII IIIII IIIII II (17)	IIIII IIIII IIII (14)	IIIII IIIII IIIII IIIII IIIII (25)	IIIII (5)
Thickness of Weakness Zones ≈ (m)	15 22	13 20 31 30 8	8 35 6 10 11 9 17 40	16 40 15 8	8 15	*regular*	*jointed*	*rock*	*massive*
Sum of thicknesses ≈ (m)	37	102	136	79	23	Σ= 377 m recorded with various seismic profile directions, typically NNE and WSW in 'focused' lows			

When assisting Acciona 9 years later, this more complete data was made available (again plotted as 'histograms' by NRB). At a depth greater than 'NRB 330 rock cuttings', it suggested e.g. typical

Q ≈ 100/3 x 1.5/1 x 1/1= 50. The reduced jointing is significant!

Approx. Q-range if 25 m depth	0.01-0.03	0.03-0.1	0.1- 0.3	0.3- 1.0	1.0-3.2	3.2- 10	10-32	32-100	100-320
V_p km/s	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0
Number of measurements in given V_p range	II	III II I II I II	 IIIII II I III IIII IIII	I II II IIIII IIIII IIII	I I I IIII IIIII	IIIII IIII III III I I	IIIII II IIIII IIII IIIII IIIII IIIII IIIII I IIIII IIII	IIIII IIIII IIIII IIIII II IIIII IIIII II IIIII II IIIII IIIII II	IIII IIIII I IIIII
Total number	2	11	19	19	12	(17)	(46)	(53)	(15)
						Well jointed	*SparseJointing*	*Quite massive*	*Massive rock*
Thickness of weakness zones/ lengths of jointed or massive bedrock ≈ (m).	22 16 100	12 20 32 30 8 14 10 38 12 20 25	34 6 10 11 9 17 25 15 15 14 20 9 10 10 5 5 5 27 5	40 15 8 16 20 17 17 6 14 11 8 10 7 8 6 14 5 10 10	20 11 65 60 17 37 5 5 15 45 20 10	18 18 52 7 50 50 15 55 35 40 175 80 250 20 50 30 30	25 35 40 60 50 50 32 110 100 115 65 35 85 75 80 100 20 50 53 225 95 100 21 115 120 115 60 16 37 54 70 38 55 20 15 10 63 30 25 65 45 20 100 50 15 10	45 95 45 15 30 55 25 32 20 16 45 65 70 70 47 60 80 75 55 100 50 65 250 25 70 58 35 70 220 95 34 61 45 34 63 40 50 25 80 45 12 60 48 130 55 45 40 65 25 104 90 65 30	25 35 60 50 175 10 60 35 70 80 65 25 22 23
Sum of thicknesses / lengths ≈ (m)	138	221	252	242	311	975	2,769	3,229	771



ZONE	6	LITHOLOGY	Tonalitic gneiss	ZONE LENGTH	7 000

INPUT DATA

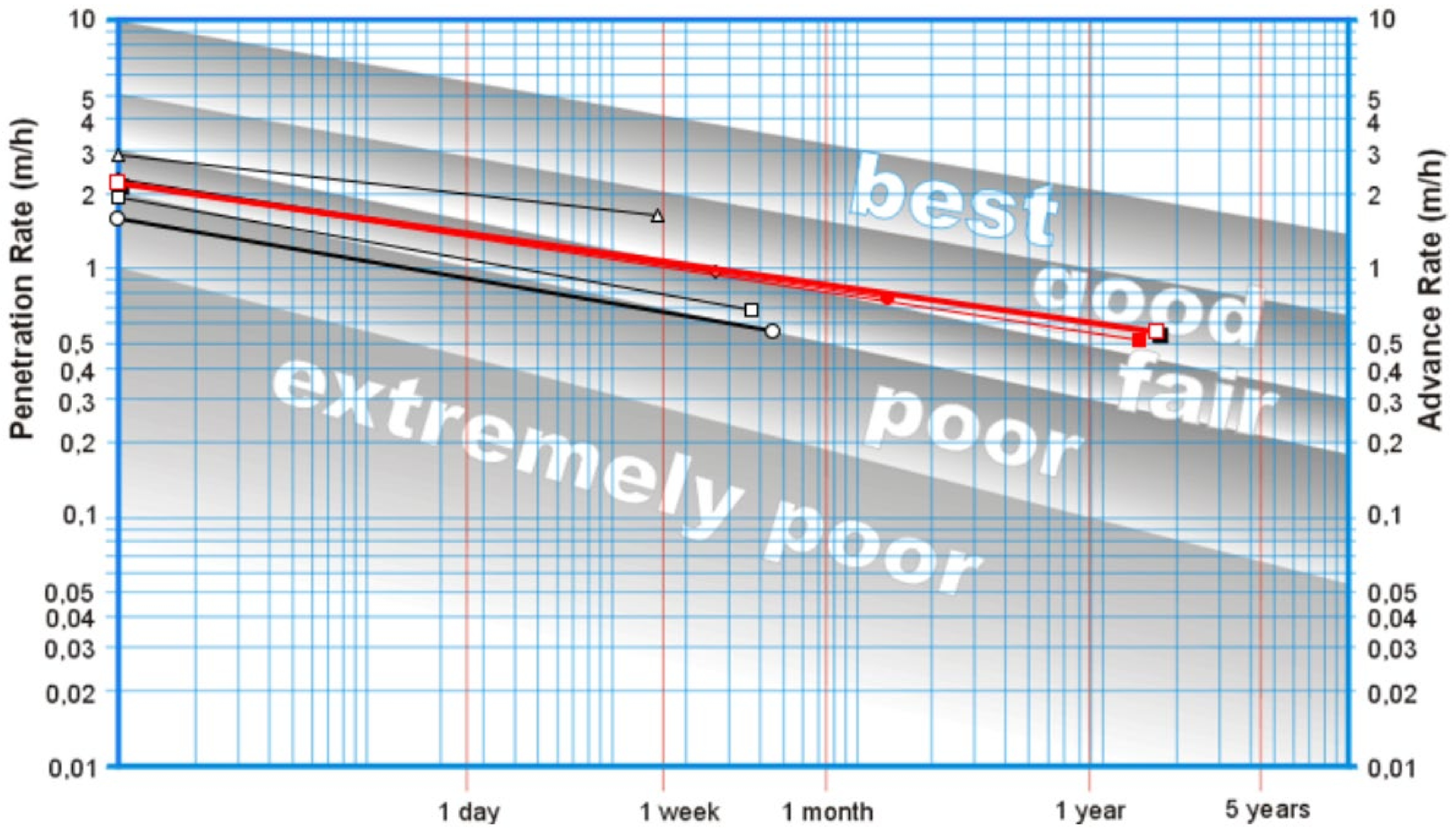
RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)	V_P (km/s)
95,0	3,0	1,5	1,0	1,00	1,0	-0,11	95,0	2,8	

First Zone

β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
45,0	205,0		25,0	6,0	30,0	4,0	10,0	1,0

THIS ‘INPUT DATA’ SCREEN OF THE QTBM MODEL (Barton and Abrahao, 2003) PRESENTS THE FINAL 7KM OF A *TEST FIT TO FOLLO LINE CONDITIONS*, WITH UPDATED (GENERALLY HIGHER) Q-VALUES FROM PROJECT LOGGING DATA AND A *MORE COMPLETE SEISMIC VELOCITY DATA BASE* THAN WAS AVAILABLE IN 2009. (Here: Q = 95/3 x 1.5/1.0 x 1/1 = 48)

THE FOUR INITIAL TRIAL 250M LENGTHS INCLUDED VARIATIONS OF CUTTER THRUST (F), QUARTZ % (q) AND CLI.



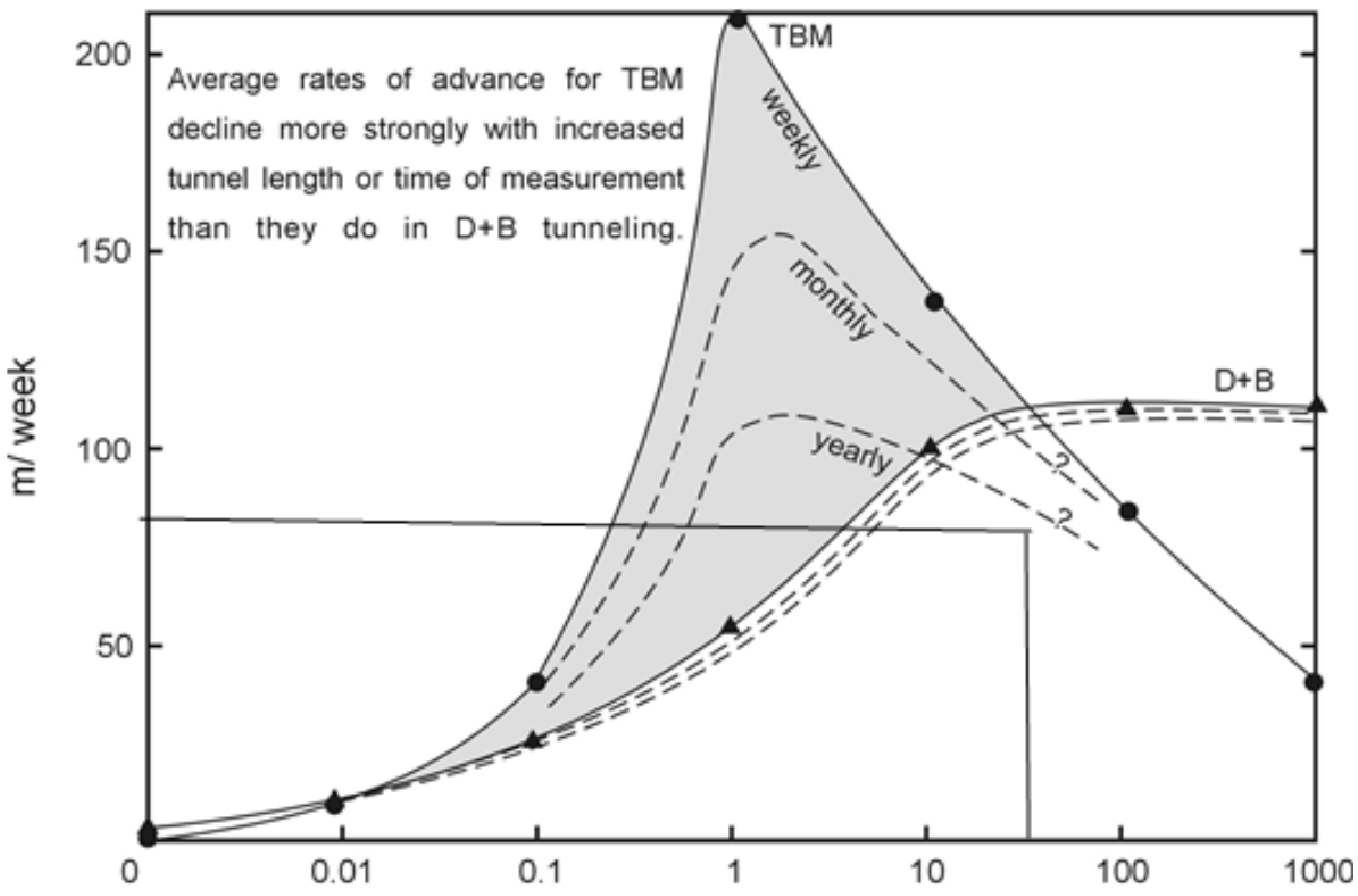
The six modelled lengths (with the dominant 7km) from last figure demonstrate PR mean = 2.3m/hr (slightly high).

AR mean = 0.5m/hr, is as experienced on average in the 36km of Follo Line TBM tunnelling.

BASIC CALCULATION

ZONE	LITHOLOGY	STABILITY	ORIENTED	ROCK MASS STRENGTH					Q	GRADIENT
		Q	Q0	Qc	QT	$SIGMA_{CM}$	$SIGMA_{TM}$	SIGMA	TBM	m
1	Tonalitic gneiss	150,00	150,00	315,00	0,00	95,26	0,00	95,26	**345,49**	-0,17
2	Granitic gneiss	71,25	71,25	171,00	0,00	77,71	0,00	77,71	**130,04**	-0,18
3	Biotite gneiss	45,00	45,00	69,75	0,00	59,69	0,00	59,69	**57,36**	-0,15
4	Amphibolite	37,50	37,50	103,13	0,00	70,34	0,00	70,34	**17,75**	-0,11
5	Granitic gneiss	45,00	45,00	108,00	0,00	66,67	0,00	66,67	**64,43**	-0,15
6	Tonalitic gneiss	47,50	47,50	97,38	0,00	64,41	0,00	64,41	**65,70**	-0,15
7									**0,00**	0,00
8									**0,00**	0,00
9									**0,00**	0,00
10									**0,00**	0,00
11									**0,00**	0,00

ZONE	LITHOLOGY	PENETRATION		TIME TO ADVANCE		OVERALL PERFORMANCE		
		PR	AR	T	check	ΣL	ΣT	
1	Tonalitic gneiss	1,55	0,54	458,85	250,00	9 000,00 m	16 382,39 h	PRL(av)
2	Granitic gneiss	1,89	0,67	373,19	250,00			2,1609
3	Biotite gneiss	2,22	0,94	264,89	250,00			
4	Amphibolite	2,81	1,61	155,23	250,00			
5	Granitic gneiss	2,17	0,75	1 326,33	1 000,00			
6	Tonalitic gneiss	2,16	0,51	13 803,89	7 000,00			ART(av)
7		0,00	0,00	0,00	0,00	9,00 km	22,75 month	0,5494
8		0,00	0,00	0,00	0,00			
9		0,00	0,00	0,00	0,00			
10		0,00	0,00	0,00	0,00			
11		0,00	0,00	0,00	0,00			

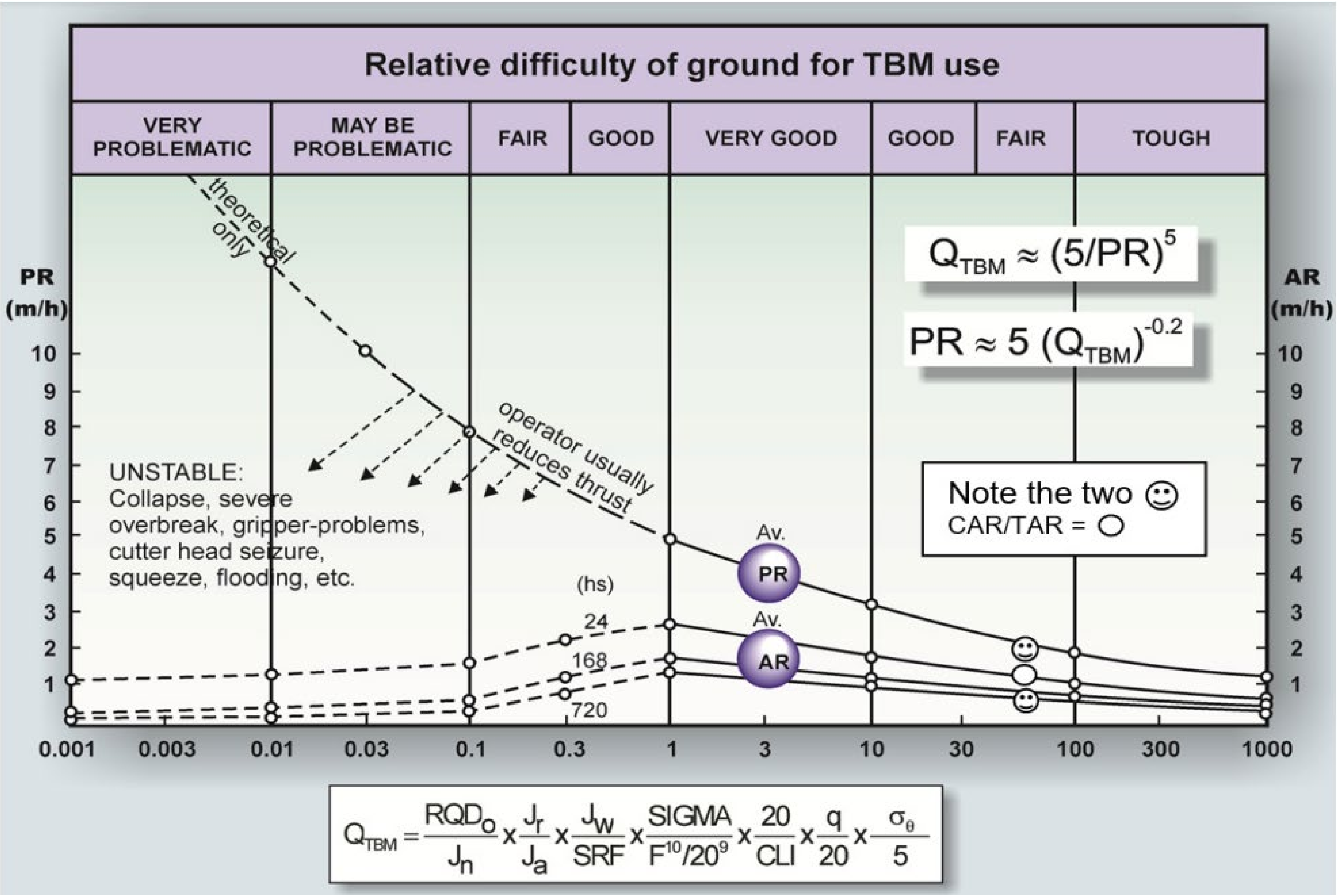


Comparison of TBM and drill-and-blast from Barton, 2000.

Added ‘rectangle’ assumes a Q-value of ≈ 40, intersecting an approx. 2 years result and with mean ≈ 80m/week on the vertical axis.

The mean completion time for the four 9km tunnels was 110 weeks.

(80 x110 ≈ 9.0km).



The two 'smiley' symbols drawn at a Q (and QTBM) value of 60 show approx. PR = 2m/hr and AR = 0.5m/hr.

These are relevant to the mean PR and AR of the 4 x ≈9km of the double-shield TBM used at the Follobanen.

CONCLUSIONS

1. NB beliefs: Need rock mass strength to compare with cutter force, number of joint sets and joint Jr (affect over-break and cutter action)

2. Pre-injection helps to improve most of the six Q-parameters, so (-m) less negative. This means fewer long delays for the TBM, despite the time needed for the pre-injections.

3. Do not 'automatically' choose TBM for long tunnels. A 'hybrid' solution might have advantages. Drill-and-blast the deeper and less investigated sections, if intermediate access is possible. Help maintain the good reputation of TBM!

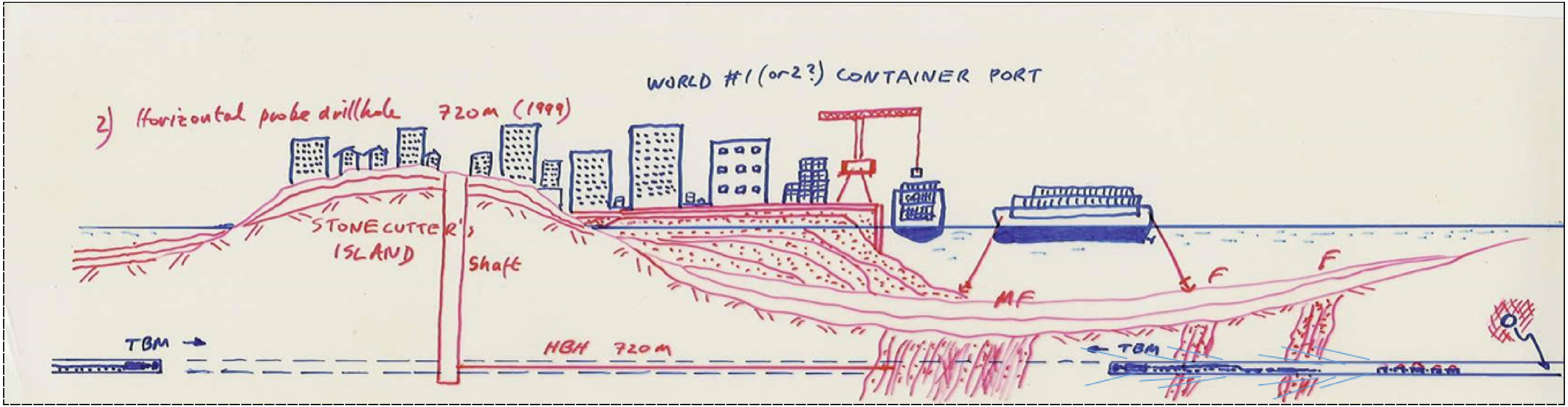
4. Descriptions of the rock mass are limited to each 24 hours (stand-still) in double-shield with PC-elements. So double-shield case records are unreliable in relation to rock mass descriptions. Critics (of TBM prognoses) should be careful using such 'data'!

APPENDIX

(if time!)

FAULTED SUB-SEA ROCK MASS: HONG KONG (SSDS, TUNNEL 'F' BY Skanska)

- MAJOR REGIONAL (TOLO CHANNEL) FAULT ZONE AHEAD – BUT UNKNOWN!
- NOT DRILLED: SUB-SEA SEISMIC INVESTIGATION STOPPED BY CONTAINER-PORT TRAFFIC.
- 'PILOT' HOLE: (DRILLED BACKWARDS FROM SHAFT). HOLE ONLY 731m….. *STOPPED* BY THE TOLO CHANNEL FAULT ZONE.
- BUT..! PRE-INJECTION ALLOWED THE 3.3m TBM TO GET THROUGH THE ZONE



Q-PARAMETER STATISTICS FOR THE (FAULT ZONE) *AT THE END OF* THE 720m LONG BOREHOLE

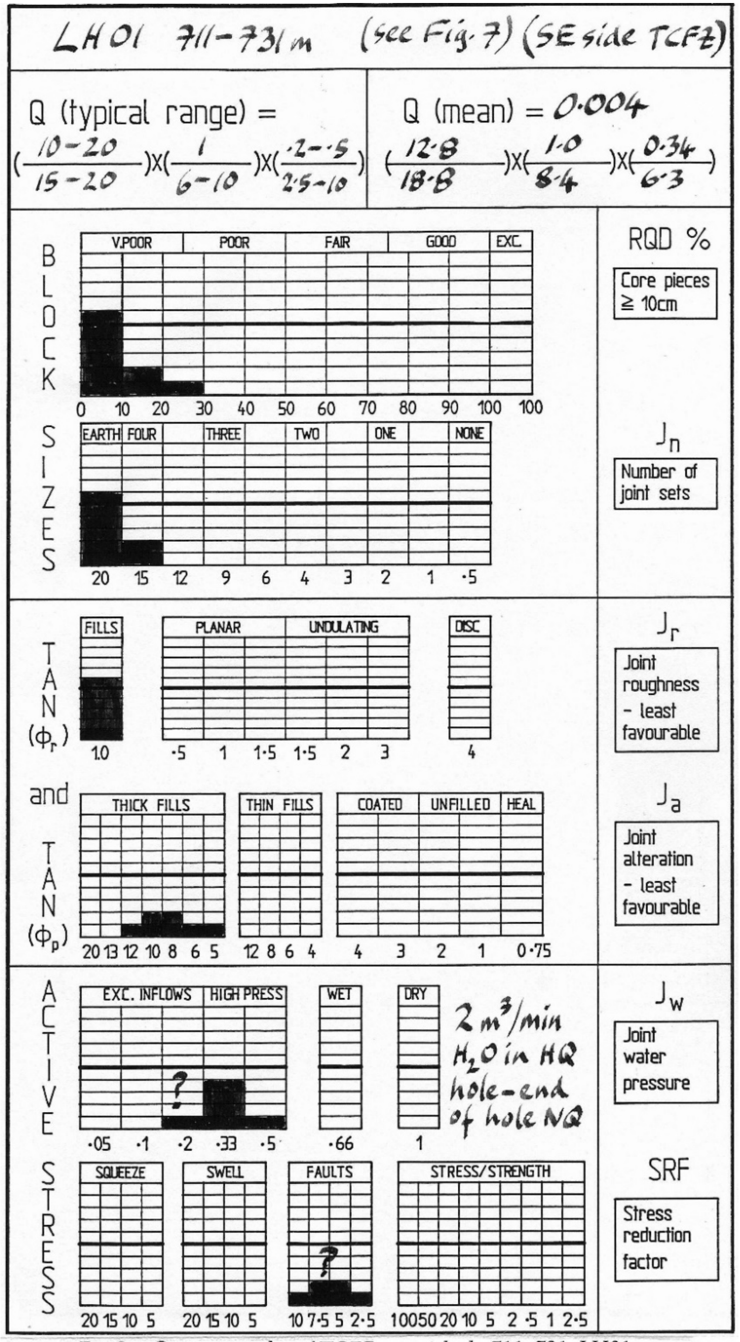
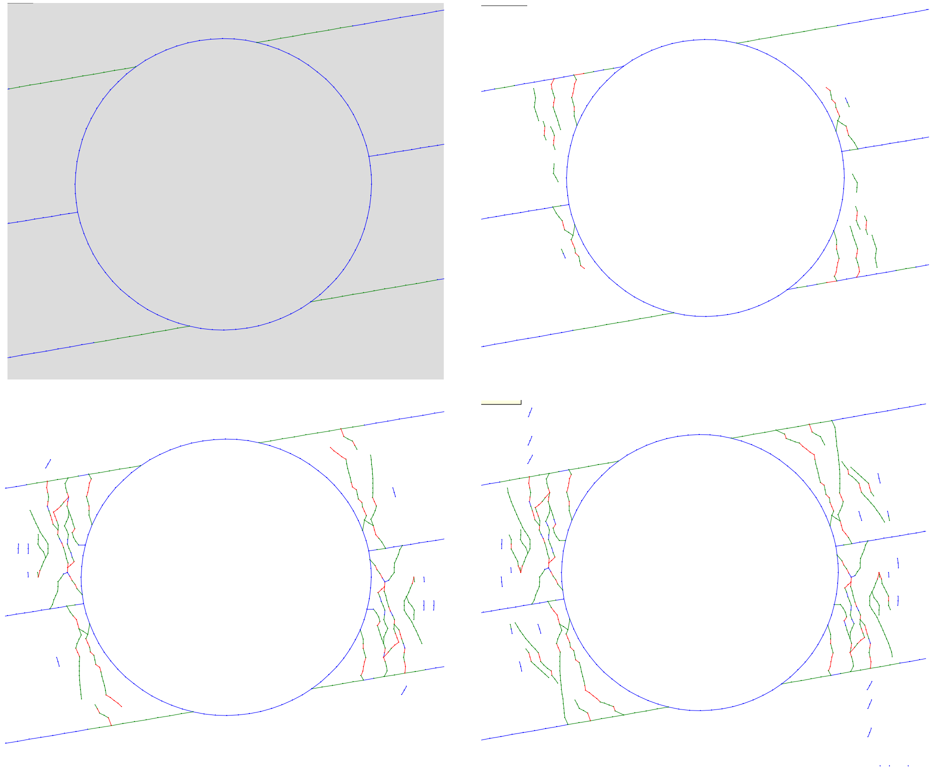


Fig. 8. Q-parameter log of TCFZ material, ch. 711–731, LH01.

CHARACTERISTICS OF THE ZONE ALL PLOT 'TO THE LEFT

Q_{MEAN} = 0.004…..NEEDS PRE-GROUTING IMPROVEMENT



CRACKING IS ACTUALLY CAUSED BY EXCEEDING THE ***CRITICAL EXTENSION STRAIN:***

Cracking in tension, then shear:

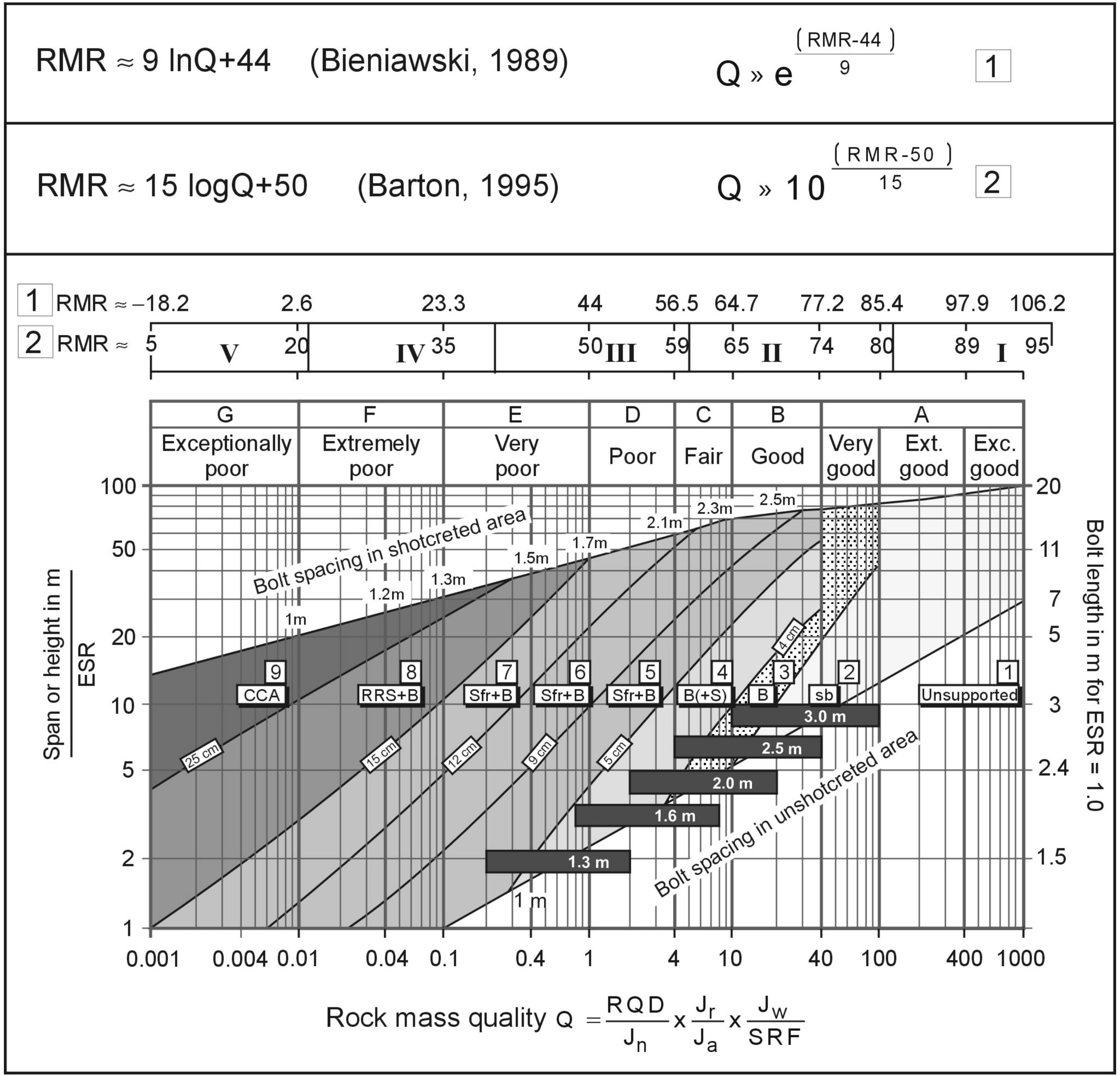
(Not 'compression' failure)

(Stacey, 1981 and Baotang Shen……Barton and Shen, 2017)

$$\sigma_{critical\ tangential\ stress} \approx (0.4 \times UCS) \approx \sigma_t/\nu$$

(derived from $\varepsilon_3 = [\ \sigma_3 - \nu.\sigma_1]\ /E$ and:)

$$\sigma_t/\nu \approx \boxed{\frac{UCS}{10\nu} = \frac{UCS}{10 \times 0.25} = 0.4 \times UCS}$$



Appropos: origin of 'central threshold' diagram (black area where rock quality assessment in TBM tunnel is changed due to lack of damage compared to D+B is:

Barton, N. 2000. *TBM Tunnelling in Jointed and Faulted Rock*. 173p. Balkema, Rotterdam.

SINTEF

Norsk Bergmekanikkgruppe

Bergteknikk for TBM - Boring i hardt fjell

Erfart stabilitetssikring i TBM-drevne tunneler i typisk norsk bergmassekvalitet (åpne, hard rock tbm'er)

Eivind Grøv

Chief Scientist SINTEF

Erfart stabilitetssikring i TBM-drevne tunneler i typisk norsk bergmassekvalitet

Postulat og bakgrunn for presentasjonen

Postulat som syntes å ha versert i fagmiljøet noen tid:

"I den gode enden av bergmassekvalitet er det liten forskjell på nødvendig bergforsterkning mellom en boret og en sprengt tunnel – likeså i den dårlige enden av skalaen – mens det i et rom derimellom kan være fordelaktig med TBM kontra B&S med tanke på omfanget av bergforsterkning!!!"

Hvor stort dette mulighetsrommet er – kan være vanskelig å være konkret på!

Erfart stabilitetssikring i TBM-drevne tunneler i typisk norsk bergmassekvalitet

Postulat/bakgrunn for presentasjonen

“Central Threshold” i figuren – beskriver de samme mulighetsrommet av Barton&Grimstad, 2014

Q-verdien her multipliseres med 2 eller 5,

når hhv. D>5 og D<5

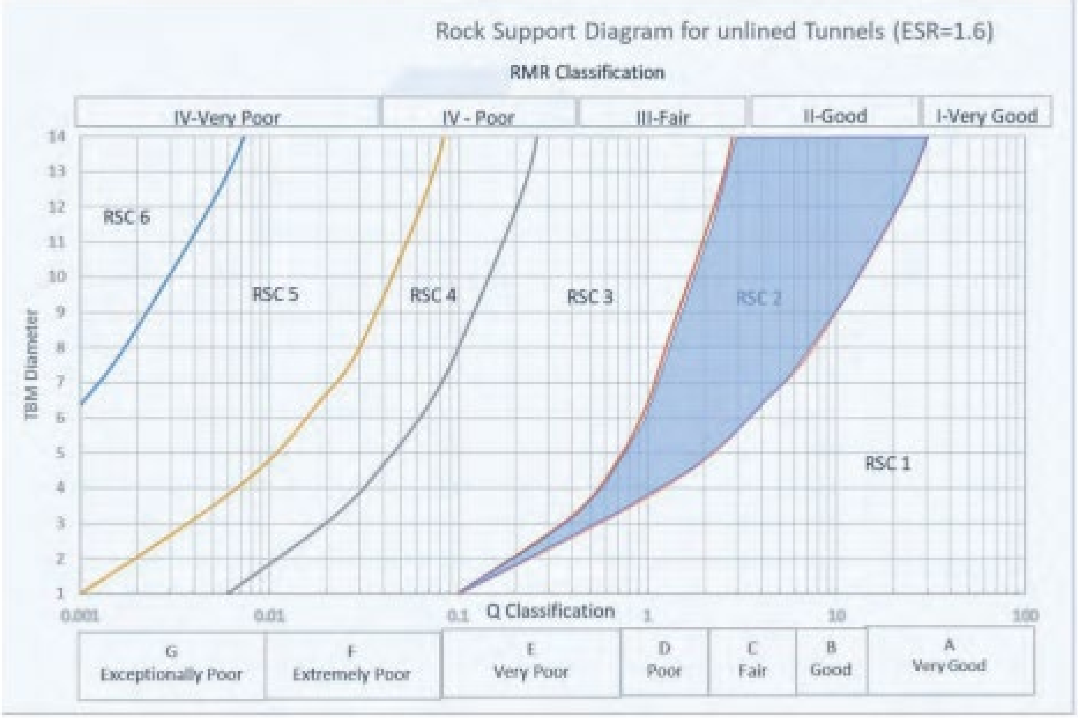
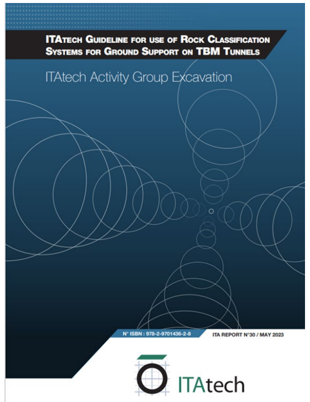


Figure 2: Rock Support Diagram for Unlined Tunnels, with the central threshold highlighted in blue.



Fra ITAtech rapport mai 2023

Erfart stabilitetssikring i TBM-drevne tunneler i typisk norsk bergmassekvalitet

Hva med tilgjengelighet på data?

Det er vanskelig å finne data på erfart sikringsomfang på TBM-prosjekter

- Ikke så mange å velge mellom idag i Norge – Nyere tunneler er få, 20 tomrom
- Ofte er det noe kontraktuelt/hemmelighetskremmeri omkring dette
- De fleste skribenter er opptatt av inndrift, matekraft, kutterslitasje
- Sikringsomfang og –bestemmelse kommer ofte dårlig frem
- Det er ofte det samme med kartleggingsskjema
- Og så har vi de prosjektene som velger hel segmentforing

Erfart stabilitetssikring i TBM-drevne tunneler i typisk norsk bergmassekvalitet

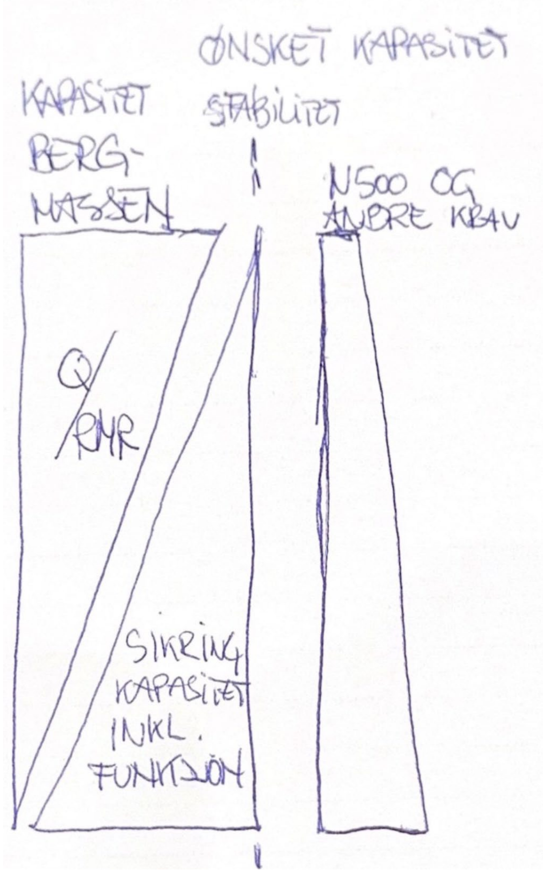
Før vi går videre; Hva mener vi egentlig med stabilitetssikring?

Bergforsterkning kontra Tunnelsikring:

Bergforsterkning = supplement til bergets egen kapasitet for å oppnå ønsket sikkerhet mtp stabilitet = eks. Basert på Q/RMR eller lign. for å bestemme supplement til bergets egen kapasitet.

Forhold (eks. ESR) knyttet til funksjon

Tunnelsikring = for eks. Sikringsklasser i hht. N500 eller tilsvarende.



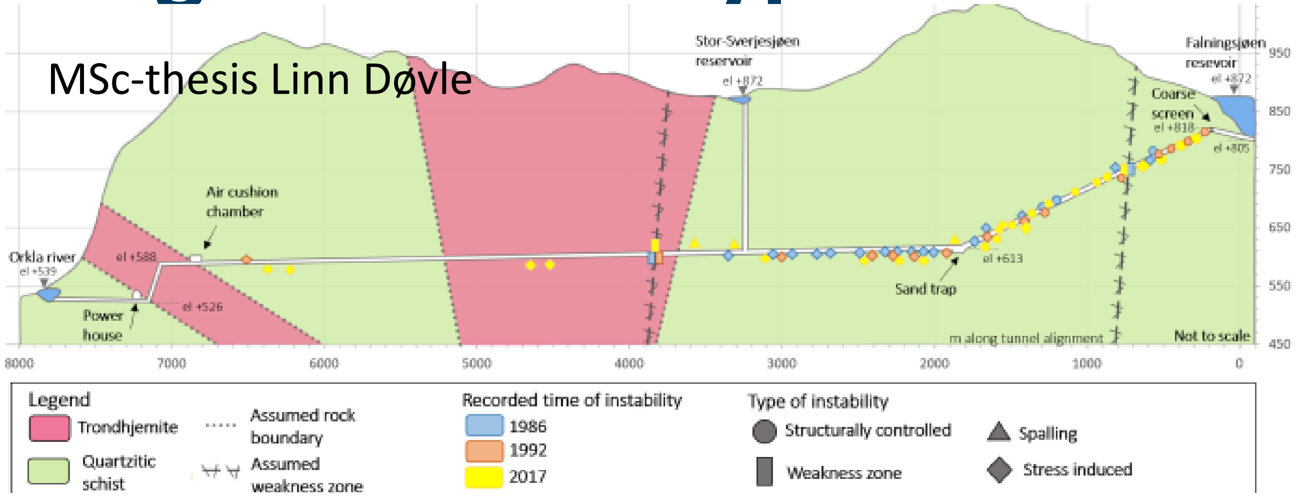
Nødvendig bergforsterkning ≠ (ofte <) antunnelsikring

SINTEF

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Innledning

MSc-thesis Linn Døvle



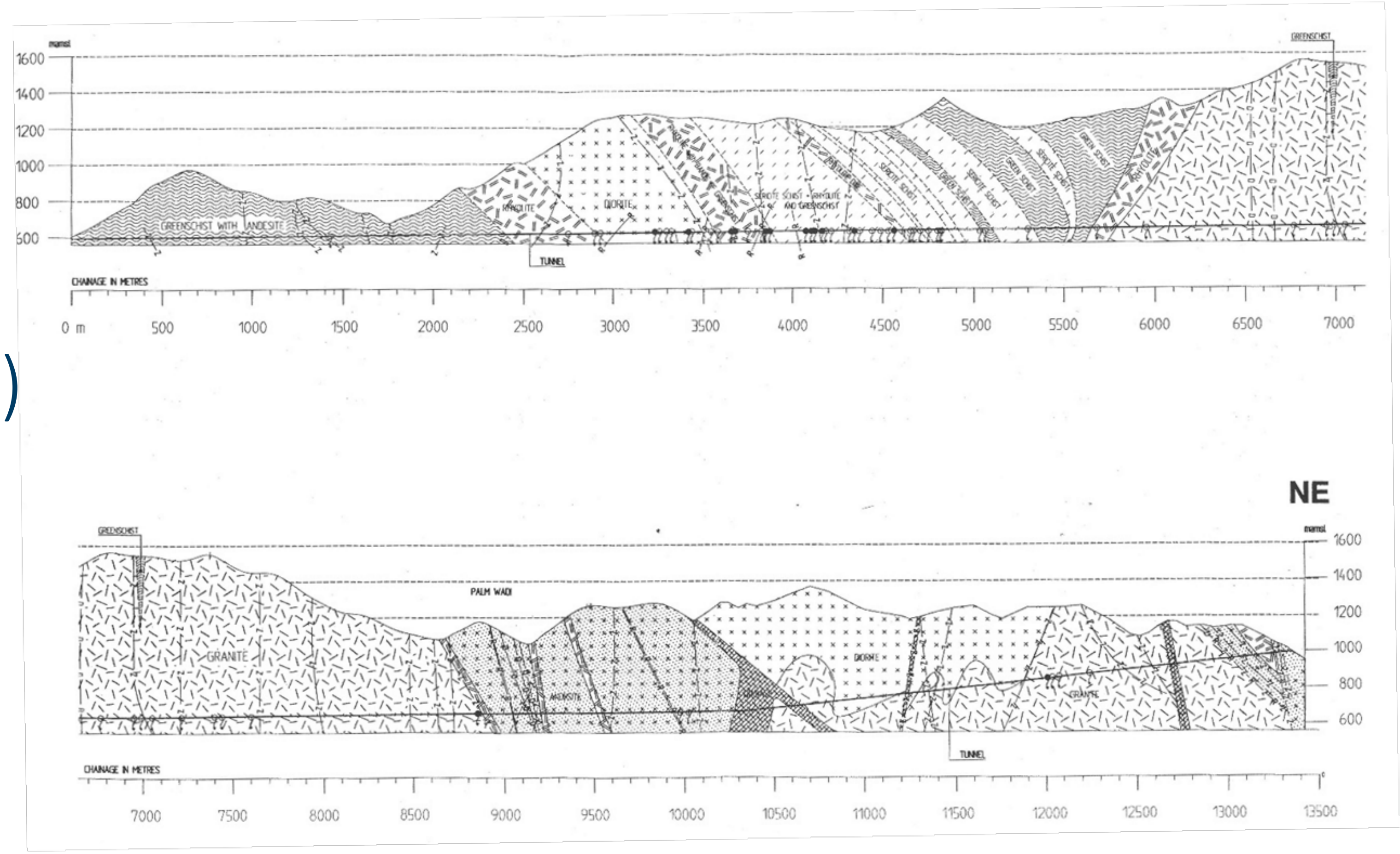
- Mitt først møte med TBM'er (-84)
- Kartla overføringstunnel til Falningssjøen og tilløpstunnel til Ulset kraftverk
- Husker det som svært krevende øvelse – hva skulle nedtegnes og hva ikke
- Husker at det var langt mellom hver bolt og sprøytebetong
- Rapport senere 25m lengde med sprøytebetong og 35m lengde boltet
- Men strekninger med senere instabilitet ble registrert – spenningsrelaterte årsaker – nedfall og flak på sålen

BUDSKAPET er: vanskelig å ha fantasi til å få med alt – og ikke for nybegynnere

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Så fulgte Saudi Arabia

- Rørledningstunnel
- Produktrør som henger i festeanordninger på veggen (jetfuel, diesel etc)
- Permanent kjøreareal for inspeksjon
- Sikring som sådan
- (I dag ESR ≤ 1)



Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Så fulgte TBM i Saudi Arabia

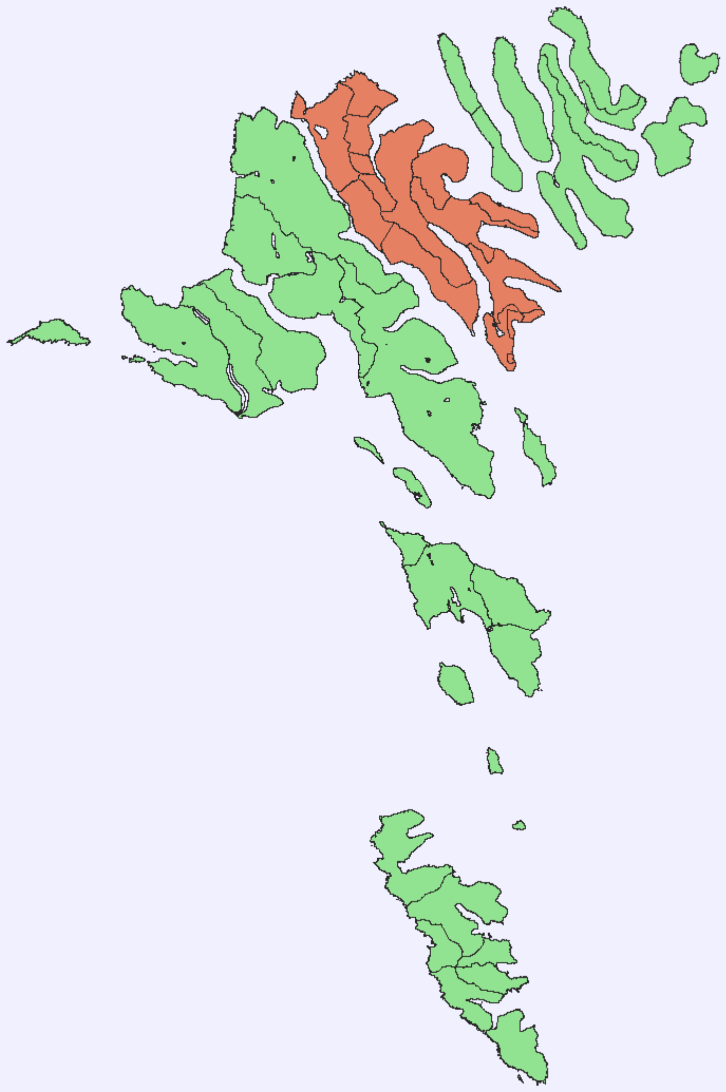
- TBM – åpen HP, diameter 4,25 meter (ombygd Robbins 257??)
- Grundig geologisk kartlegging underveis – gjengs for hele SSSP-prosjektet
- Sikring som sådan og i hht gjeldende standard da – bolteboring bak stuff
- Utstyr ettermontert for boring foran stuff – pga vannproblemer tidligere
- Nært tilslutning til D&B-seksjonen går det ras på stuff – Palm Wadi
- 13 m bred svakhetssone ble forsøkt boret gjennom uten forbehandling –påvist ved sonderboring - maskinen stod flere dager i sonen og raset – snurret ikke
- TBM'en ble demontert der og da og gjennomslag ble utført fra D&B-siden etter at sonen var 'gjenfylt' med betong

BUDSKAPET er: til tross for nitidig oppfølging – løs problemet, ikke vent

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

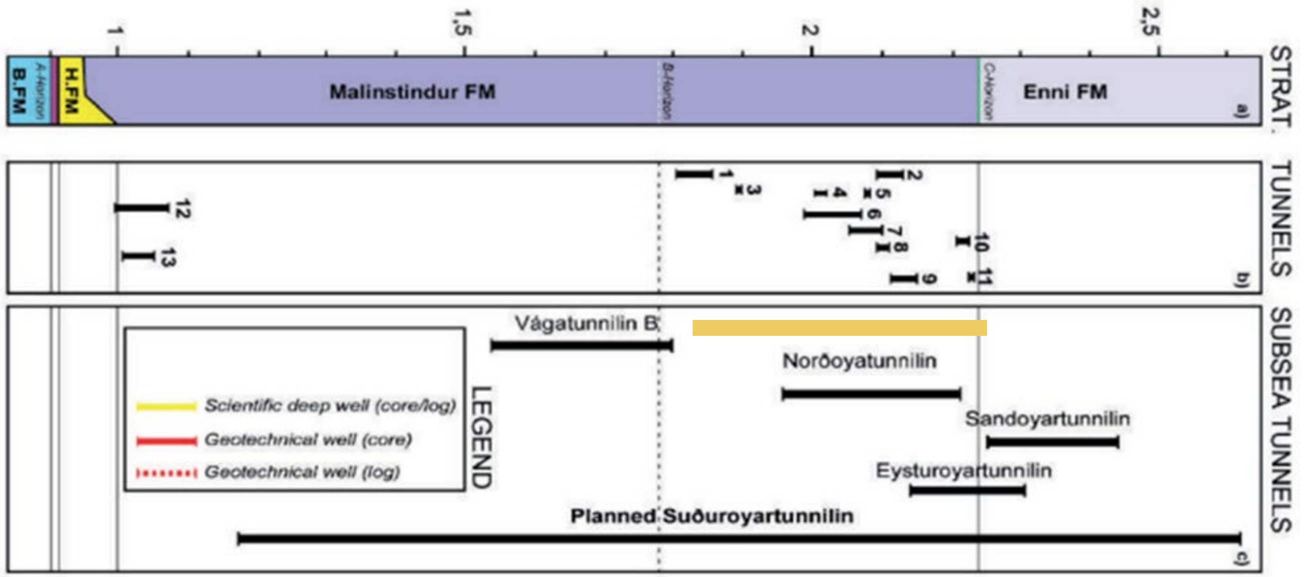
En kjapp tur innom Færøyene

- SEV har egen TBM – en ordinær maskin fra 80-tallet (Robbins)
- Benyttet hovedsaklig på Eidi-prosjektet – et vannkraftprosjekt
- Siste utvidelsen var ca. 15 år tilbake
- Det er generelt lite sikringsbehov i TBM-tunnelen – i størrelsesorden 200 stk bolter over 8200 meter TBM-tunnel



SINTEF

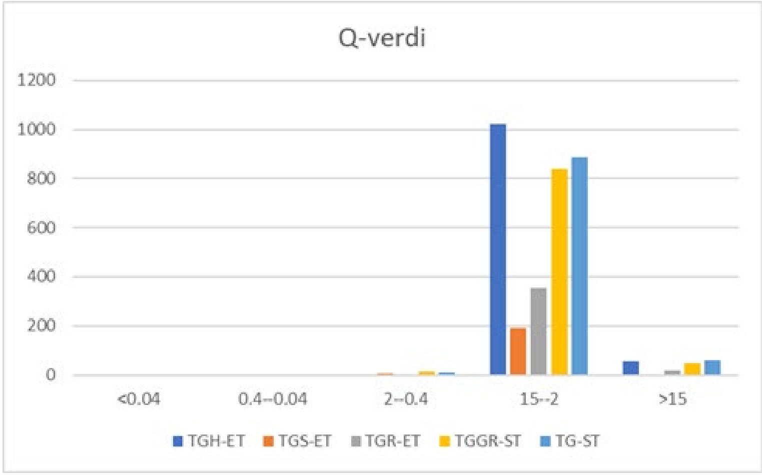
Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse



En kjapp tur innom Færøyene

- Godt tallmateriale fra nye vegtunneler på Færøyene

Sikringselement	Erfarte mengder			
	Vagatunnelen	Nordøya-tunnelen	Eysturøy-tunnelen	Sandøy-tunnelen
Tverrsnitt (m3)	65	65	75	71
Tetthetskrav (l/min/100m)	30	30	20	20
Målt innlekkasje (l/min/100m)	8,5	16,8	12	12
Bolter (stk pr lm)	5,5	5,4	4,42	4,02
Sprøytebetong (m3 pr lm)	0,5	0,9	1,58	1,44



BUDSKAPET her: postulatet er OK

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Ulriken Jernbanetunnel

9,3 meter DIA TBM i granittiske gneiser – 6,9 km TBM

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Ulriken jernbanetunnel

Bergmasseklasse	Prosentfordeling
A	5,5
B	80,5
C	11,0
D	3,0
E	0,0
F	0,0

Bergmasseklasse	Prosentfordeling
A	26 %
B	35 %
C	24 %
D	12,9 %
E	1,9 %
F	0,3 %

Q-verdi	Bergforhold
40-100	Svært godt
10-40	Godt
4-10	Middels
1-4	Dårlig
0,1-1	Svært dårlig
0,01-0,1	Ekstremt dårlig
0,001-0,01	Eksepsjonelt dårlig

Tabellene viser kartlagte bergmasseklasser for ulike strekninger i prosjektet

Overveiende Middels bergmassekvalitet eller bedre

SINTEF

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Ulriken jernbanetunnel

Sikringsbolter i L1*, endeforankrede med polyester, 3,0 m	stk	666,00	19 982,00
Sikringsbolter i L1*, endeforankrede med polyester, 4,0 m	stk	908,00	
Sikringsbolter i L1*, kombinasjonsbolter, 3,0 m	stk	14 547,00	
Sikringsbolter i L1*, kombinasjonsbolter, 4,0 m	stk	2 751,00	
Sikringsbolter i L2*, endeforankrede med polyester, 3,0 m	stk	175,00	
Sikringsbolter i L2*, endeforankrede med polyester, 4,0 m	stk	54,00	
Sikringsbolter i L2*, kombinasjonsbolter, 3,0 m	stk	748,00	
Sikringsbolter i L2*, kombinasjonsbolter, 4,0 m	stk	133,00	

= 19982/7km = 2,9 stk/m

sprøytebetong uten fiber i L1*, Sikringsklasse 5	m3	47,00	12 531,70
sprøytebetong med fiber i L1*, E1000, Sikringsklasse 4 - 5	m3	7,00	
sprøytebetong uten fiber i L2*, Sikringsklasse 1 - 3	m3	27,50	
sprøytebetong uten fiber i L2*, Sikringsklasse 4 - 5	m3	266,50	
sprøytebetong med fiber i L2*, E700, Sikringsklasse 1 - 3	m3	8 229,70	
sprøytebetong med fiber i L2*, E1000, Sikringsklasse 4 - 5	m3	3 850,50	
sprøytebetong med fiber i L3, E700	m3	103,50	

= 12531/7km = 1,8m3/m

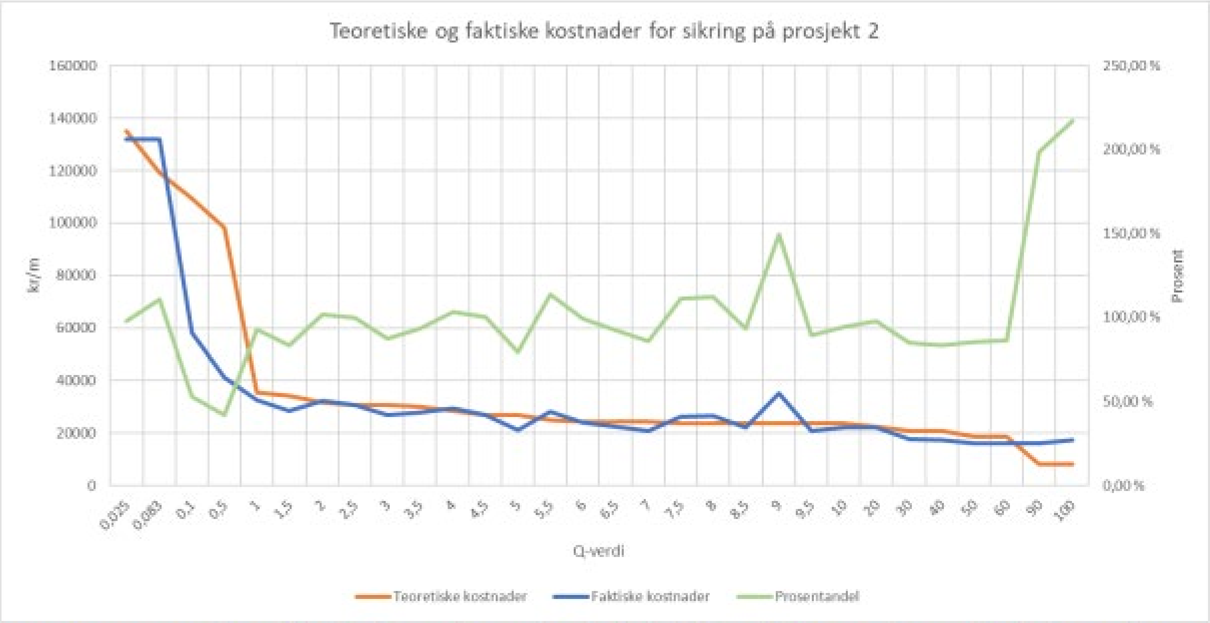
Relativt store mengder - så her slår krav til funksjon til! ESR= 0,5

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Ulriken jernbanetunnel

Figuren viser at forventet kostnad knyttet til de ulike Q-verdiene stemte godt med det det faktisk ble.

Men det sier ingenting om sikringen som sådan ble mer omfattende totalt sett eller ikke enn det som var planlagt



Figur 7.4 - Teoretiske og faktiske sikringskostnader i forhold til Q-verdi for prosjekt 2. Faktiske kostnader er tegnet i blå, mens teoretiske i oransje. Den grønne linjen indikerer prosentvis forskjell i fra faktisk til teoretiske kostnader.

Fra MSc-thesis Helle Nilsen

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Røssåga

Veldig begrenset informasjon – hevdet å bli sikret med 1 bolt per lm

Områdene som ble permanent sikret hadde

0,07<Q<2,7

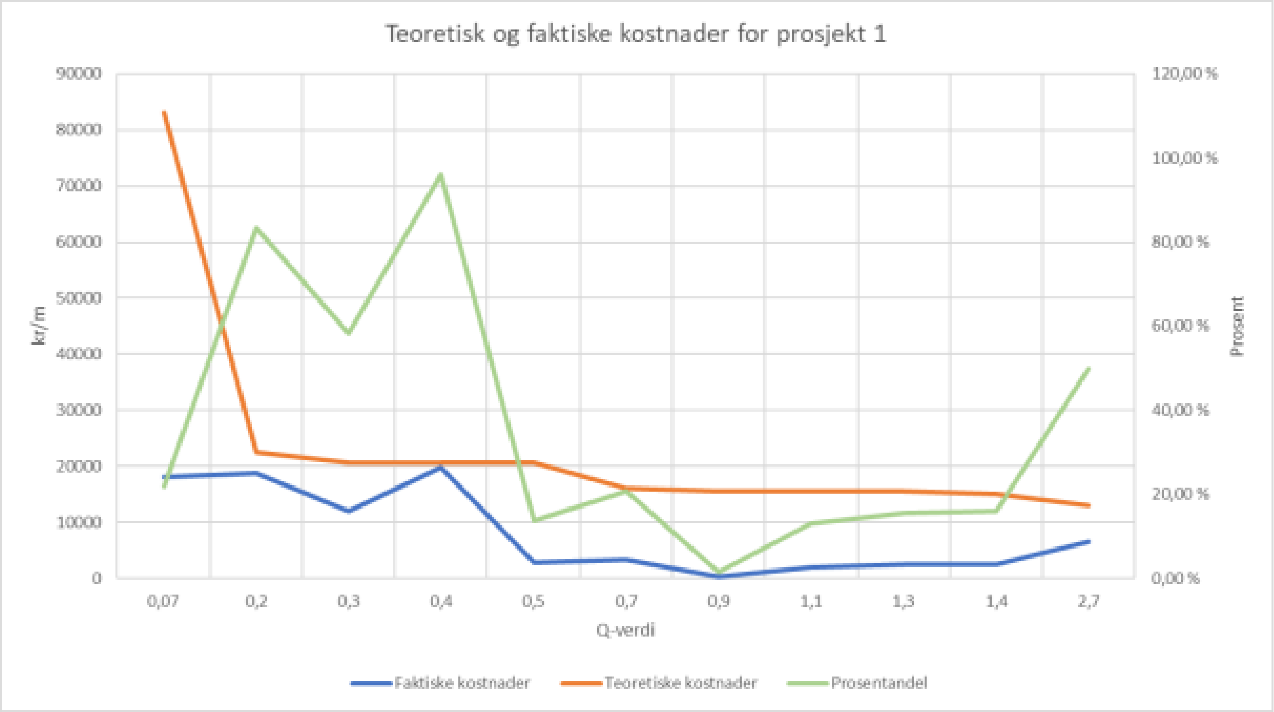
Foto: Ådne Homleid

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Røssåga

Dette er et interessant bilde:

Forventet kostnad (som sier noe mengden sikring knyttet til hver Q-verdi) ble betydelig redusert for nært alle Q-verdier > 0,5, ikke så mye for de < 0,5



Figur 7.1 - Teoretiske og faktiske sikringskostnader i forhold til Q-verdi for prosjekt 1. Faktiske kostnader er tegnet i blå, mens teoretiske i oransje. Den grønne linjen indikerer prosentvis forskjell i fra faktisk til teoretiske kostnader.

Fra MSc-thesis Helle Nilsen

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Glendoe HEP project in Scotland

8 mnd etter oppstart kraft-
Produksjon opptrer uregel-
messigheter under drift –
Urent vann renner ut i Loch
Ness – effekten i verket avtar og driften stoppes helt

Photograph from Woolman (20

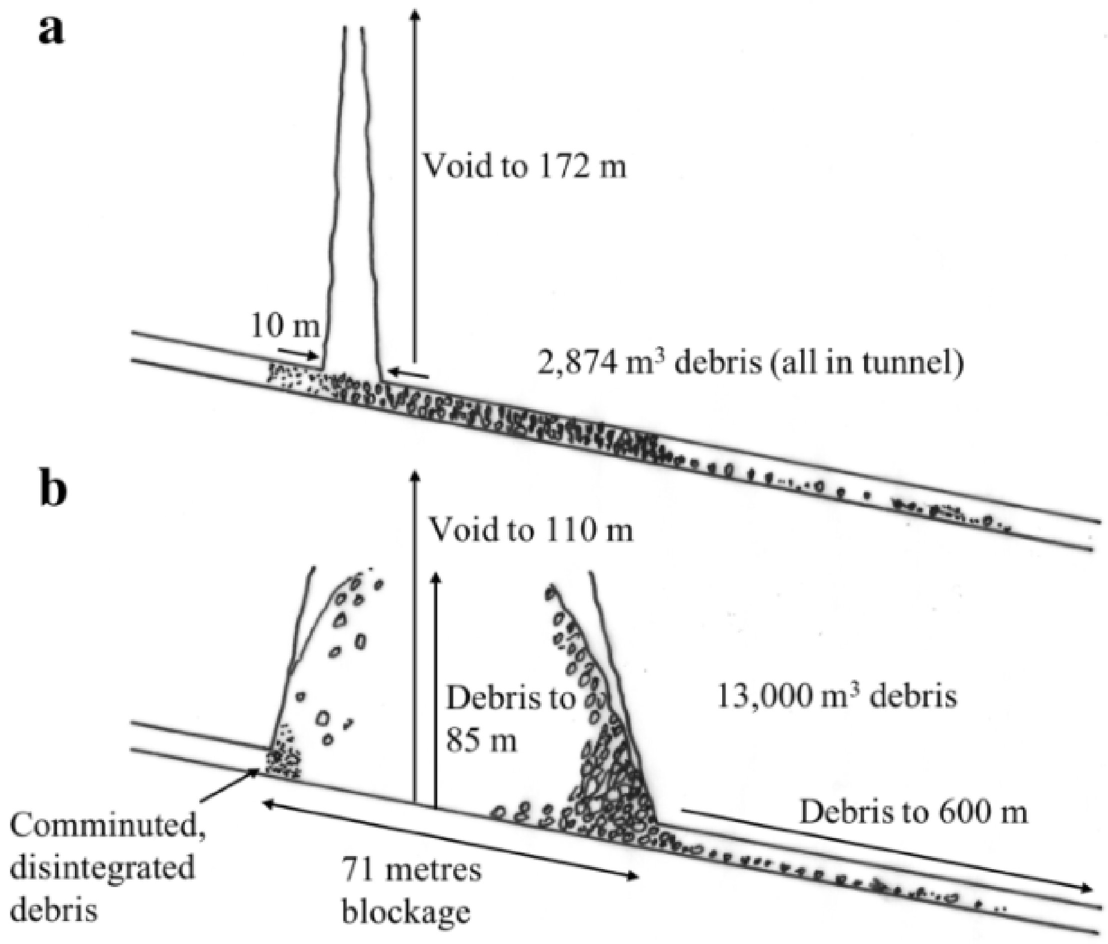
Ved nedtømming finner man propp oppstrøms og steinrøys nedstrøms

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Glendoe HEP project in Scotland

To vesentlig ulike tolkninger av Rasomfanget – uansett store mengder masse

Woolman (2016)



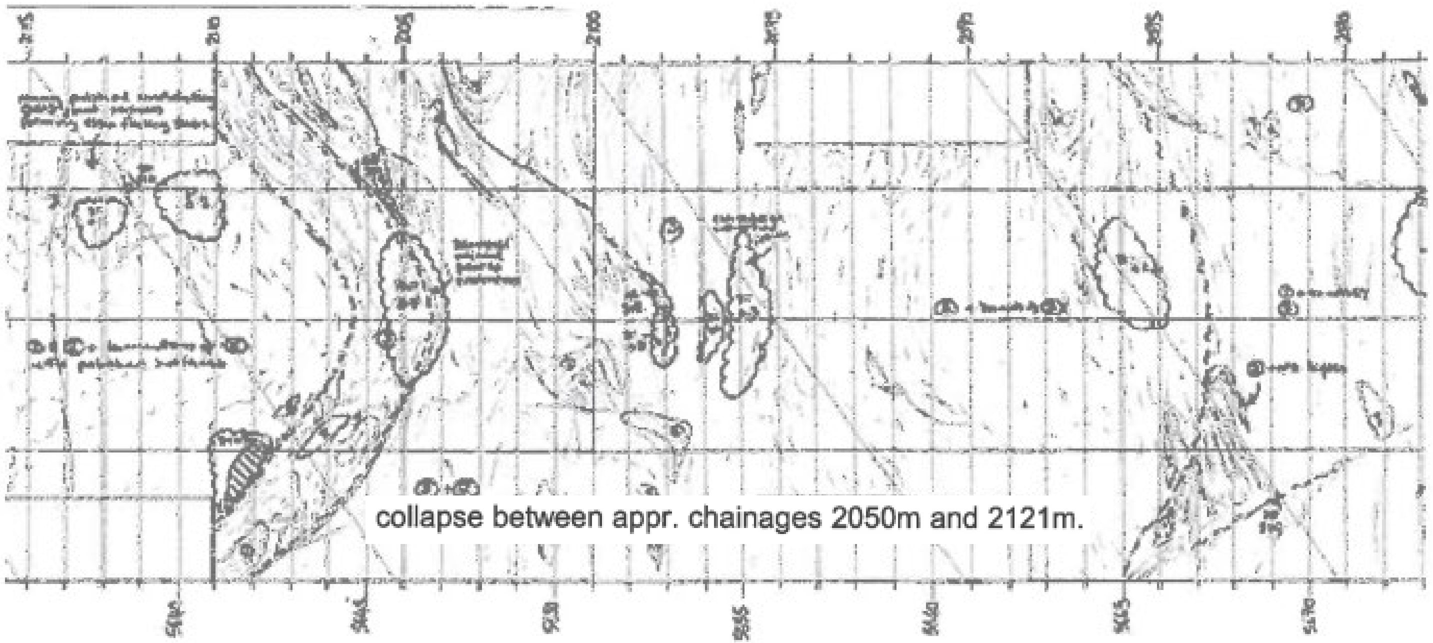
Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

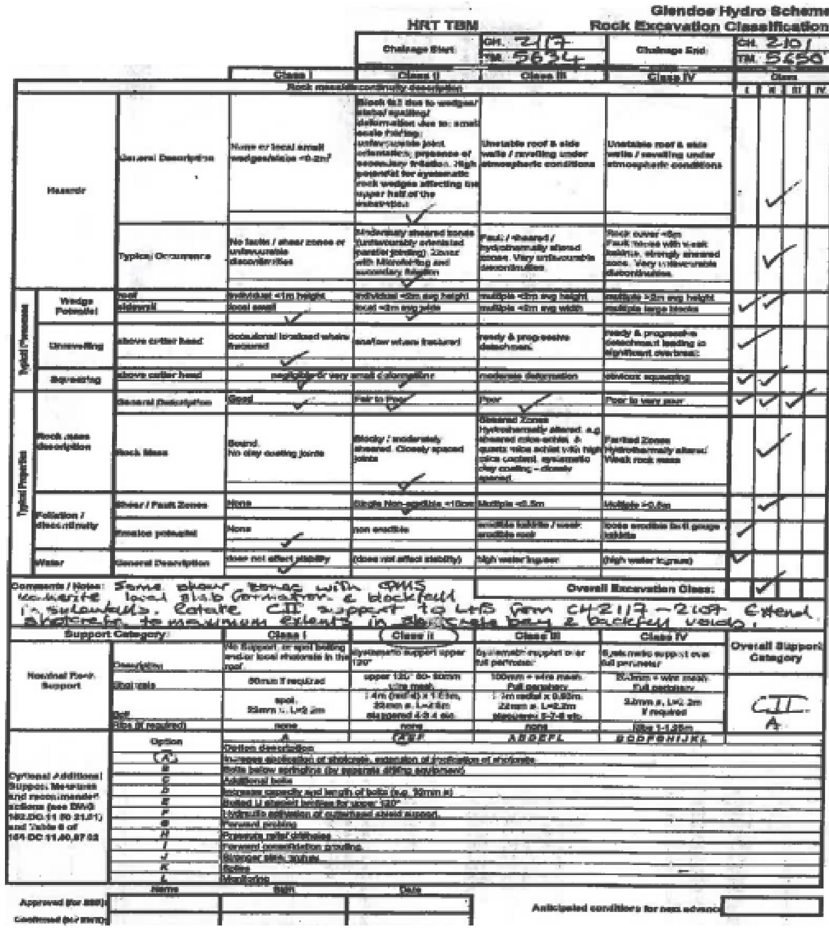
Glendoe HEP project in Scotland

Photo BGS – nature er en stor kunstner

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

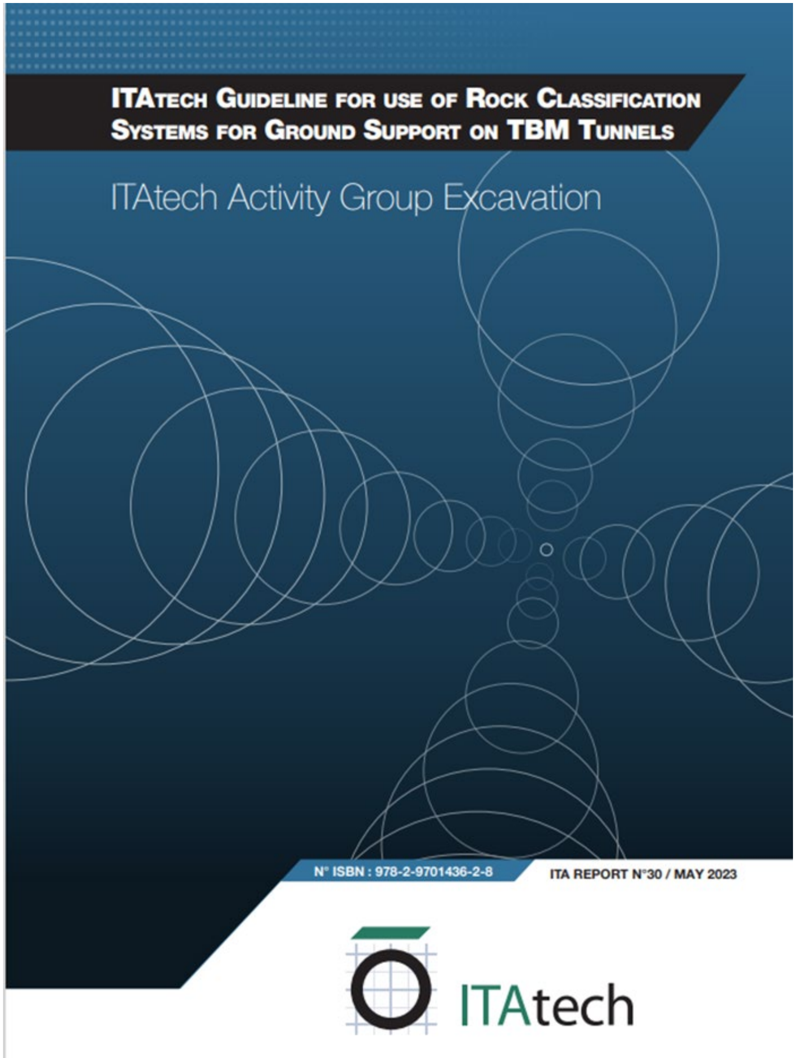
Glendoe HEP project in Scotland





Budskap: Mye rett ble gjort, grundig kartlegging og relevante systemer, men sviktet i 'nedslaget' – viktige ting ble oversett/utelatt

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse



ROCK SUPPORT CLASSES (RSC)

Rock Support Class 1
Rock Support Class 1 is in a very competent rock mass that requires no or very limited rock support. If needed, rock support measures are spot bolting if there is any local occurrence of fractures that intersect with the tunnel.

Rock Support Class 2
Rock Support Class 2 applies where the rock masses are competent. The rock mass in Rock Support Class 2 has some fissures, joints and fractures that gives a need for local rock support on a limited amount of the tunnel circumference. The rock support consists of some spot bolting, McNally slats and/or wire mesh or similar when needed locally.

Rock Support Class 3
Rock Support Class 3 applies in a fairly competent rock mass where there is a need for systematic rock support. The rock support used is systematic bolting with varying patterns, McNally slats, wire mesh and/or reinforced shotcrete when needed.

Rock Support Class 4
Rock Support Class 4 applies in a less competent rock mass with a need for continuous rock support.

The rock support methodology typically consists of systematic bolting, McNally slats, wire mesh and/or shotcrete with fiber or ring beams.

Rock Support Class 5
Rock Support Class 5 applies in weaker rock masses where there is a continuous need for heavy rock support. In such conditions the support methodology should be carefully evaluated and determined on a case-to-case basis.

Typical rock support is systematic bolting, McNally slats with or without heavy steel ribs, ring beams, wire mesh and fiber reinforced shotcrete

If longer stretches of Rock Support Class 5 are expected, special capabilities on the TBM should be considered:

A) The TBM should have the capability to operate in closed mode, which usually means installing precast concrete segmental lining concurrent to advance. Considerations for a fully equipped Crossover-type TBM should be evaluated.

B) The TBM should have sufficient torque to rotate the cutterhead with a full load of loose material against the excavation face.

C) Alternatively, special features should be implemented to efficiently pretreat the ground prior to excavation.

Rock Support Class 6
Rock Support Class 6 applies in severe conditions where special considerations and evaluations need to be made with regard to rock support on a case-to-case basis. Typically, these conditions are running and collapsing ground, high water ingress, etc. Typical support measures include installation of precast concrete segments or other continuous lining like steel lining. In some conditions, pre-treatment of the ground such as grouting, forepoling, etc., should be considered even though precast concrete segments are being installed.

If longer stretches of Class 6 are expected, special capabilities on the TBM are strongly recommended such as:

1. The TBM should be fully shielded with the capability to operate in closed mode. Considerations for a fully equipped Crossover-type TBM should be evaluated to facilitate advancing while holding water pressure.
2. The TBM should have sufficient torque to rotate the cutterhead with full pressure of material against the excavation face.

Alternatively, special customization of the TBM should be implemented to efficiently detect and pre-treat the ground prior to excavation, through probe drilling and pre-excavation grouting.

It is strongly recommended that special features for control of difficult ground be built into the TBM design.

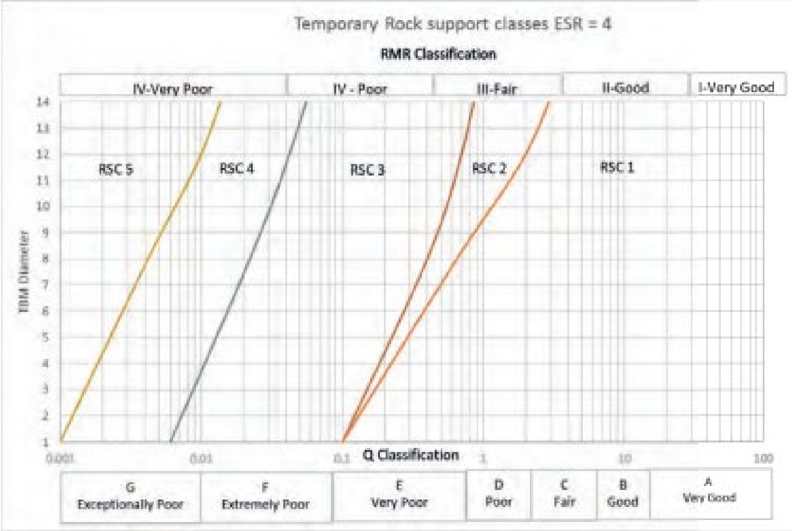
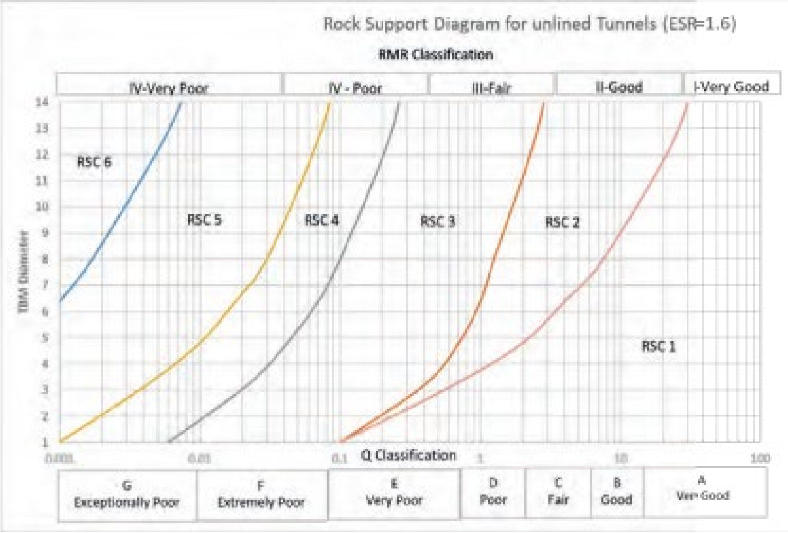


Figure 4: Rock Support Diagram for temporary support (ESR = 4).



SINTEF

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

ITATech Activity Group Excavation

Risiko-matriser og tiltaksforslag tabellarisk

PHENOMENA HAZARDS	LEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE			EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
			■	**Not concerned**
			✓	Easy to implement on site, to be previously considered in the design
			⚠	Medium difficulty of implementation
			❗	Very difficult to implement, (could have an impact on the requirements)
Brittle behaviour: Rockburst, spalling				
1- Spalling	■	■	✓	1.1) Selection of the appropriate type of the telescope in order to limit the material accumulation, and so prevent its blockage
	■	■	⚠	1.2) Operation of the double shield TBM as a single shield TBM. (The prediction of spalling is difficult, so these changes of mode will probably require cleaning of the telescopic section before)
		⚠	⚠	1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tailskin or segments)
	✓	■	■	1.4) Installation of radial bolting (friction anchors) in combination with wire mesh and eventually ribs
	✓	✓	✓	1.5) Appropriate torque reserve high torque low speed gear)
2- Rock-burst	✓	✓	✓	2.1) Execution of subhorizontal destructive drilling eventually combined with blasting around the perimeter of the TBM (in order to release the in-situ stresses)
	✓	⚠	■	2.2) Drilling of large diameter holes (approximately 100 mm), as close as possible to the cutterhead (in order to release the in-situ stresses)
	✓	✓	✓	2.3) Avoid front loading cutterhead; change cutter tools from inside (back-loading cutterhead)
	❗	❗	❗	2.4) Avoid face inspections and work in front of the cutterhead in risk zone.
	✓	✓	✓	2.5) Install face inspection cameras and wear cutters tools
	✓	■	■	2.6) Depending on the level and the location of risk, the presence of workers in the machine zone (0- 2 diameters) should be analysed (statistics, geological, stress monitoring) Over high risk stretches, avoid the presence of workers **close to exposed rock surfaces** during the first hours lapsing after excavation

Table 6a: TBM Tunnelling Related Hazards & Mitigations Measures.

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE			EXAMPLE OF MITIGATION MEASURES TO IMPLEMENT
			■	**Not concerned**
			✓	Easy to implement on site, to be previously considered in the design
			⚠	Medium difficulty of implementation
			❗	Very difficult to implement, (could have an impact on the requirements)
Brittle behaviour: Rockburst, spalling				
2- Rock-burst	✓	■	■	2.7) Passive protection[7]: • Finger shield, that allows bolting in between • Mesh and bolts with or without ribs; in all cases, these added protection should be done under the protection of a finger shield • Create safe and protected walkways
	✓	■	■	2.8) Installation of radial bolting (friction anchors or other energy adsorbing bolts, e.g. D-bolts) combined with wire mesh and ribs, and shotcrete in the machine zone
	■	■	✓	*1.1) Selection of the appropriate type of the telescope in order to limit the material accumulation, and so prevent its blockage*
	■	■	⚠	*1.2) Operation of the double shield TBM as a single shield TBM. (The prediction of spalling is difficult, so these changes of mode will probably require cleaning of the telescopic section before)*
	■	⚠	⚠	*1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tailskin or segments)*
	✓	✓	✓	1.4) Appropriate torque reserve (high torque low speed gear)
Highly deformable behaviour				
3- Squeezing and buckling	✓	✓	✓	3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey
	✓	✓	✓	3.2) Non-stop operations (requiring modification of the shift system)
	✓	⚠	⚠	3.3) Increase the radial over-cutting (and consequently the annular gap around the shield) The difficulty to implement the measure increases with the increase of the amount of overcutting (easier up to 5 cm on radius, more difficult requiring stop of the machine for more than 10 cm on the radius)
	■	✓	✓	3.4) Appropriate **shield geometry** (conical shape, reduction of the shield length) The choice of this geometry is a compromise of different constraints and a key point of the design The use of Double shield TBM is not recommended for small tunnel diameter for which the ratio between diameter and shield length is unfavourable in respect to jamming
	✓	✓	✓	3.5) Lubrication of the shield extrados
	✓	✓	✓	3.6) Installation of a high thrust force – with sufficiently high factor of safety (overdesign). The high (axial) thrust force has to be considered in the design of the lining
	✓	✓	✓	*1.4) Appropriate torque reserve (high torque low speed gear)*
	■	⚠	⚠	3.7) Increase of steel ratio in the pre-cast concrete, use high strength concrete, identify different type of rings
	■	⚠	⚠	3.8) Double lining concept (cf. [4]): this concept allows a reduction of the load acting on the final lining
	⚠	■	■	3.9) Installation of a yielding support (e.g. sliding ribs, openings in the shotcrete, closed or not closed with compressive elements)
	■	⚠	⚠	*1.3) Improvement of the annular void filling in order to stabilize the ring as early as possible: • by a correct design of the method of injection • by calibrating the methods on site (changing the materials, the location, using bi-component, injection from tail skin or segments)*
	■	❗	❗	3.10) Deformable annular filling in extreme squeezing conditions (the low stiffness of the embedment has to be considered in the design of the lining)

Table 6b: TBM Tunnelling Related Hazards & Mitigations Measures (cont'd).

PHENOMENA HAZARDS	CLEVEL OF DIFFICULTY TO IMPLEMENT THE MITIGATION MEASURE			EXAMPLE OF MITIGATION MEASURES TO IMP
			■	**Not concerned**
			✓	Easy to implement on site, to be previously considered in the design
			⚠	Medium difficulty of implementation
			❗	Very difficult to implement, (could have an impact on the requirements)
Presence of water				
4.1- Extremely high water inflow	✓	✓	✓	*3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey*
	⚠	⚠	⚠	4.1.1) Reduction of the permeability by grouting ahead of the machine It is suitable to grout before the water flows into the tunnel Maybe unsuccessful due to the layout imposed by the TBM equipment or by the quantity of water inflow.
	■	⚠	■	4.1.2) Closed mode operation in the case of using a Single Shield Multimode TBM, and low water table (up to 15 bar)
	✓	✓	✓	4.1.3) Installation of a muck chute closure gate
	⚠	❗	❗	4.1.4) Try to separate the water inflow from the mucking material, in order to manage mucking-out difficulties. Drainage solution could be implemented to collect the water
	❗	❗	❗	4.1.5) Reduction of the permeability by freezing (in advance)
4.2- High water pressure	⚠	❗	❗	*3.1) Advance exploration to detect the phenomena - systematic sub-horizontal probe drilling survey ahead of the machine, with registration of parameters, and eventually geophysics survey. It is mandatory to do it with preventer in case of high water pressure*
	⚠	❗	❗	4.2.1) Long advance drainage, at least 2 diameter long, in the periphery and /or front the face of the machine to release the pressure
	⚠	❗	❗	4.2.2) Improve the ground characteristic by grouting ahead of / and around the machine
	■	⚠	■	*4.1.2 Closed mode operation in the case of a mix-shield TBM and low water table (up to 15 bar)*
	❗	❗	❗	*4.1.4. Reduction of the permeability by freezing (in advance)*
		❗	❗	4.2.3) Improve the ground characteristic by grouting around the segmental lining
	■ ⚠	❗	❗	4.2.4) Drainage boreholes around the lining
		⚠	⚠	4.2.5) Double lining concept

Table 7: Working Group 17 recommendations for water inflows.

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Det kunne vært interesssant med grundige studier av Ulriken/Røssåga vs Blixtunnelen/VAV-tunnelene

Tid/kost/stabilitet/utslipp – alt omgjort til sammenlignbare equivalenter

Vanskelig å sammenlikne direkte – velger vi objektivt rett maskintype??

NFF Temadag 2013, trusselbildet

MODERNE VEG- OG JERNBANETUNNELER

Follobanen: TBM med segmentforing gjennomgående; erstatter injeksjon-, berg-, vann- og frostsikring i hht JBV

Vegtunneler: alle tunneler over ÅDT=4000 skal ha plass-støpt betong

- Overreaksjon på FDV-spøkelset
- Feil teknologi og gal anvendelse
- Misforstått norsk tunnelbyggemetode
- Miljømessig tilbakesteg
- Gammeldags og teknologikonserverende

BEVEGER OSS I FEIL RETNING I FHT SCL


FJELLSPRENGNING - VEI - TUNNEL OG JERNBANE

Norske grunnprinsipper må gjelde

Grunnleggende prinsipp ved norsk tunnelteknologi må gjelde også ved TBM som drivemetode.

KOMMENTAR

Eivind Grøv

76 BYGGEINDUSTRIEN NR 17 - 2012

Ulrikke har brutt igjennom – 635 dager etter at tunnelboremaskinen startet

Boret seg gjennom 6896 meter med fjell.

Del Kommenter

Mari Gisvold Solberg Journalist

Eirik Helland Urke Journalist / foto

29. aug. 2017 - 10:41

BERGEN: Tirsdag formiddag kom den enorme tunnelboremaskinen "Ulrikke" ut gjennom fjellveggen i Fløen, i Bergen. Hundrevis av mennesker var samlet seg ved Fløen for å se gjennomslaget.

Maskinen, som er den største tunnelboremaskinen brukt i en samferdselstunnel i Norge noen gang, har i løpet av 635 dager boret seg gjennom 6896 meter med fjell.

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

Konklusjoner

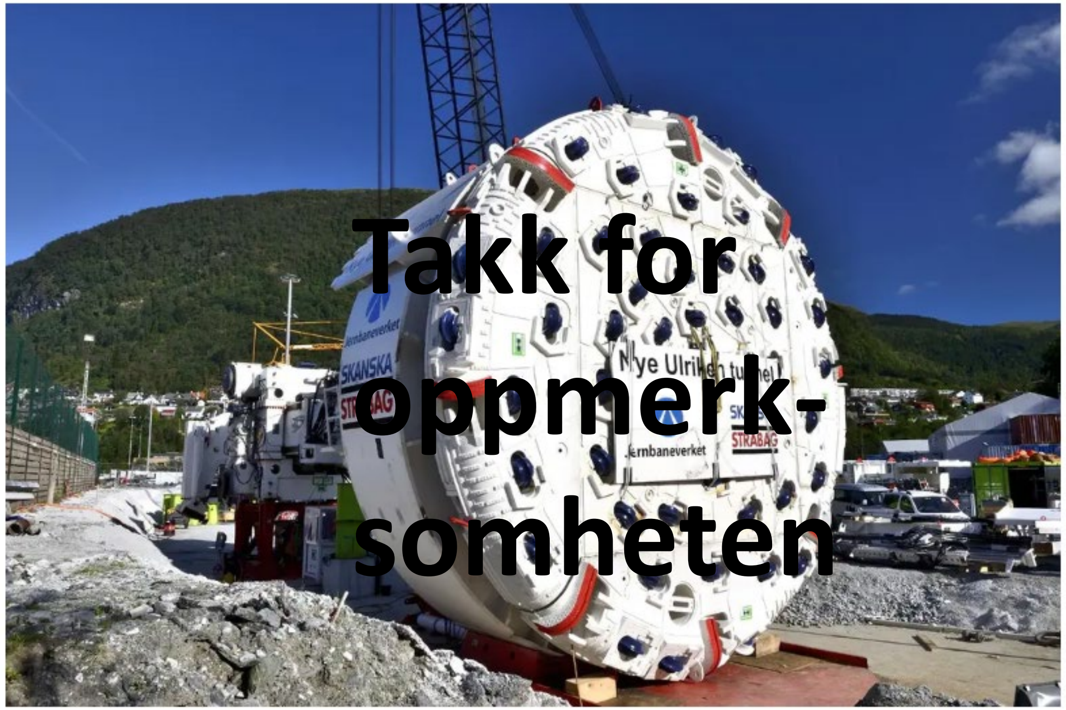
- Det er åpenbart potensielle fallgruver knyttet til overestimering av bergmassekvalitet i TBM-drevne tunneler og derav for snau bergforsterkning
  - Jevn kamuflerende overflate, ingen sekundær oppsprekking, tangentialspenningene tett på kontur, eroderbart materiale ikke lett å identifisere
- Det setter krav til kvalitetsmessig god beskrivelse av bergmassekvalitet og funksjonell forståelse av berg og forsterkningsbehov
- Lett å bli revet med i fremdriftsjaget – rekorder i antall m per t/dag/uke/mnd
- Risikabelt å legge til grunn postulatet som en forutsetning
- Skulle hatt mer data og nøyaktig data tilgjengelig fra prosjektene

Erfart stabilitetssikring i TBM'er i typisk norsk bergmasse

De har vært bannlyst i Norge - nå er monstermaskinene tilbake

Nå skal fem tunnelboremaskiner først ta Ulriken - så Follobanen. Det skaper både begeistring og sinne.

Publisert: 17. oktober 2015



Takk for oppmerk-somheten

Oppsummerende:

Mye ny lærdom de siste 10-15 årene

Dette må foredles, forstås og praktiseres i bransjen

Til å bli et attraktivt verktøy

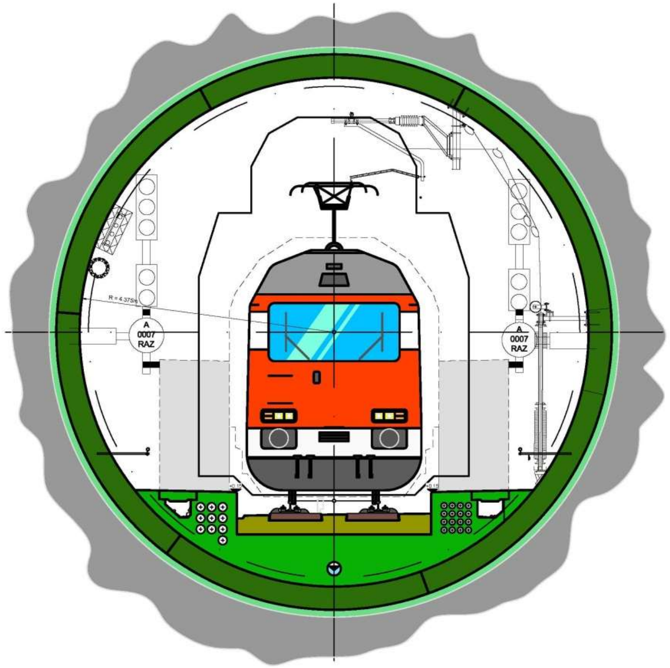
NORSK BERGMEKANIKKGRUPPE

Bergmasseparameter for design av lining

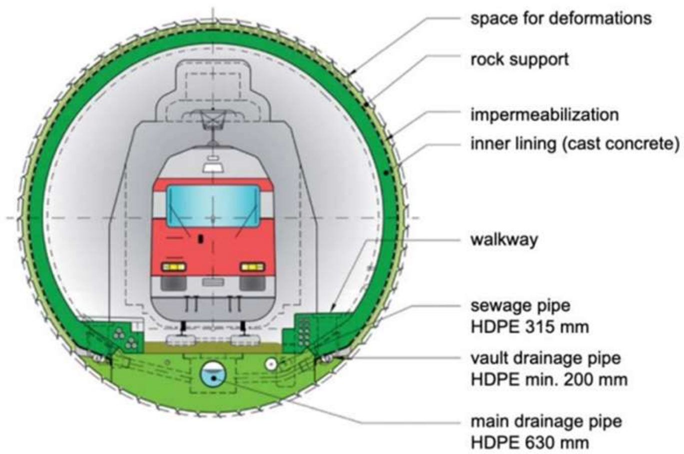
- Bergteknikk for TBM – Boring i hardt fjell, 09. – 10. Januar 2024
- Johannes Gollegger, Acaraho Consulting AS

Typical cross sections

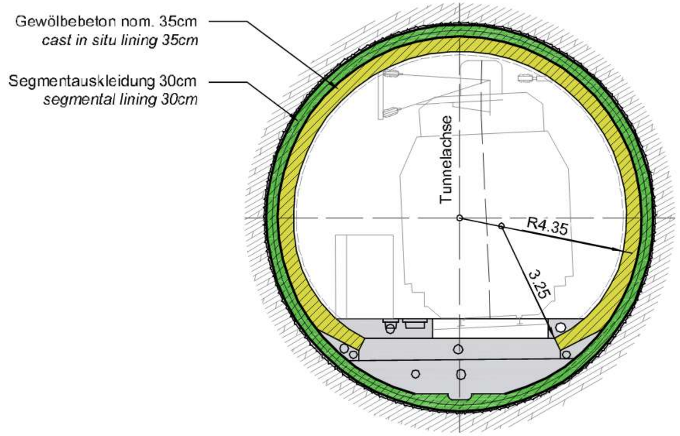
Follo Line Tunnel



Gotthard Basetunnel

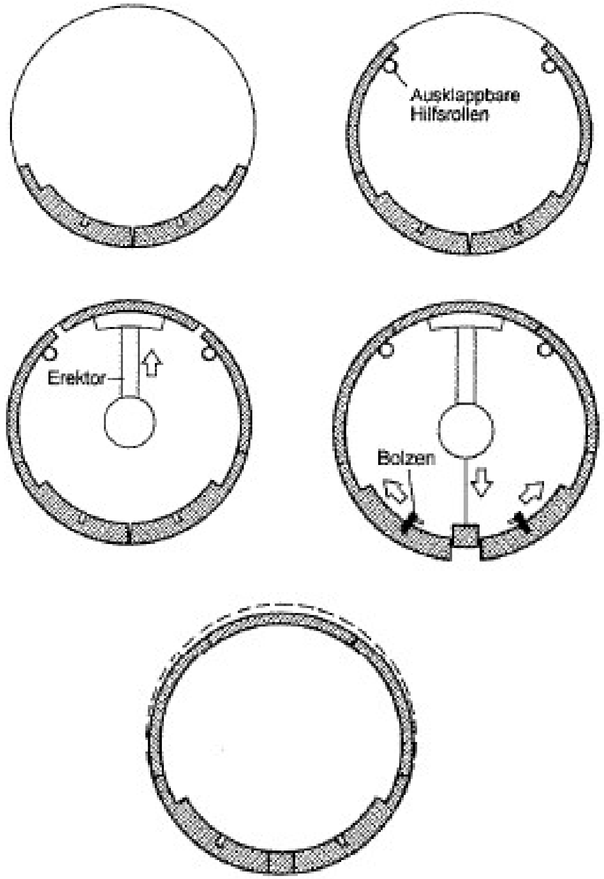


Wienerwald Tunnel



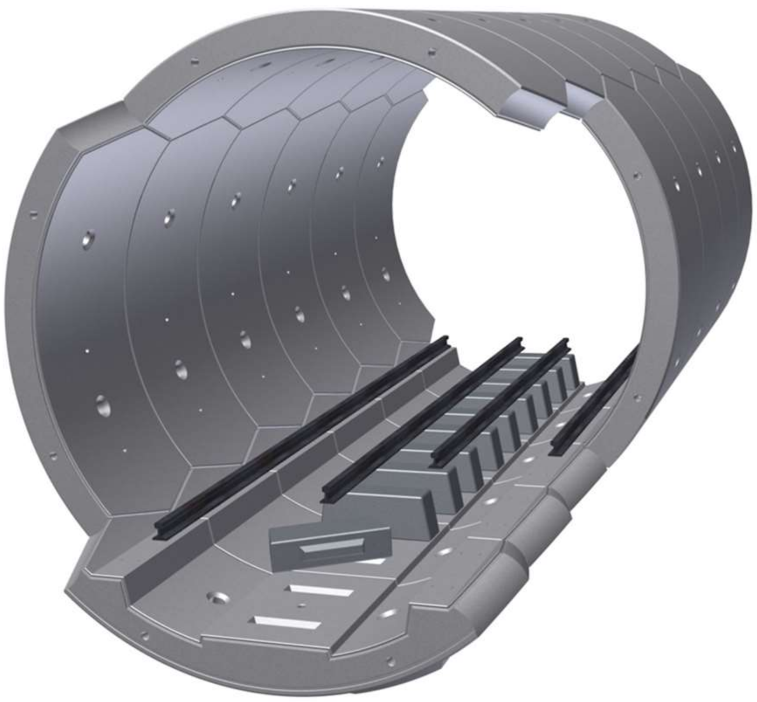
Swiss strut lining

- Ring consists of 6 segments
- No bolts or dowels
- No gasket
- Key stone always at the bottom
- Especially used for project with low requirements to segmental lining (double shell lining)

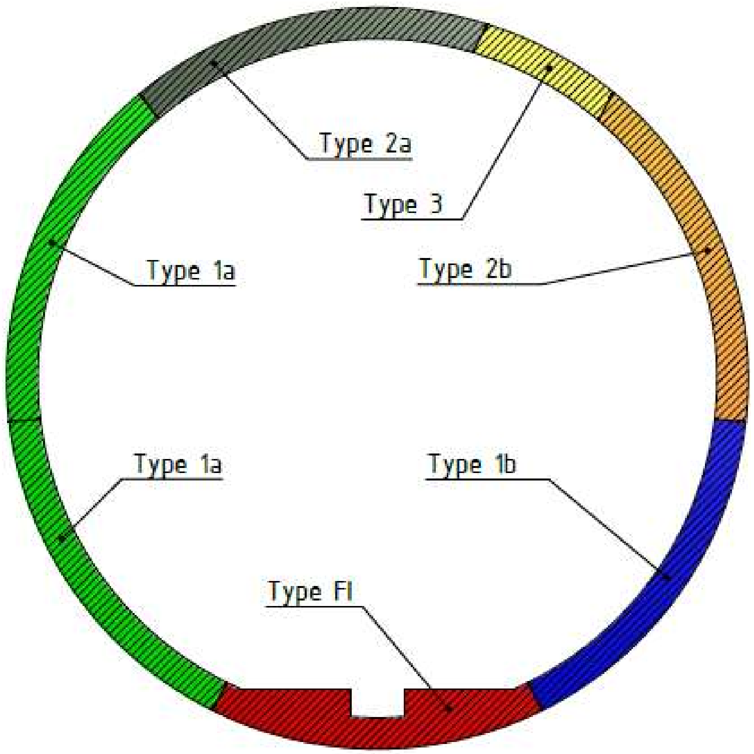


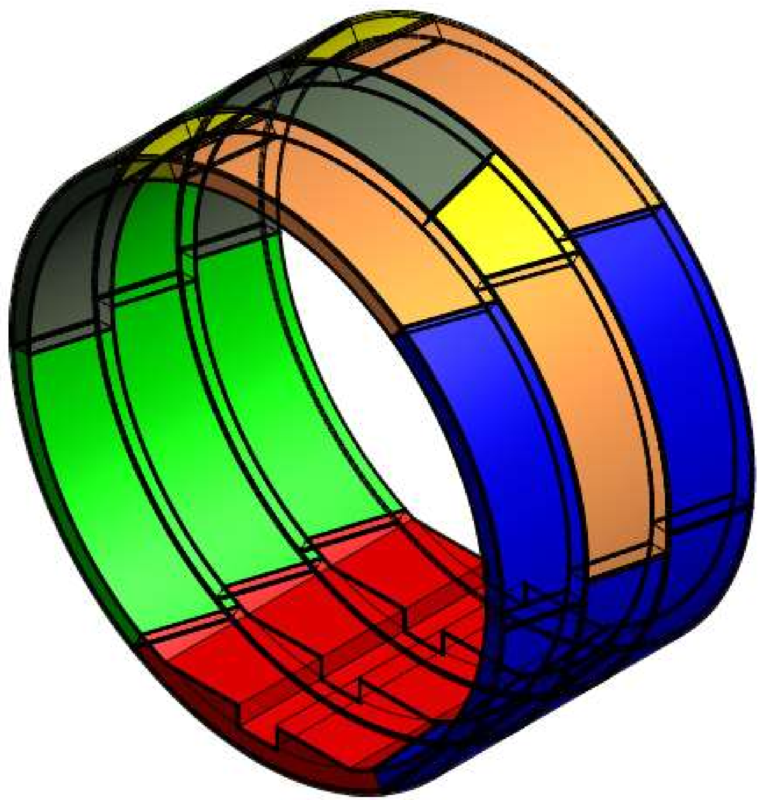
Hexagonal ring (Honeycomb)

- Ring consists of 4 segments
- Especially used for hydropower projects (i.e. headrace tunnel)
- The joints are not planar, but convex/concave

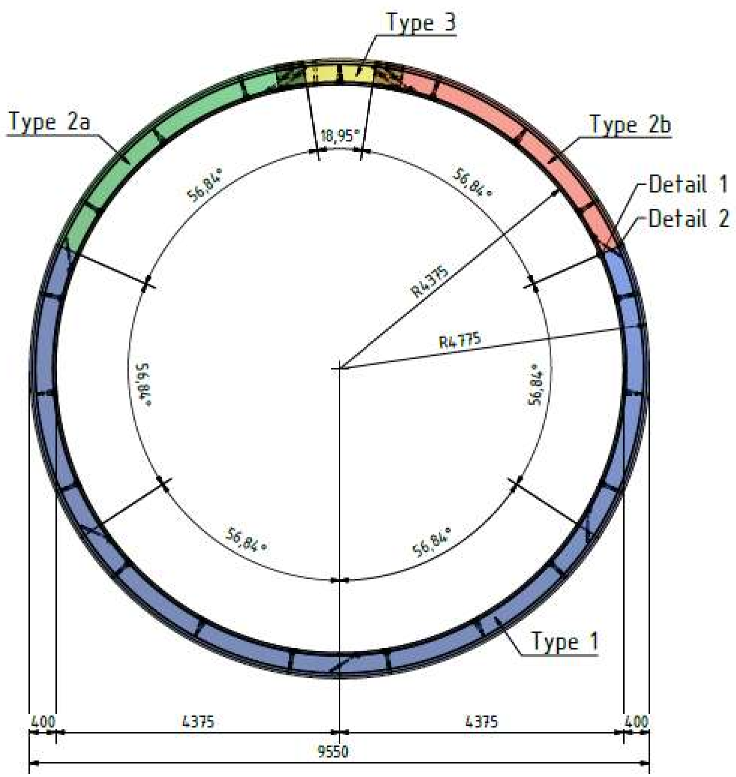


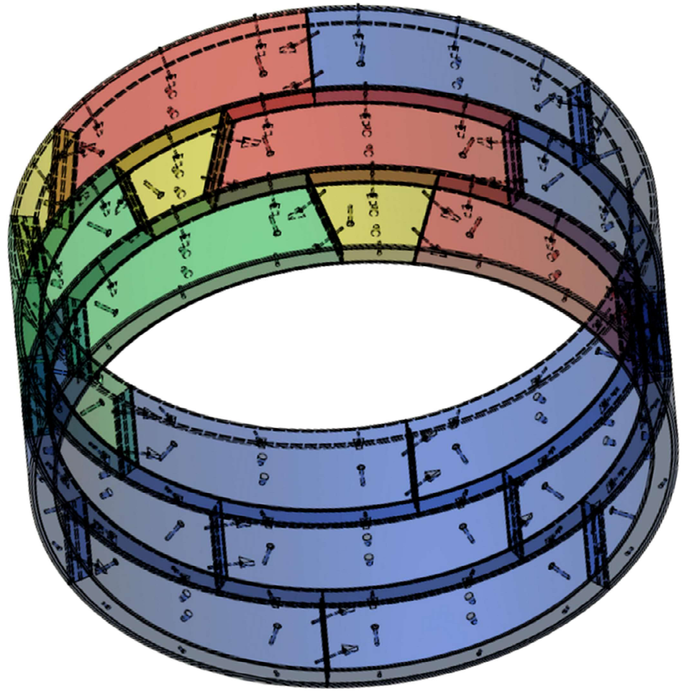
Left and right ring





Universal ring





Basic design requirements

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Ring geometry

- Ring consists of 5 to 8 segments
- Optimization according to project specific factors

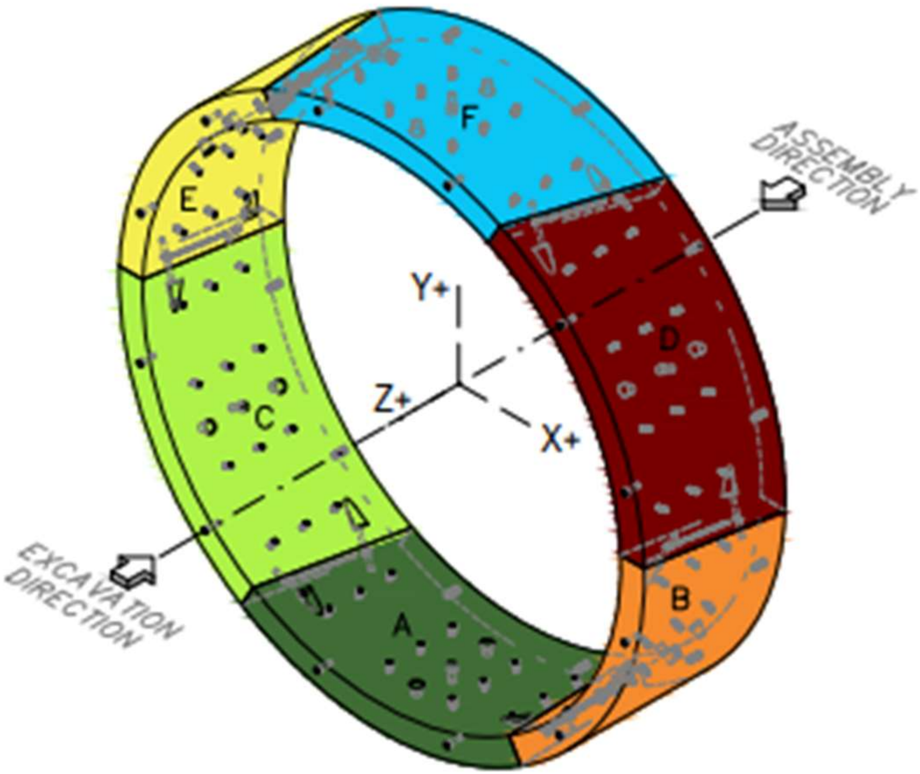
Ring division is influenced by

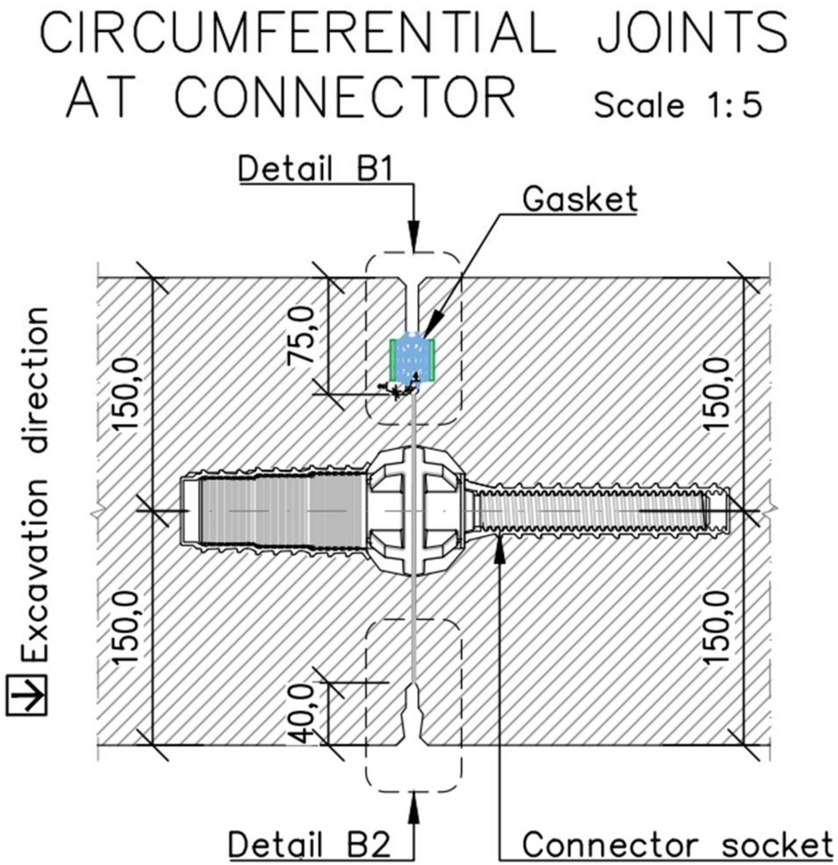
- Tunnel diameter
- Max. permissible size of segments for intended transport
- Mechanical mechanisms for installing segments by erector
- Number of thrust jacks and their distribution over range of ring

Ring conicity

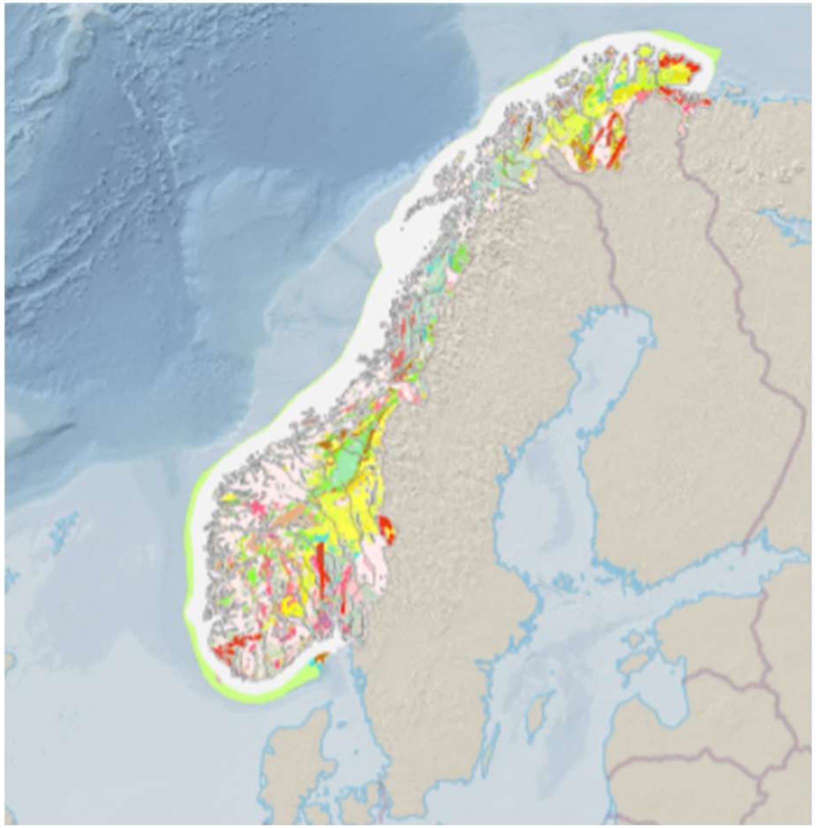
- Tunnel alignment
- Each curve can be produced by rotating rings
- Water tightness

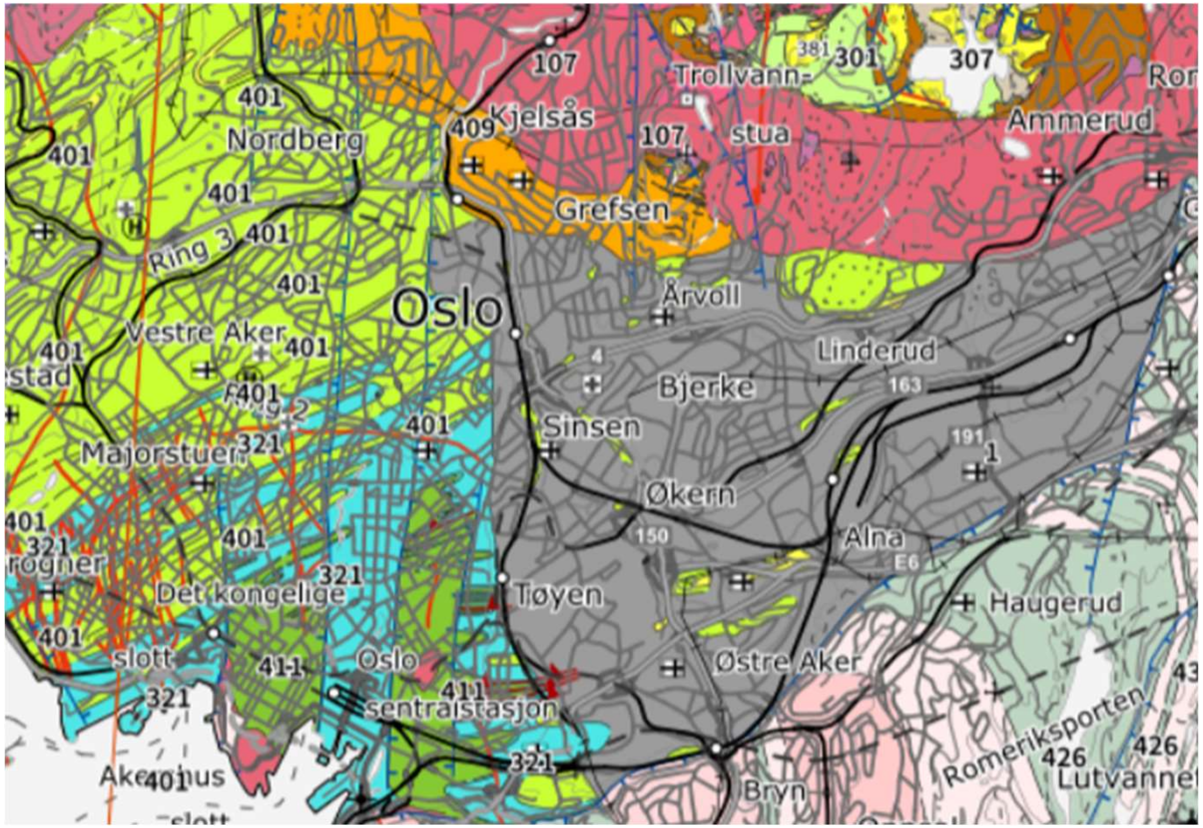
Segment ring with joint detail





Geological overview (NGU)





Core drillings

BH 731. Box 4. 17.4 – 23.2 m.

Core drill logging

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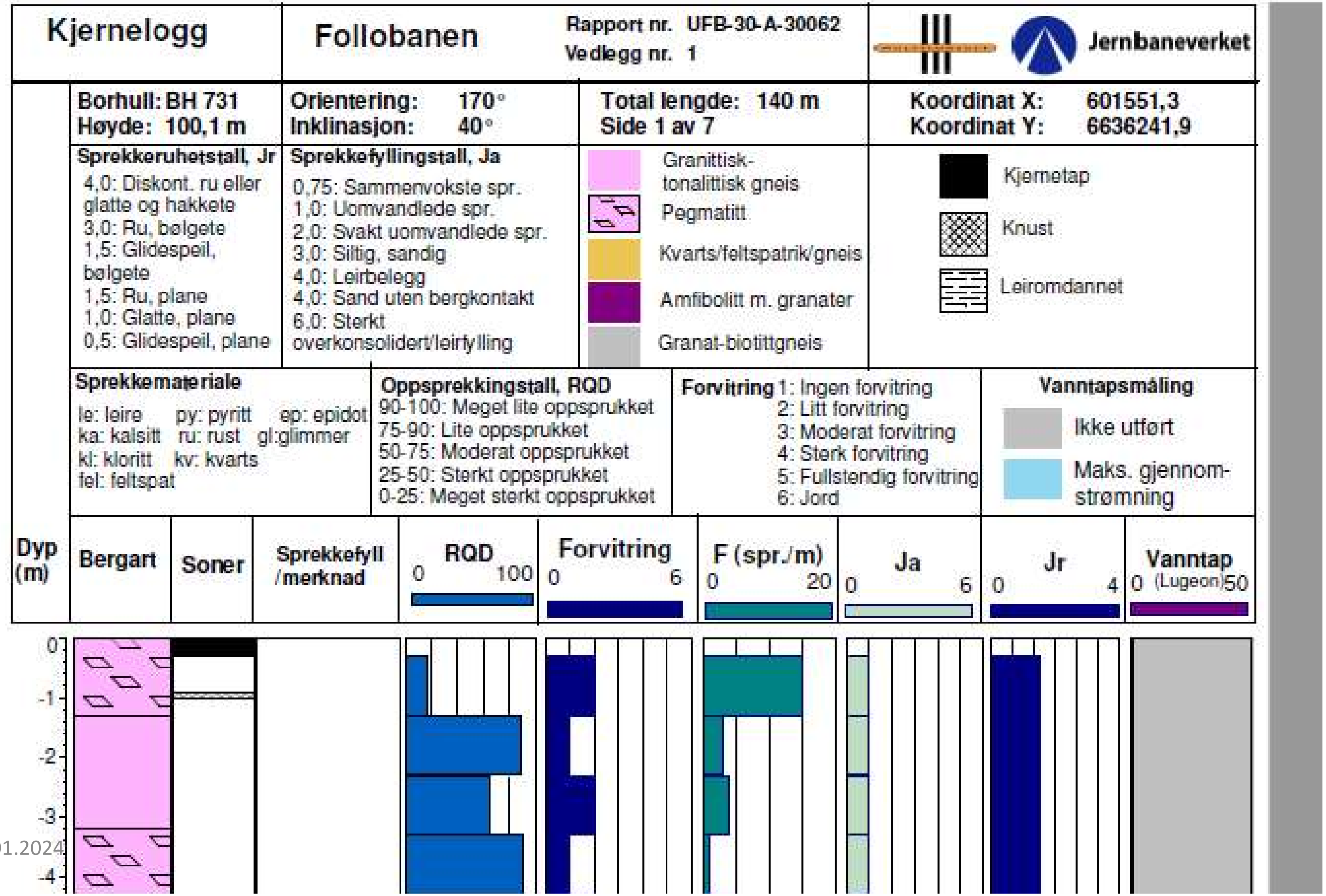

Most relevant parameters

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Rock mass parameters

- Young’s modulus
- Poisson’s ratio
- Uniaxial strength
- Friction angle
- Cohesion
- Fractures with their properties
- Stress conditions

Most relevant parameters

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Ring gap filling

- Bi-component grout
- Pea gravel
- Pea gravel injected with cement-based grout
- Mortar
- Mechanical properties of the ring gap filling

Laboratory testing – uniaixal compressive strength test

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Prøve nr.	Diameter [mm]	Lengde [mm]	Lengde/diameter forhold	Densitet $[kg/m^3]$	E-modul [GPa]	Poisson`s forhold	Trykkfasthet [MPa]	Bruddvinkel [°]	Bruddtype (visuell evaluering)
1-1	50,6	116,3	2,30[1]	2692	19,4	0,20	63,0	20	Skjær
1-2	50,6	118,6	2,34[1]	2693	22,2	0,24	54,5	-	Langs glidespeil
1-3	50,5	100,6	1,99[1]	2869	22,7	0,25	27,8	-	Langs glidespeil
1-Res.	50,5	98,1	1,94[1]	2681	22,4	0,17	79,9	40	Skjær
Gjennomsnitt				**2734**	**21,7**	**0,22**	**56,3**	**30**	
St. avvik				90	1,54	0,04	21,7	14	

[1] *Ihht. ISRM skal prøvens lengde/diameter forhold være 2,5, pga. begrenset lengde på mottatt kjerneseksjon var det ikke mulig å preparere kjerneprøven ihht. standarden.*

Bilder av enaksielle trykkfasthetsbrudd

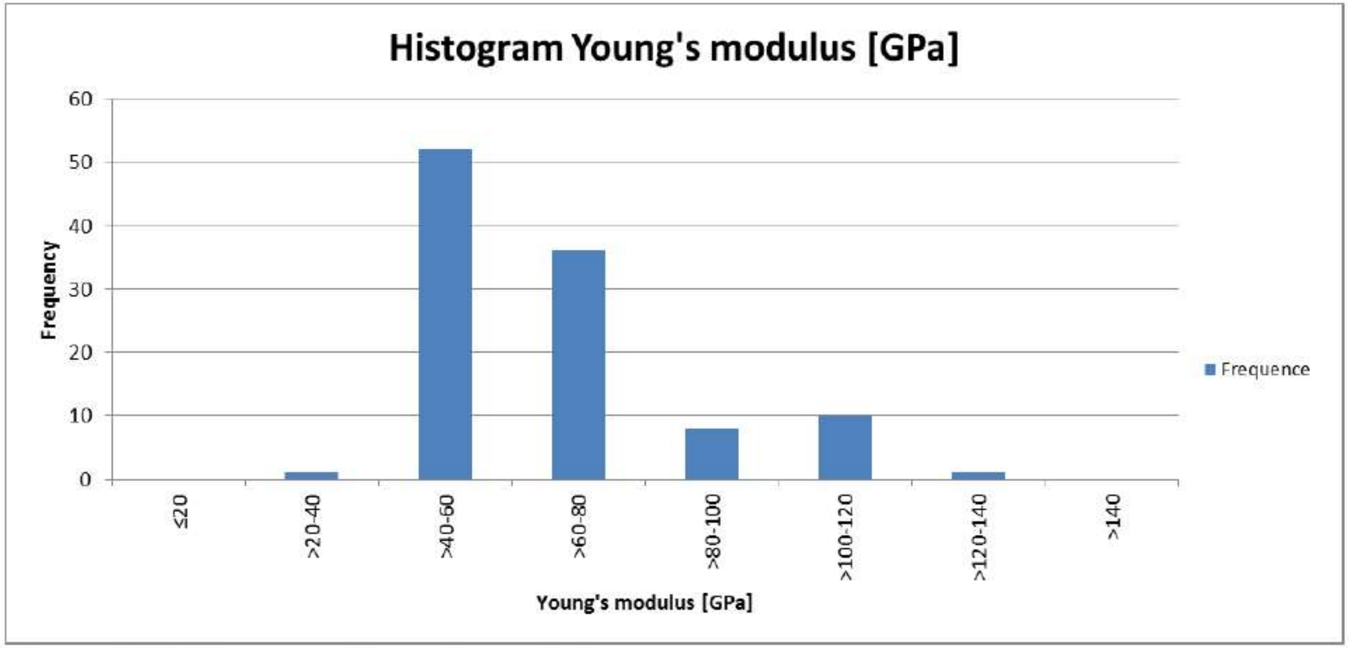
1-1 etter testing

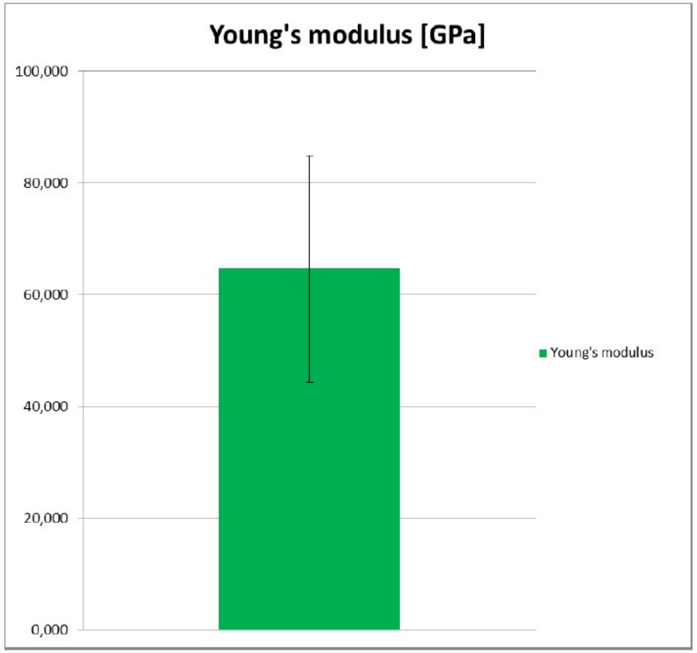
1-2 etter testing

1-3 etter testing

1-Res. etter testing

Youngs' modulus





Geological longitudinal section

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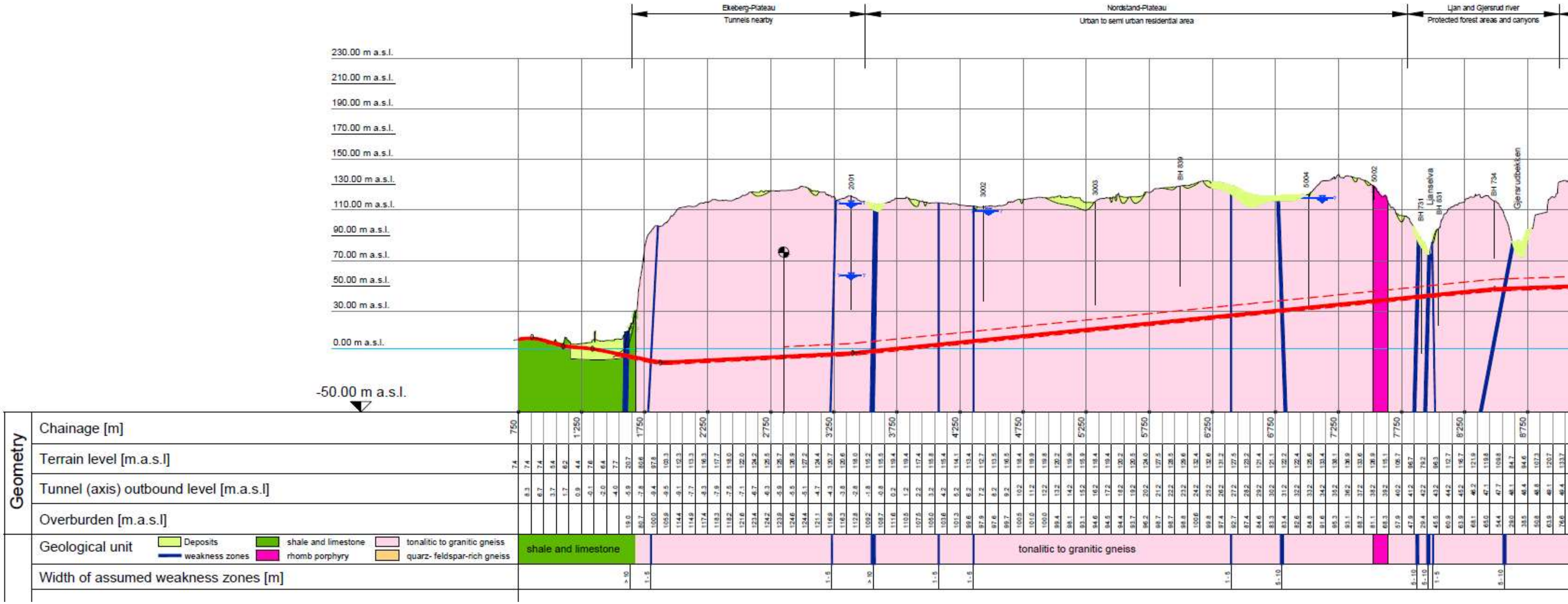

Geotechnical parameters

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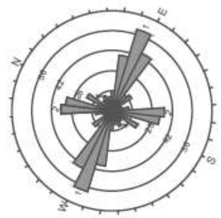
Rock Mechanical Properties

Laboratory testing of rock samples from core drillings	Borehole number (core section)	BH 839 (111.83 - 113.73 m)	BH 731 (129.6 - 131.6 m)	BH 831 (86 - 88 m)	BH 734 (56.4 - 58.4 m)
	Rock type description	granitic - tonalitic gneiss	mica rich amphibolite with garnets	granitic - tonalitic gneiss	banded mica gneiss with garnets
	DRI = Drilling Rate Index	43	39	42	39
	CLI = Cutter Life Index	6.0	8.1	4.8	7.7
	UCS [MPa] = Uniaxial Compressive Strenght	125.6	146.3	157	91.8
	PLT (I_{s50}) [MPa] = Point Load Test	5.7	10.5	9.0	7.5
	CAI = Cerchar Abrasivity Index	4.0	3.3	4.2	3.1
	Quartz [%]	35	5	35	31
	γ [kN/m^3]	27.6	30.2	28.3	27.3
	E [GPa]	48.2		54.3	
	ν [-]	0.17		0.15	
RQD, medium value (%)	Weakness zones excl.	43	81	91	73
	Weakness zones incl.	87	74	88	88

Discontinuities

Jointing [strike/dip]	Ekeberg to Nordstrand: 1. foliation NW-SE 2. joint ENE-WSW/steeply dipping	Nordstrand to Bjørndal: 1. foliation NNW-SSE/35°-80° 2. joint E-W/steeply dipping
Spacing [m]	Ekeberg to Nordstrand: 1. 0.5 m 2. 0.8 m	Nordstrand to Bjørndal: 1. 0.6 m 2. 0.9 m



Hydrogeology

Sensitive areas	Locations	Below Ekeberg (to Holtet)	Holtet - Lambertseter	Nordstrandsplatået	Ljanselva - Gjersrudbekken	Bjømerud
	Area classification	(green)	(yellow)	(red)	(green)	(yellow)
	Sensivity	Small sensivity	Moderate sensivity	Sensitive	Small sensivity	Moderate Sensitivi

Hydraulic conductivity * Measured water loss was 0	Rock type description	2001 Gneiss	3002 Gneiss	3003 Gneiss	BH 839 Mainly gneiss with amphibolite and some pegmatite	5004 Gneiss	BH 731 Granitic-tonalitic gneiss, supracrustal gneiss, pegmatite and some amphibolite	BH 831 Granitic-tonalitic gneiss, and amphibolite with garnets	Primarily garnet-bi... pegmatite and gra... plus one section
	Average [m/s] (Lugeon value)	$3.5*10^{-7}$ (1.5)	$1.3*10^{-7}$ (0.58)	$3.3*10^{-8}$ (14.2)	$2.6*10^{-7}$ (1.1)	$1.1*10^{-7}$ (0.49)	$5.1*10^{-7}$ (2.20)	$6.1*10^{-7}$ (2.62)	$3.7*10^{-}$...
	Max / Min [m/s] (Lugeon value)	$2.0*10^{-6}$ (8.8) / 0*	$3.26*10^{-7}$ (1.41) / 0*		$1.4*10^{-6}$ (6.1) / 0*	$8.43*10^{-7}$ (3.67) / 0*	$>3.1*10^{-6}$ (13.3) / 0*	$>2.76*10^{-6}$ (12) / $9.6*10^{-8}$ (0.42)	1.0*10... (High value clo... / 2.7*1...

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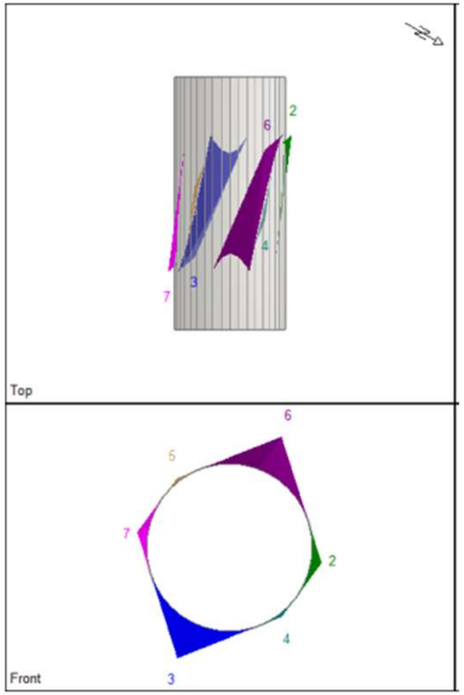
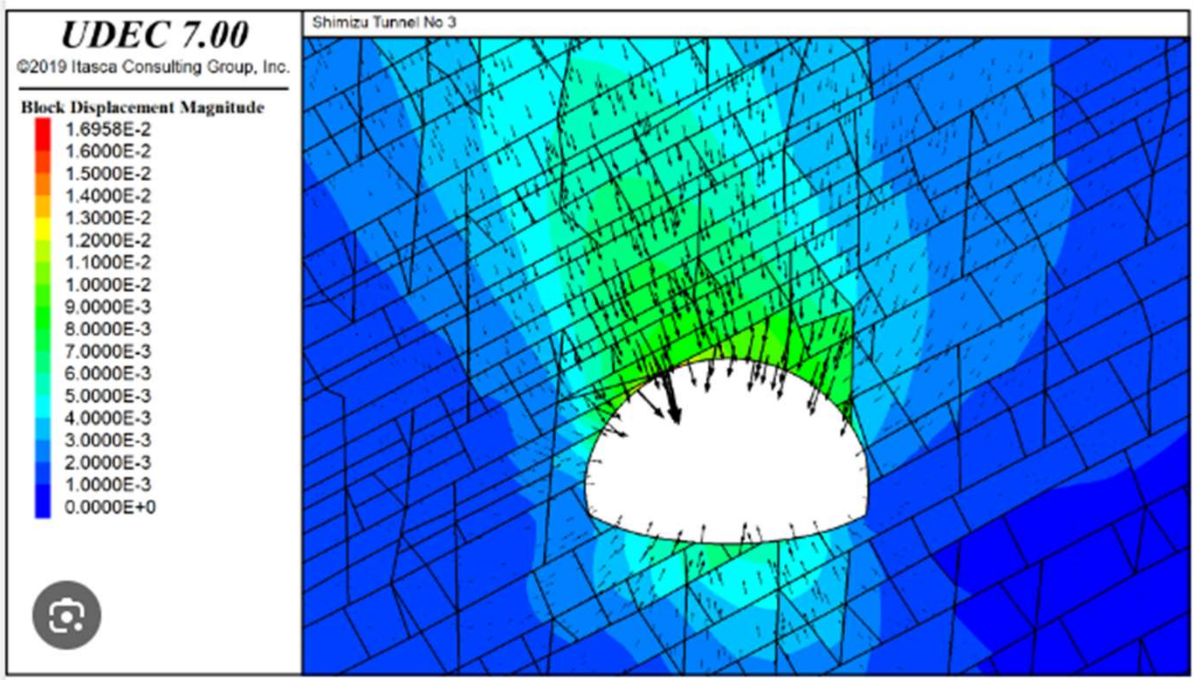
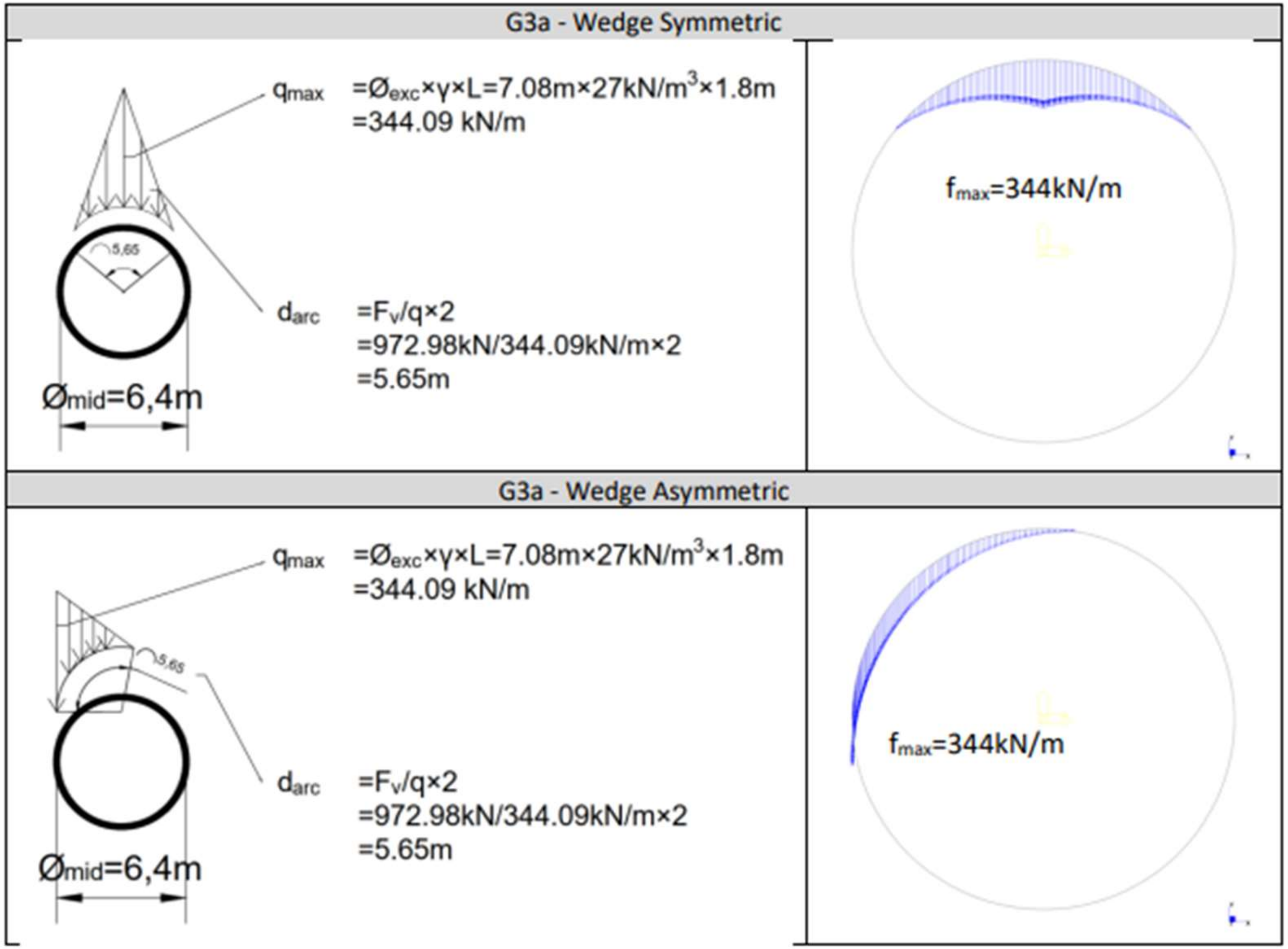
Unwedge



UDEC



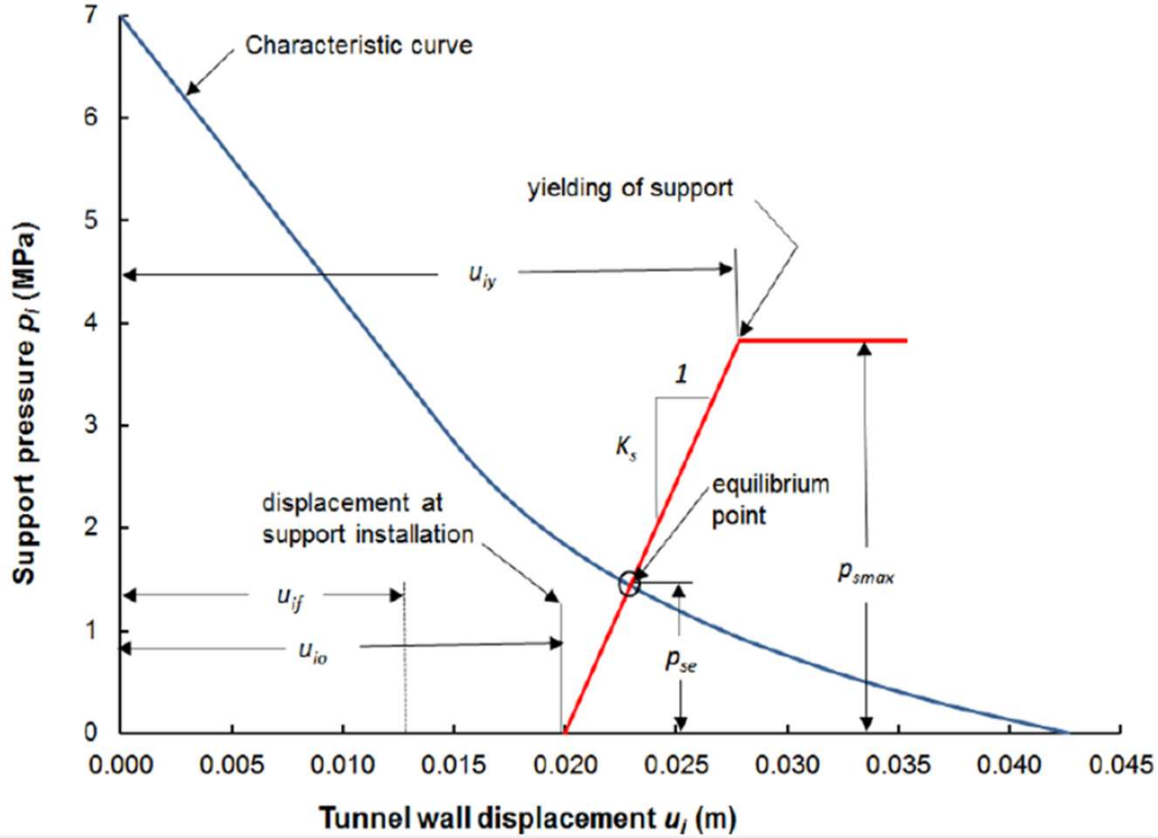
Rock loads



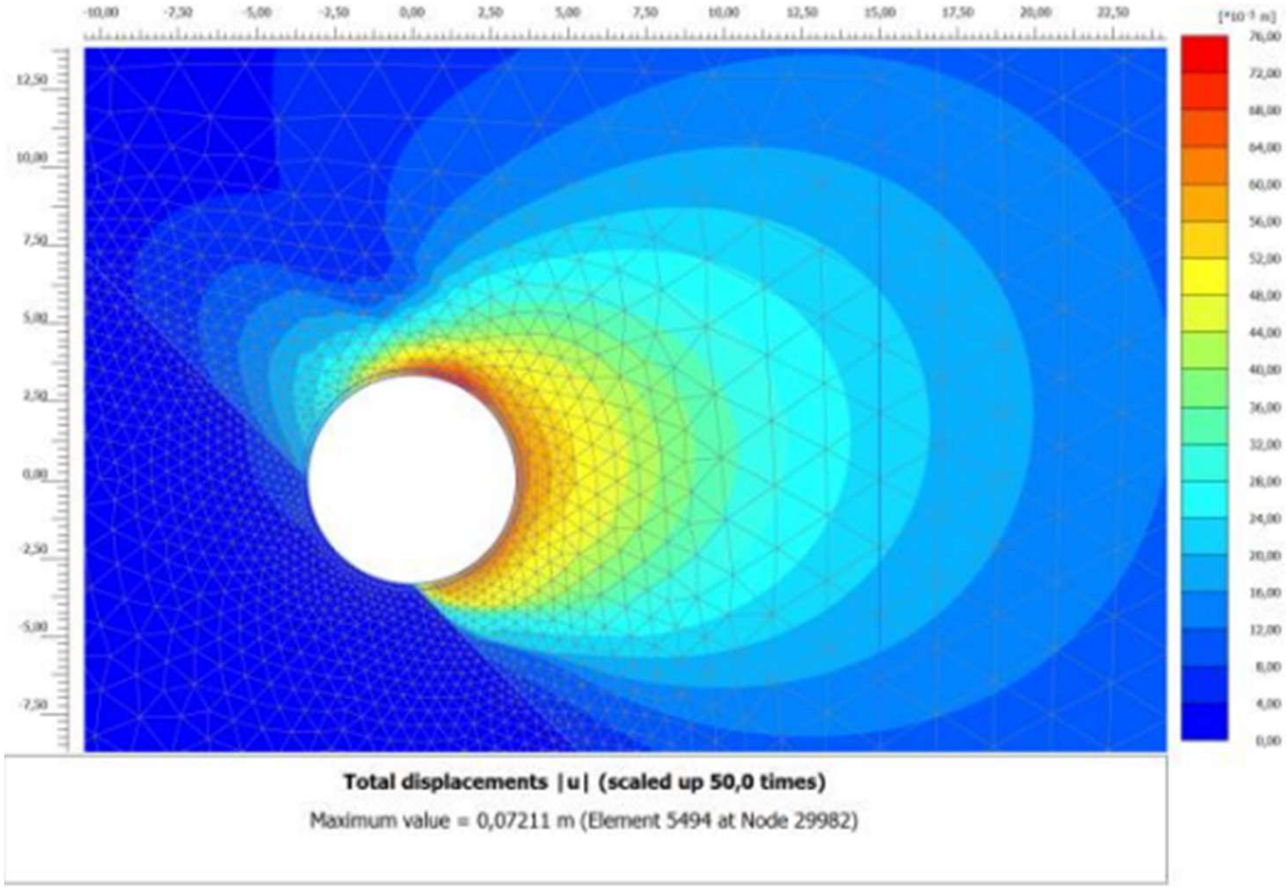
G3a - Wedge Symmetric
q_{max} $=Ø_{exc}×γ×L=7.08m×27kN/m^3×1.8m$
=344.09 kN/m
5,65
d_{arc} $=F_v/q×2$
=972.98kN/344.09kN/m×2
=5.65m
$Ø_{mid}$=6,4m
f_{max}=344kN/m
G3a - Wedge Asymmetric
q_{max} $=Ø_{exc}×γ×L=7.08m×27kN/m^3×1.8m$
=344.09 kN/m
5,65
d_{arc} $=F_v/q×2$
=972.98kN/344.09kN/m×2
=5.65m
$Ø_{mid}$=6,4m
f_{max}=344kN/m

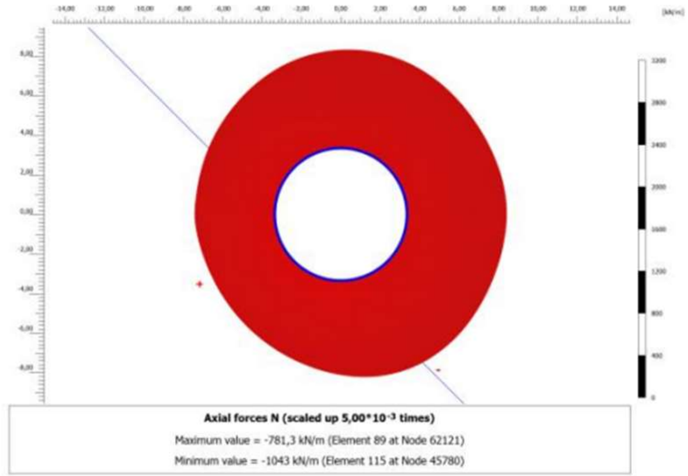
Ground reaction curve

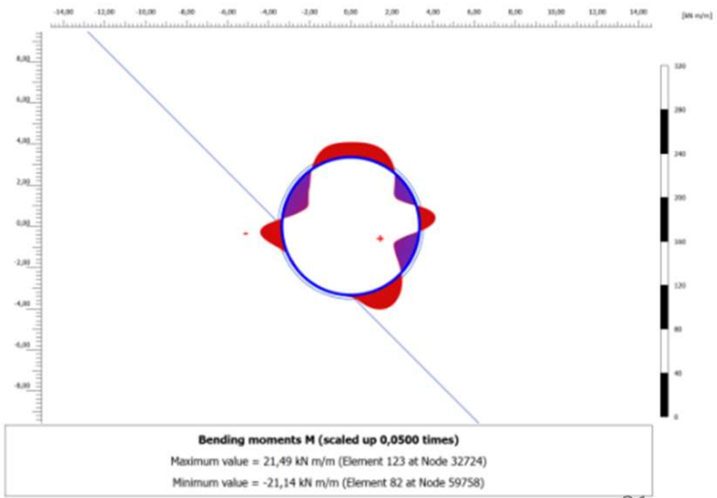
- Empirical formulas
- Numerical calculation



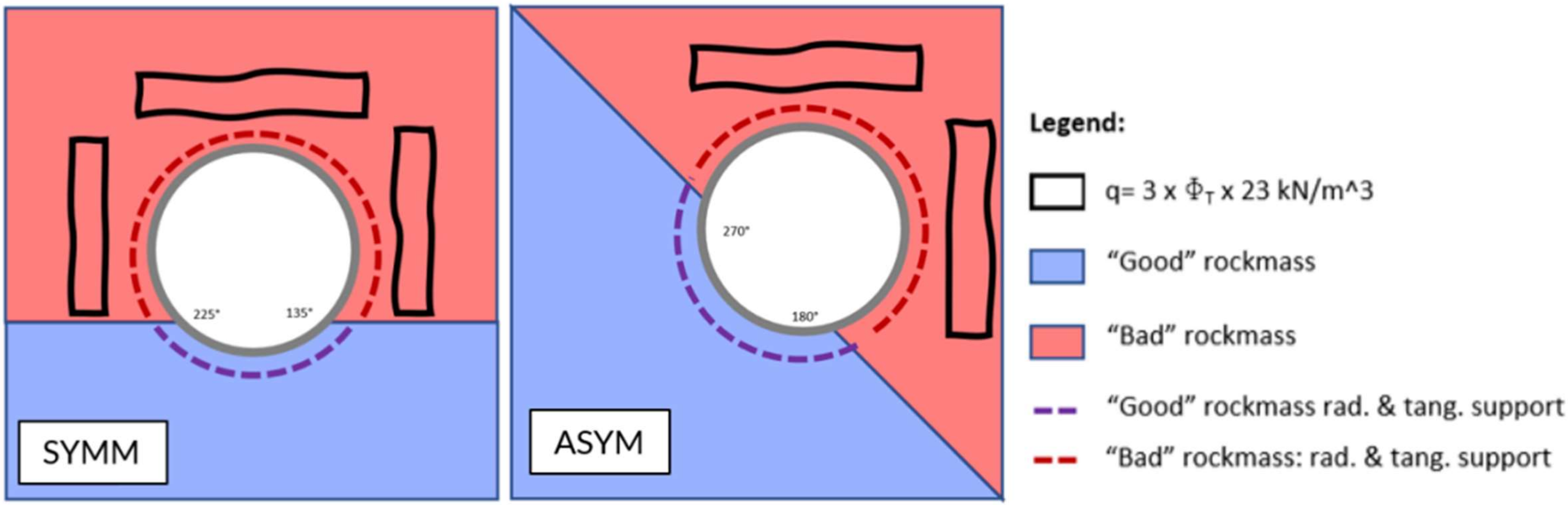
Numerical modelling of rock mass and lining



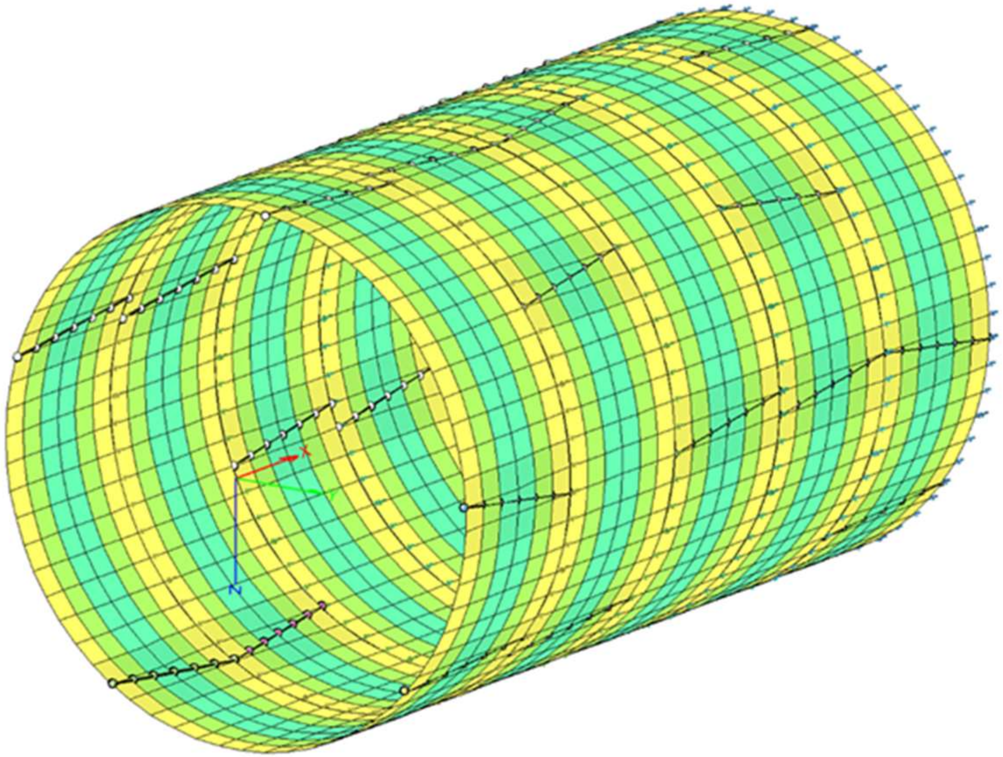




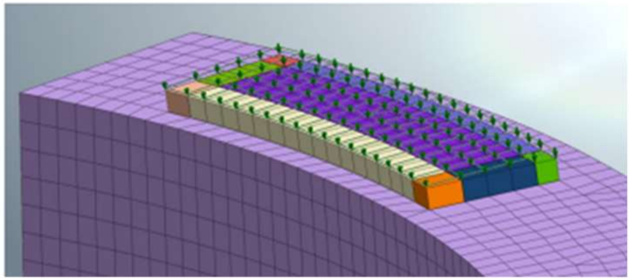
Rock loads for unfavourable rock mass conditions



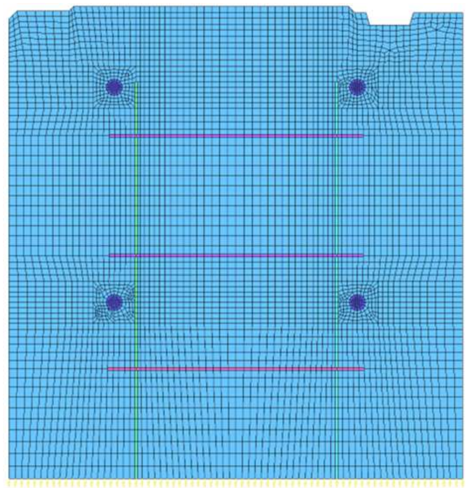
Shell model



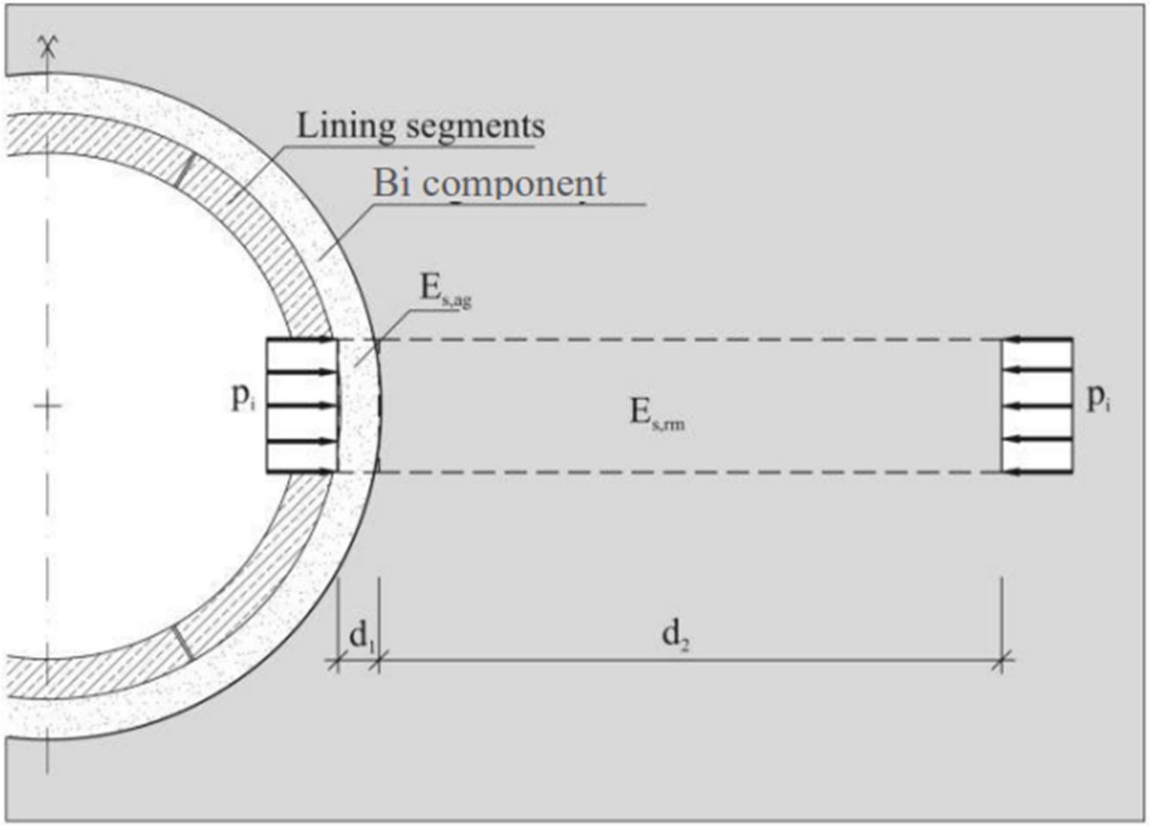
Segment joint with loaded thrust cylinders



Joint with reinforcement



Bedding for structural models



$$k_r = \frac{1}{\frac{d_{ag}}{E_{s,ag}} + \frac{d_rm}{E_{s,rm}}}$$

k_r : bedding modulus [MPa/m]

d_{ag}: width of the anular gap [m]

d_{rm}: influence depth of the rock mass [m]

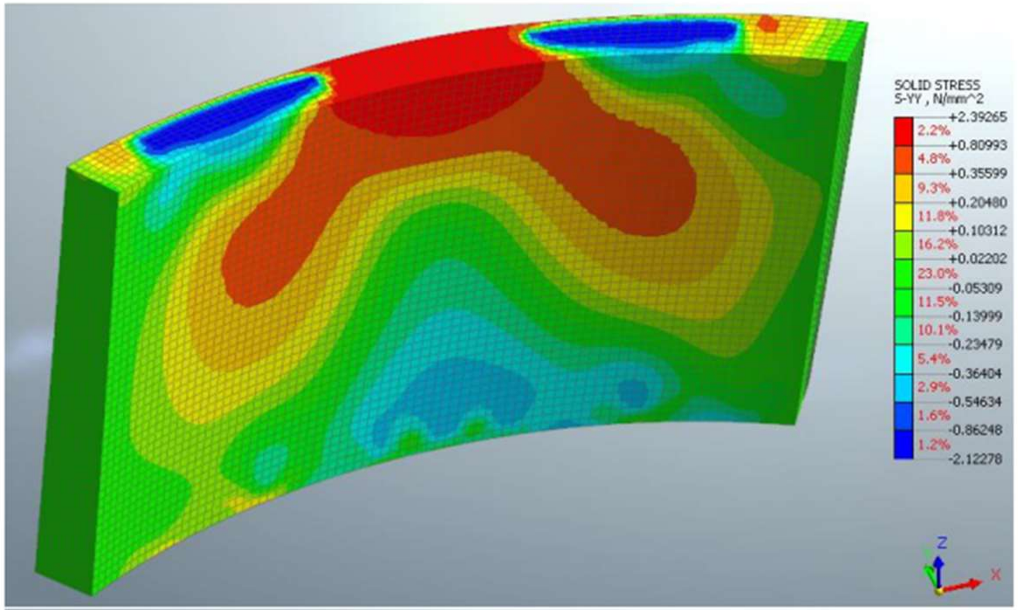
$E_{s,ag}$: constrained modulus of backfilled material [MPa]

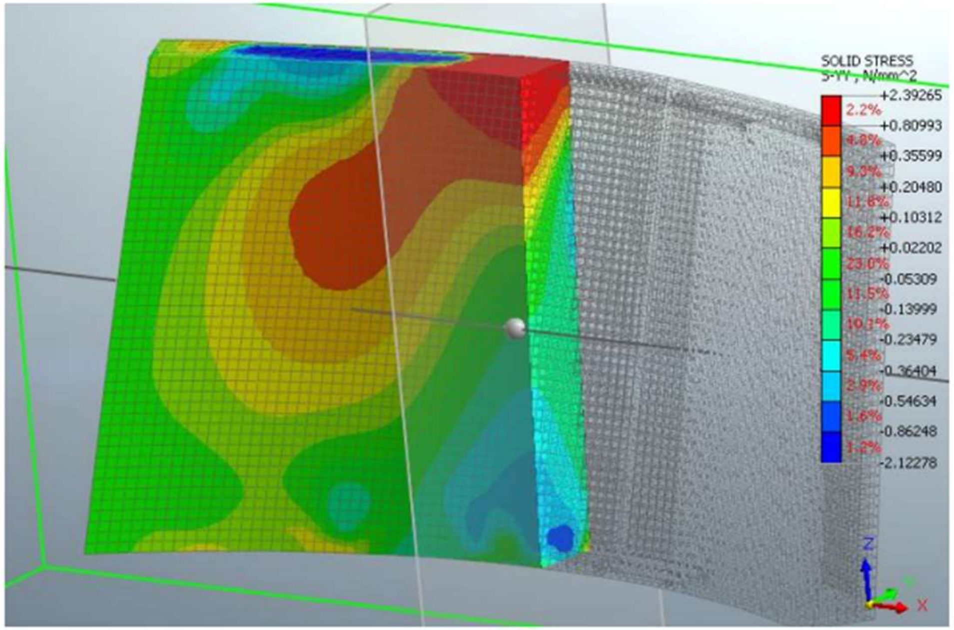
$E_{s,rm}$: constrained modulus of the rock mass [MPa]

Equation presented by different researchers

Number	Reference	Equation	Considerations
1	Bieniawski (1978)	$E_{rm} = 2RMR - 100(GPa)$	RMR > 50
2	Serafim and Pereira (1983)	$E_{rm} = 10^{\frac{(RMR-10)}{40}}(GPa)$	$30 < RMR \leq 50$
3	Nicholson and Bieniawski (1990)	$E_{rm} = Ei\left[0.0028RMR^2 + 0.9e^{\left(\frac{RMR}{22.921}\right)}\right]$	–
4	Mehrotra (1992)	$E_{rm} = 10(RMR - 20)/38$	–
5	Grimstad and Barton (1993)	$E_{rm} = 25 \log Q(GPa)$	$Q > 1$
6	Mitri et al. (1994)	$E_{rm} = E_i[0.5(1 - \{\cos \pi \frac{RMR}{100}\})](GPa)$	–
7		$E_{rm} = H^{0.2} \cdot Q^{0.36}$	$Q < 10$
8	Read et al. (1999)	$E_{rm} = 0.1\left(\frac{RMR}{10}\right)^3(GPa)$	–
9	Palmstrom and Singh (2001)	E_{rm}= 5.6 Rmi 0.375	0.1 < Rmi < 1
10		E_{rm}= 7 Rmi 0.5	$1 < Rmi \leq 30$
11		E_{rm}= 7 Rmi 0.4	Rmi > 30
12	Palmstrom and singh (2001)	$E_{rm} = 0.5MR\,\sigma_c i$	–
13	Barton (2002)	$E_{rm} = 10Q_C^{1/3}(GPa)$	$Q_c = Q\ (\sigma_{ci}/100)$
14	Hoek et al. (2002)	$E_{rm} = \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}}10^{(GSI-10)/40}$	$\sigma_{ci} \leq 100$ Mpa
15		$E_{rm} = \left(1 - \frac{D}{2}\right)10^{(GSI-10)/40}$	$\sigma_{ci} > 100$ Mpa
16	Kayabasi et al. (2003)	$E_{rm} = 0.135\left(Ei\left(1 + \frac{RQD}{100}\right)/WD\right)^{1.911}$	–
17	Gokceoglua et al. (2003)	$E_{rm} = 0.001\left(\frac{Ei}{\sigma_{ci}}\left(1 + \frac{RQD}{100}\right)/WD\right)^{1.5528}$	–
18	Sonmez et al. (2004)	$E_{rm} = E_i(s^a)^{0.4}(GPa)$	$S = e^{\left(\frac{GSI-100}{9}\right)}$ $a = 0.5 + \frac{1}{6}e^{(GSI-15)} - e^{\left(\frac{-20}{3}\right)}$
19	Zhang & Einstein (2004)	$E_{rm} = Ei(10^{0.0186RQD-1.91})$	–
20	Jose et al. (2005)	$E_{rm} = Ei\ e^{(RMR-100)/36}$	–
21	Hoek and Diederichs (2006)	$E_m = 100\left(\frac{1-D/2}{1+e^{((75+25D-GSI)/11)}}\right)(GPa)$	–

NORSK BERGMEKANIKKGRUPPE





Reinforcement

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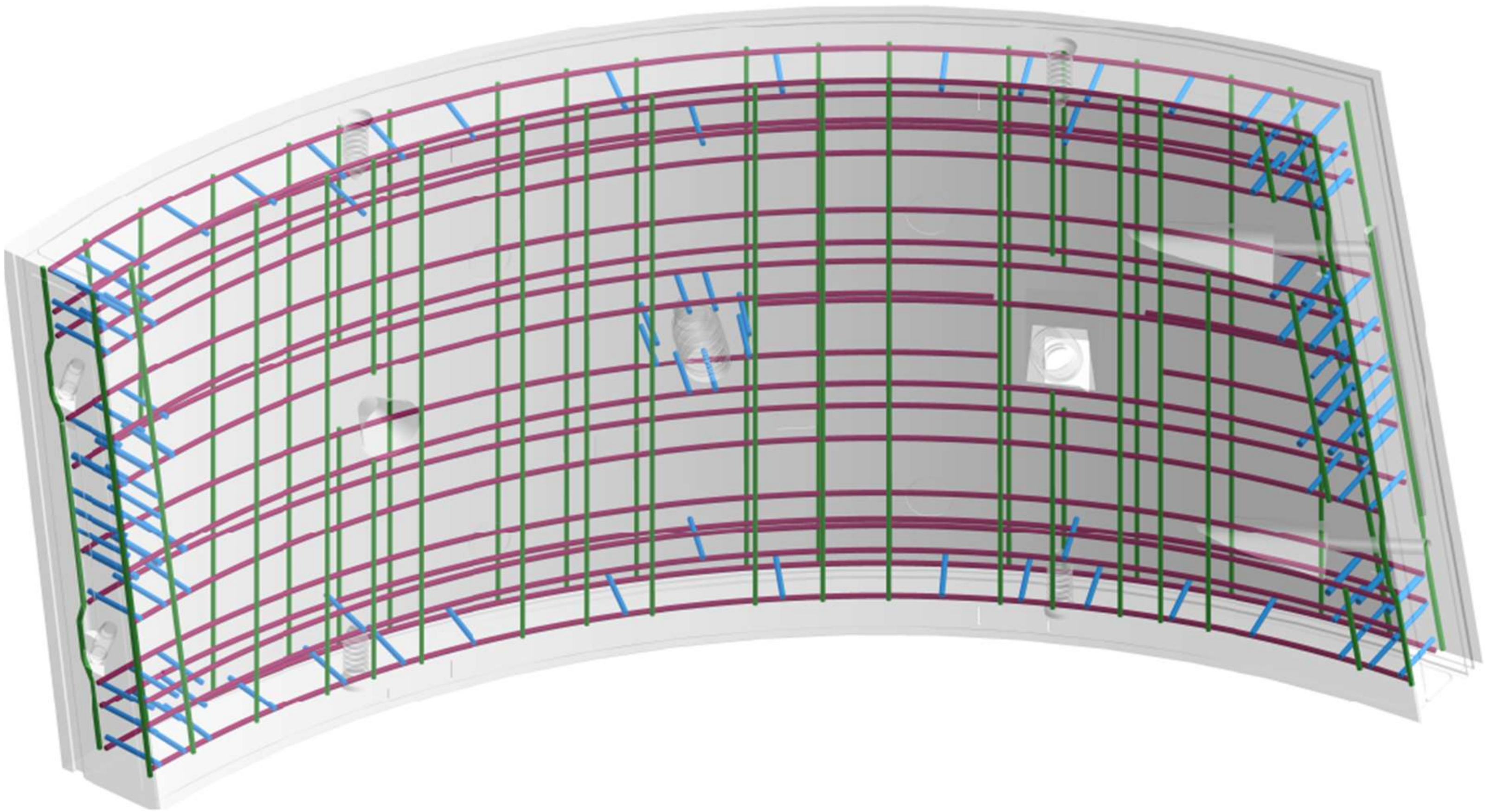


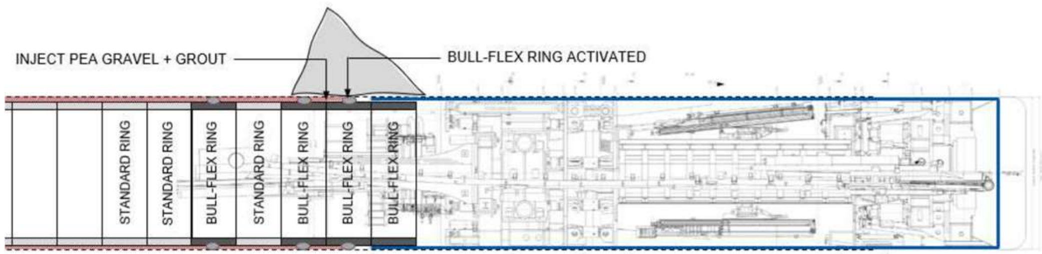
Basic reinforcement requirements

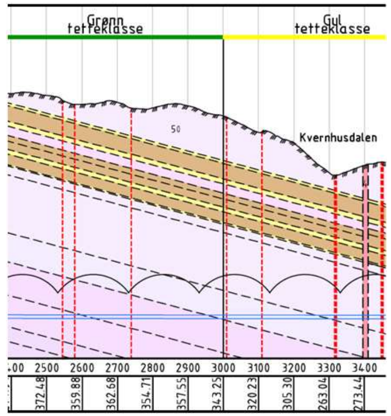
- A combination of steel bars, wire mesh and steel fibres maybe used. However, the minimum reinforcement requirement shall be provided by steel bars.
- For fire protection PP-fibres shall be added, if required.
- The combination of steel bars, steel fibres and PP fibres make the concrete very difficult to work.
- Suitable excavated muck to be used for segment production.

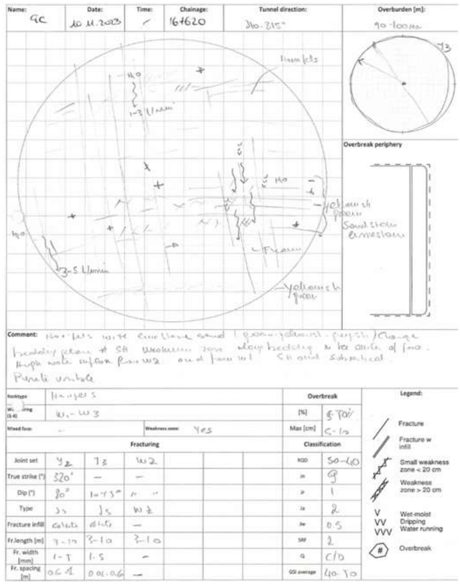
Verification during construction

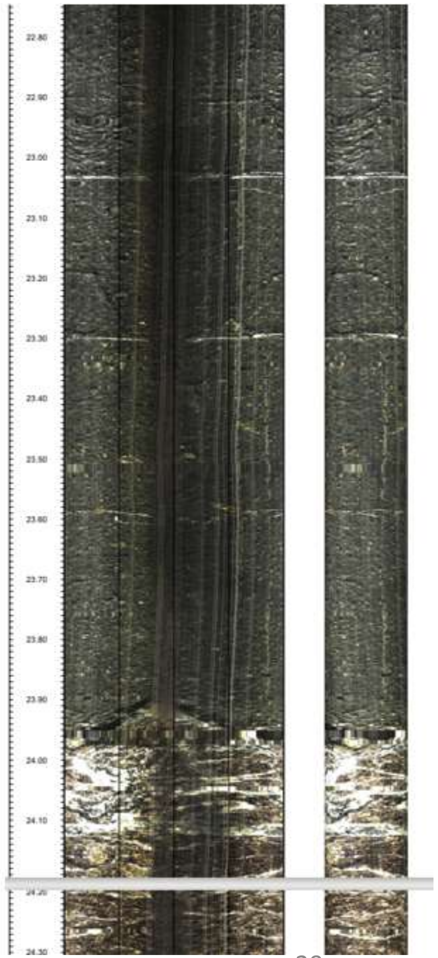
- Longitudinal geological profile
- Probe holes with MWD
- Probe holes with OTV
- Face mapping

- Machine data (penetration, thrust force, torque, electrical power consumption,…)









Summary of segment design and verification

NORSK BERGMEKANIKKGRUPPE

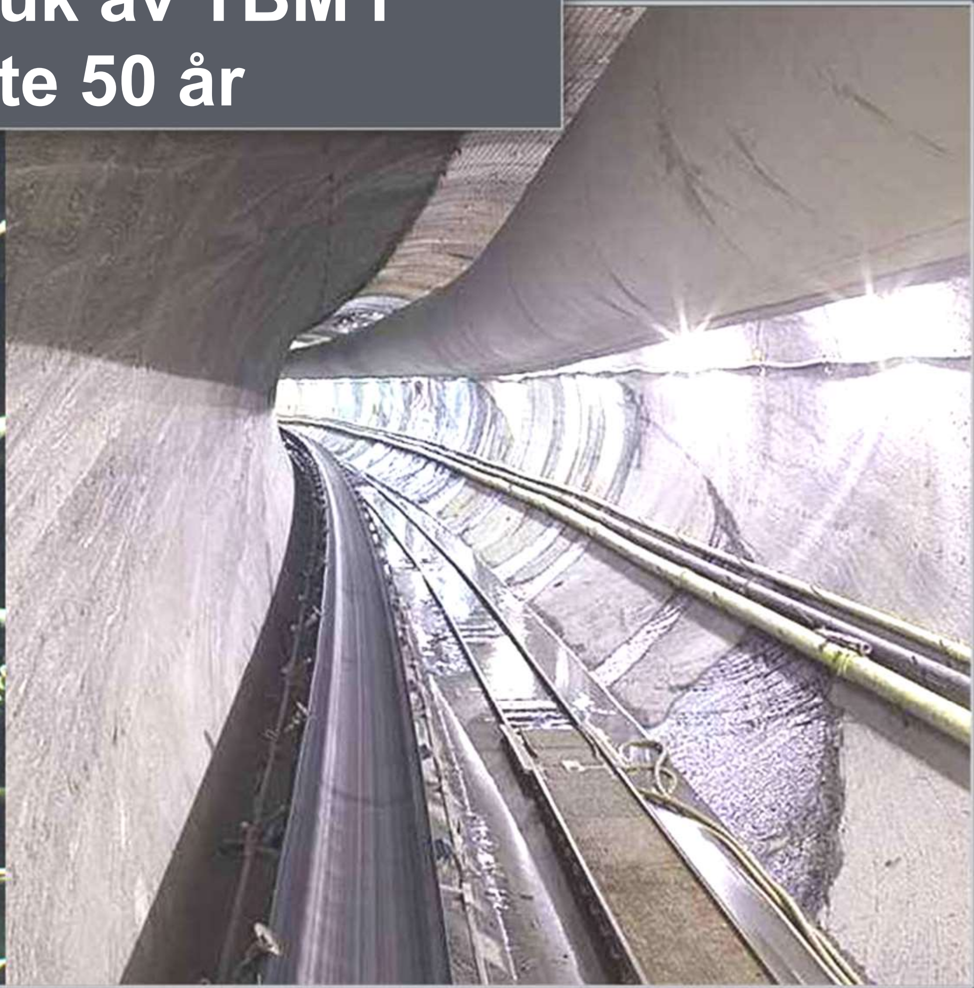
- Constant segment thickness
- Different amount of reinforcement to account for different load situations
- Different concrete grade to account for different load situations

- Follow-up the design assumptions are meet during construction (tolerances, thrust cylinder loads, load assumptions,..)
- Develop a clear procedure how to choose different segment types
- Secure the ring gap is properly filled

Thank you very much for your attention!

NORSK BERGMEKANIKKGRUPPE

Erfaringer med bruk av TBM i Norge over de siste 50 år



Thor Skjeggedal

Oslo, januar 2024

SCS Skjeggedal Construction Services AS

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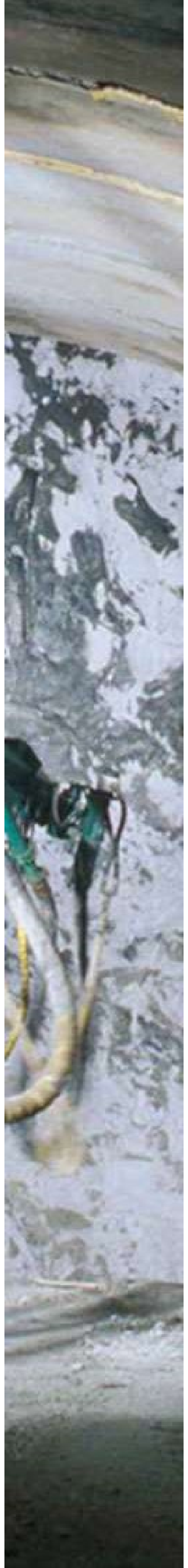

Oversikt

- ❖ Historie
- ❖ Spesielle forhold i Norge
- ❖ Valg av TBM som drivemetode og type TBM
- ❖ Kontraktsmessige forhold
- ❖ TBM design
- ❖ Risiko

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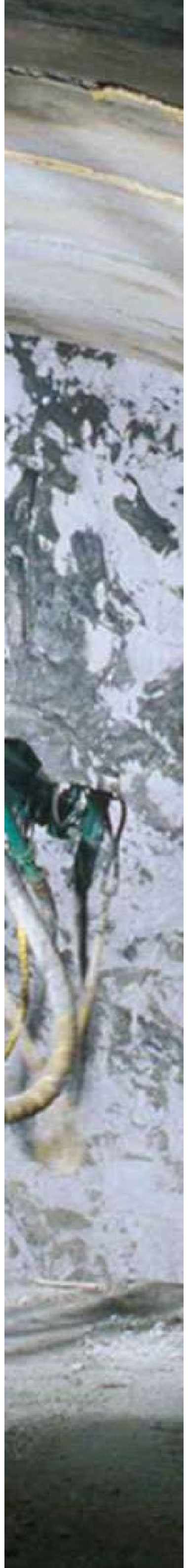

TBM boring i Norge

- Trondheim 1972, Demag maskin, 4,3 km, Ø2,3 m
- VEAS prosjektet, over 40 km på 70 – 80 tallet
- Vannkraft, mange prosjekter
- Fløyfjellet, veitunnel i Bergen, midten av 80 tallet
- NVE/Statkraft, Ulla Førre, Jostedal og Svartisen
- Skråsjakter (45 gr.) for vannkraft
- Jernbaneverket/BaneNOR, Follo og Ulrikken
- NVO, ny vannforsyning til Oslo

- Totalt boret lengde i Norge, ca. 330 km

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Norske forhold

- Stort sett harde og stabile bergarter
- Tradisjonelle sikringsmetoder, bolter og SFR, senere også betongutforing
- Lange tunneler
- Behov for vanntetting (forinjeksjon)

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Valg av drivemetode

Viktig, vurder drivemetode i en tidlig planleggingsfase

- Tunnllengde
- Krav til tverrsnitt
- Geologi
- Adkomst, logistikk

Men som alltid, kostnader er som regel avgjørende

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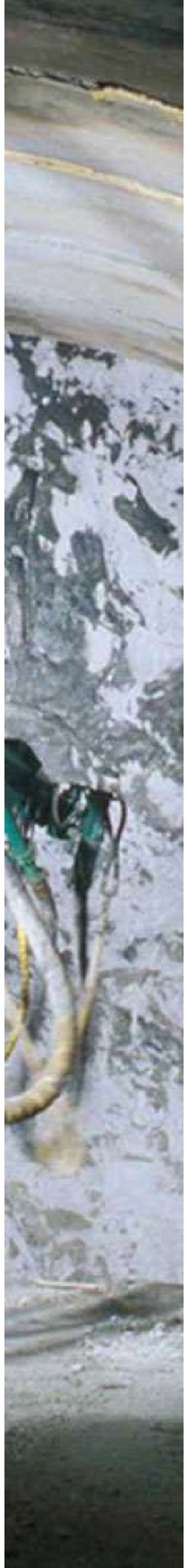

Type TBM

Velge rett TBM ut fra prosjektets særegenhet

- Åpne maskiner, mest vanlig i Norge. God inndrift i harde bergarter som ikke krever spesiell tung sikring
- Skjoldmaskiner. God inndrift, men bergforholdene krever tyngre stabilitets- og vannsikring
- EPB. Ikke i Norge så langt. I løsmasser og/eller kombinasjon løsmasser/berg

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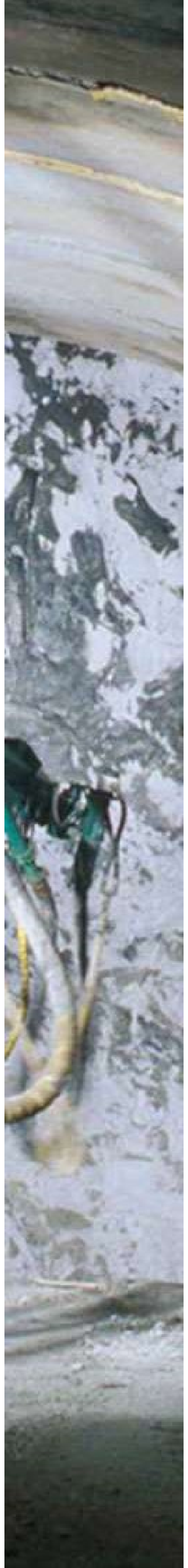

Kontraktsmessige forhold

Byggherren må velge drivemetode

- ❖ Er TBM valgt må prosjektet spesifisere for det
- ❖ Ikke la entreprenør velge maskintype
- ❖ Byggherren bør/må sette krav til spesifikasjoner
- ❖ Risikofordeling byggherre/entreprenør. Geologisk risk tilhører byggherren, det operative entreprenøren
- ❖ Enhetspriskontrakt med oppgjør etter medgåtte mengder for stabilitets- og vannsikring

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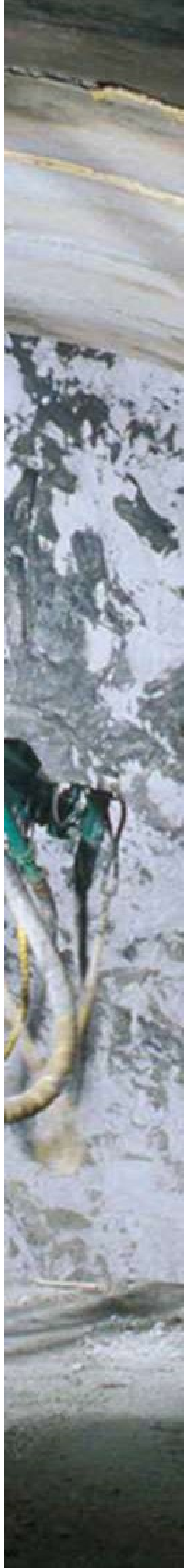

Kontraktsmessige forhold

Geologi og grunnforhold

Grundige geologiske undersøkelser er viktig

- **Dårlige og ustabile soner /overdekning spesielt**
- **Borbarhet**
- **Mengdeberegninger**

For fremdrifts- og kostnadsanalyser:

- **Bruk av NTNU modellen for netto inndrift**
- **Ekvivalenttidsregnskap**

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Kontraktsmessige forhold

TBM design

- **Hvorfor spesifisere dette?**
- Vi ønsker oss en maskiner som er «skreddersydd» til de spesifikke geologiske forholdene på prosjektet fordi bl. annet:
- Eventuelle internasjonale entreprenører kjenner ikke de harde norske bergartene og kan ha liten erfaring med forinjeksjon. Risiko for at de kan tilby maskiner som ikke mestrer forholdene

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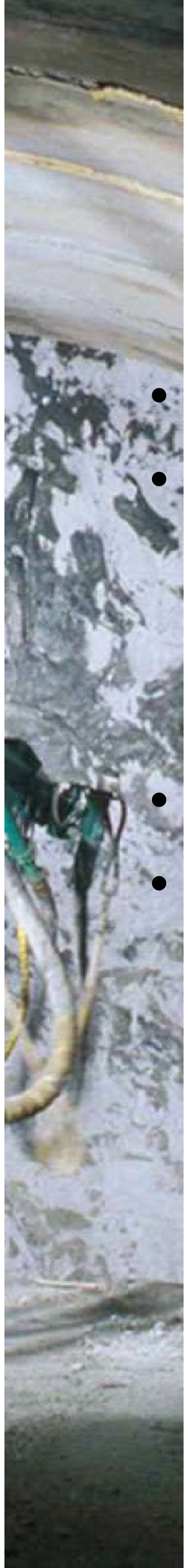
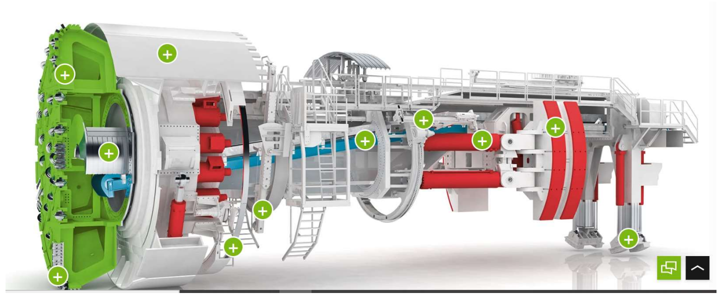
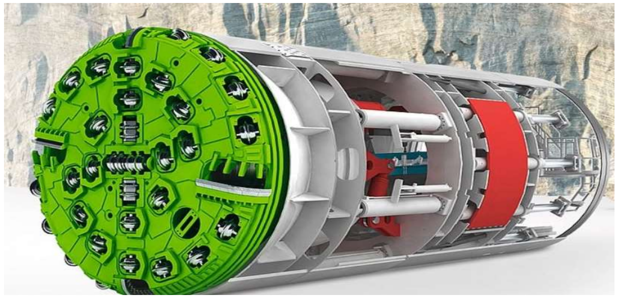


TBM valg/design

- *Åpen gripper TBM*
- Passerer der hvor en har harde og stabile bergarter



- *Dobbeltskjold TBM*
- Effektiv maskintype der en kan forvente partier som vil kreve mye stabilitetssikring og betongutforing er nødvendig. Kan bore mens betongsegmentene plasseres



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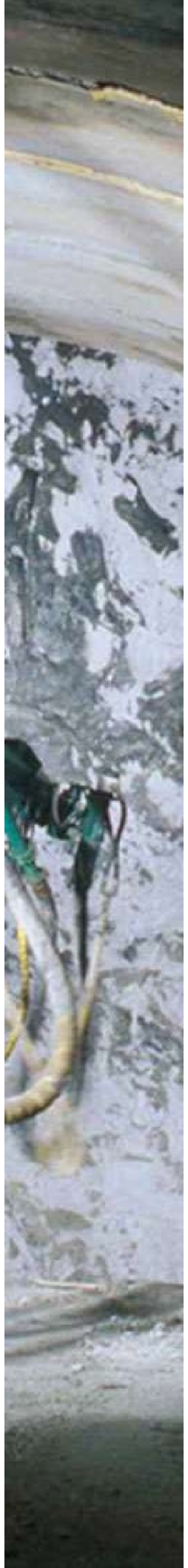
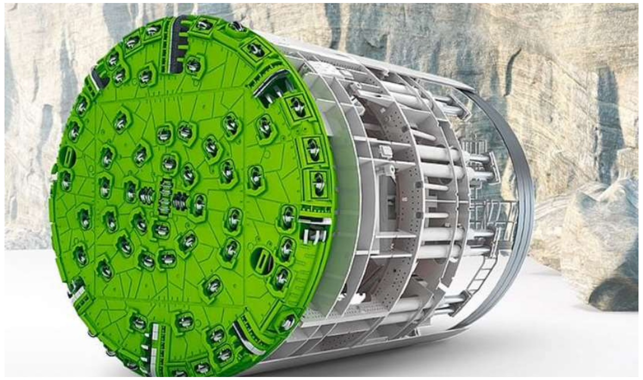


TBM valg/design

Enkeltskjold TBM

Brukes der hvor en forventer ustabile bergforhold. Krever at der installeres betongutforing. Enklest adkomst frem mot stuff for sonderboring. Kan ikke bore mens betongelementene plasseres. Lavere fremdrift enn DS maskiner.



EPB maskiner

Mer komplekse maskiner med lav inndrift og høye driftskostnader. Ikke benyttet i Norge så langt

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Kontraktsmessige forhold

TBM spec.

Inn i kontrakts bestemmelsene som minimumskrav

Pt. 1
Type TBM basert på geologiske forhold
Diameter etter prosjektets krav

Pt. 2
Tekniske krav, åpen maskin
Tilgjengelig sikringsutstyr, boltet, SFR, buer, mfl.

Event. Injeksjonsutstyr inkl. kapasiteter

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TBM spec.

Inn i kontrakts bestemmelsene

Pt. 3

For åpne og skjoldmaskiner i hardt berg

Kutterhode og drivverk

- Vekt, ønsker et solid kutterhode
- Kutterstørrelse, 19 tommer, event. 20 tommer
- Matertrykk, må tåle nominell belastning på 315 kN
- Avstand kutterspor, så lav som mulig (spesielt viktig i hardt og massivt berg)
- Omdreiningstall, variabelt opp til 170 m/min. pereferihastighet
- Inst. Effekt, avhengig av Ø
- Størrelse på hovedlager, 0,6 – 0,7 X Ø
- Levetid på hovedlager, 15 – 20 000 timer

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TBM spec.

Inn i kontrakts bestemmelsene

Pt. 3 forts.
To trinns girkasser for å kunne øke dreiemoment i vanskelige soner

Eventuelt injeksjonsutrustning
Antall boremaskiner
Krav til hullengde, 30 m eller mer
Avstand mellom hull, helst rundt 1 m
Hullvinkel, 5 – 8 grader
Pumpekapasitet og trykk

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TBM spec.

Inn i kontrakts bestemmelsene

Pt. 3 forts.

Bakrigg

- Kurveradius
- Kapasitet på transportbånd
- Ventilasjonsanlegget
- Høyspentanlegget, Cosinus fi, osv.
- Drenasjekapasitet, spesielt dersom det bores på synk
- Navigasjonssystemet, nøyaktighet
- Nettforbindelse for oppfølging, feilsøking, mm
- Dataloggingssystem

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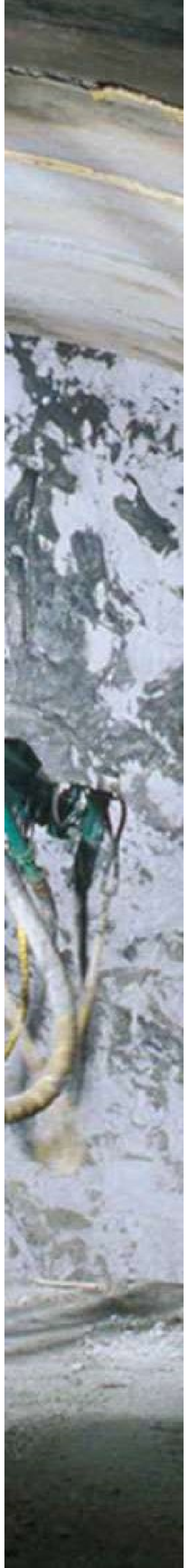

Øvrig spec.

Inn i kontrakts bestemmelsene

Helse, miljø og sikkerhet (HMS)

Redningskammer:

- Et så langt frem mot stuff som mulig
- Et kjørbart bak bakriggen
- Et kjørbart i portal for nødetatene

Øvrig:

- Selvreddere
- Gassdeteksjon
- Merking av evakueringsrute
- Sikkerhetsrutiner for kutterbytte
- TV overvåkning og kommunikasjon
- Vanngardiner
- mm.

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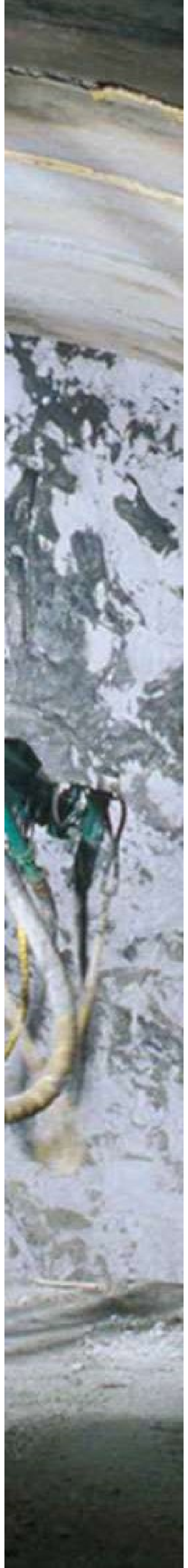

Øvrig spec.

Inn i kontrakts bestemmelsene

Reservedeler

Krav til beholdning og lagringsplass for 3 forskjellige kategorier av reservedeler

Liste med minimum beholdning skal til enhver tid kunne fremlegges for byggherren

Kutterverksted skal etableres rimelig avstand fra tunnelportalen

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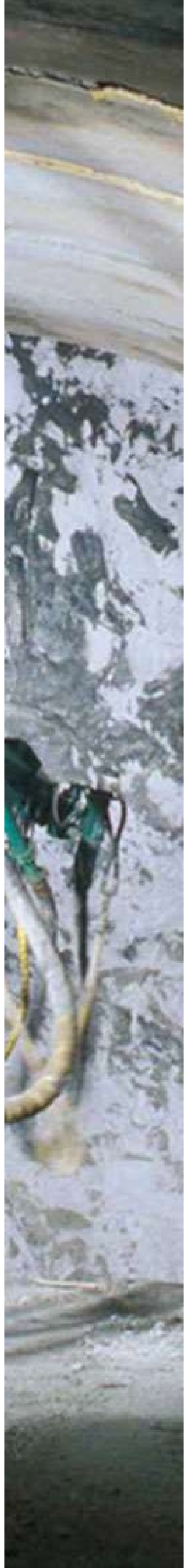

Øvrig krav

Inn i kontrakts bestemmelsene

Entreprenøren skal fremlegge all teknisk informasjon, inklusive tegninger av dette for byggherren, også vedlikeholds- og brukermanualer

Prosedyrer for montasje/demontasje, injeksjon, mm.
Ventilasjonsberegninger
Entreprenøren skal dokumentere for byggherren at TBM og bakrigg tilfredsstiller de tekniske kravene som spesifisert innen at 500 m tunnel er boret mm.

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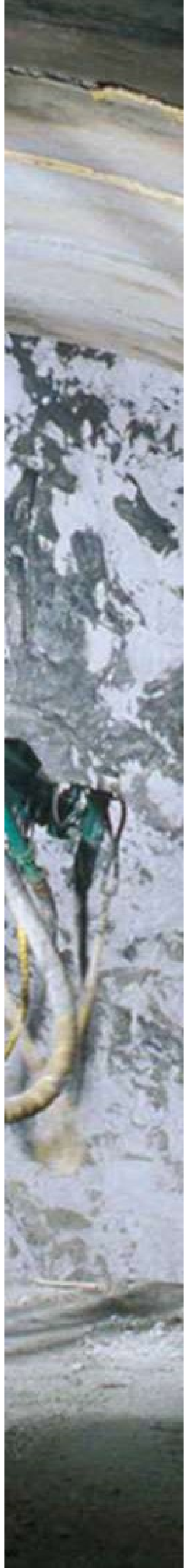
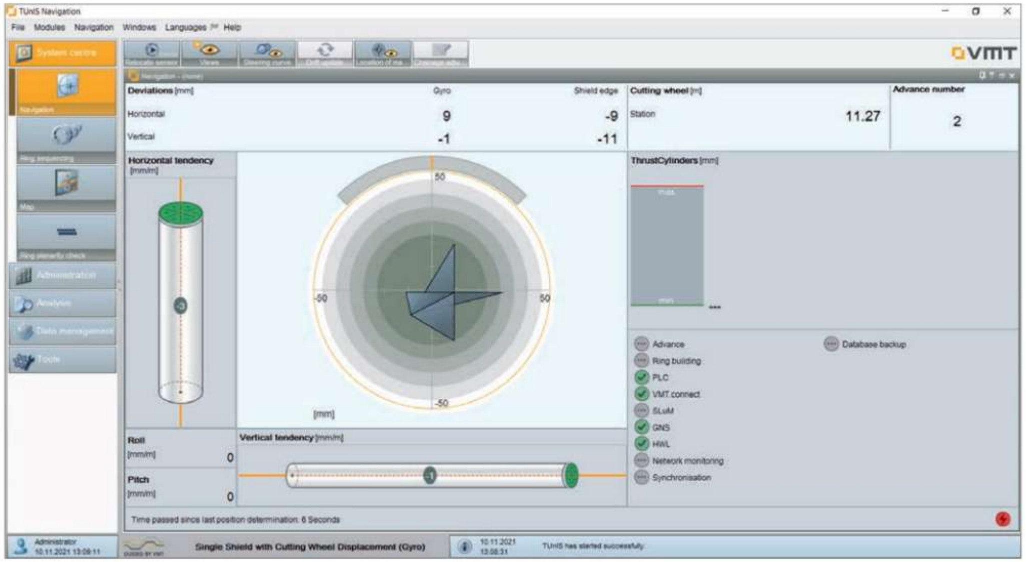


Øvrig krav

Inn i kontrakts bestemmelsene

Datalogging

- Produksjonsdata fra tunnelboremaskinen
- Event. montering av betongelementer
- Bakrigg aktiviteter
- Sonderboring og forinjeksjon
- Stikningsdata
- Luftkvalitetsmålinger
- Mfl.



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Oppsummert

Basert på > 50 års TBM erfaring i Norge

1. Gjør valg av drivemetode tidlig i prosjektfasen
2. Velg maskintype hovedspesifikasjoner etter de geologiske forholdene
3. Kontraktfest hovedspesifikasjonene til TBMen i hht. Prosjektets spesifikke krav («skreddersøm»)

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Takk for oppmerksomheten!

Rock Engineering

JMConsulting-Rock Engineering

Bergmassensborbarhet i Hardt Fjell

Javier Macias, PhD
Rock Engineering Consultant and Researcher
JMConsulting-Rock Engineering AS

Bergteknikk for TBM - Boring i hardt fjell
09.01.2024, Oslo

NORSK BERGMEKANIKKGRUPPE

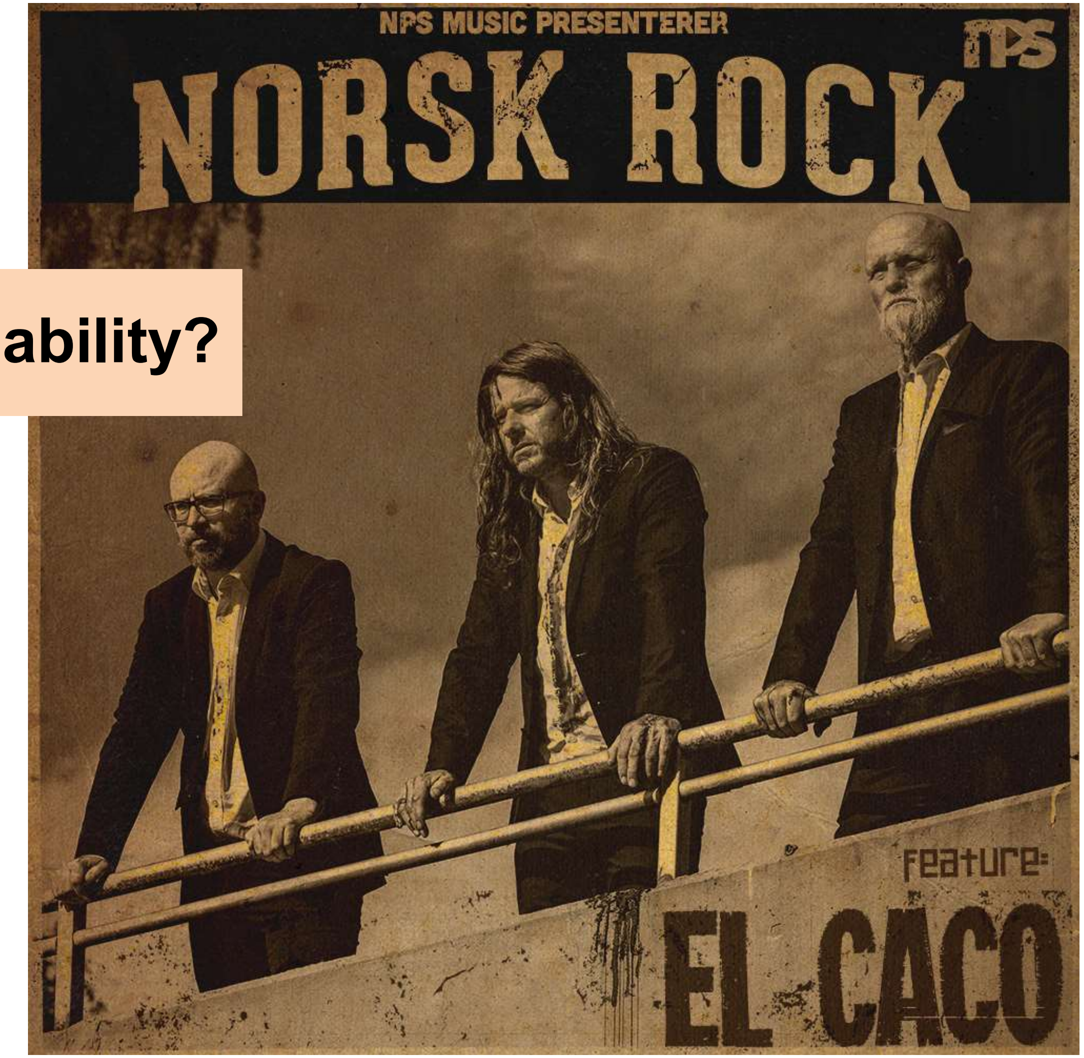
Rock Engineering

Rock boreability

- What is rock boreability?

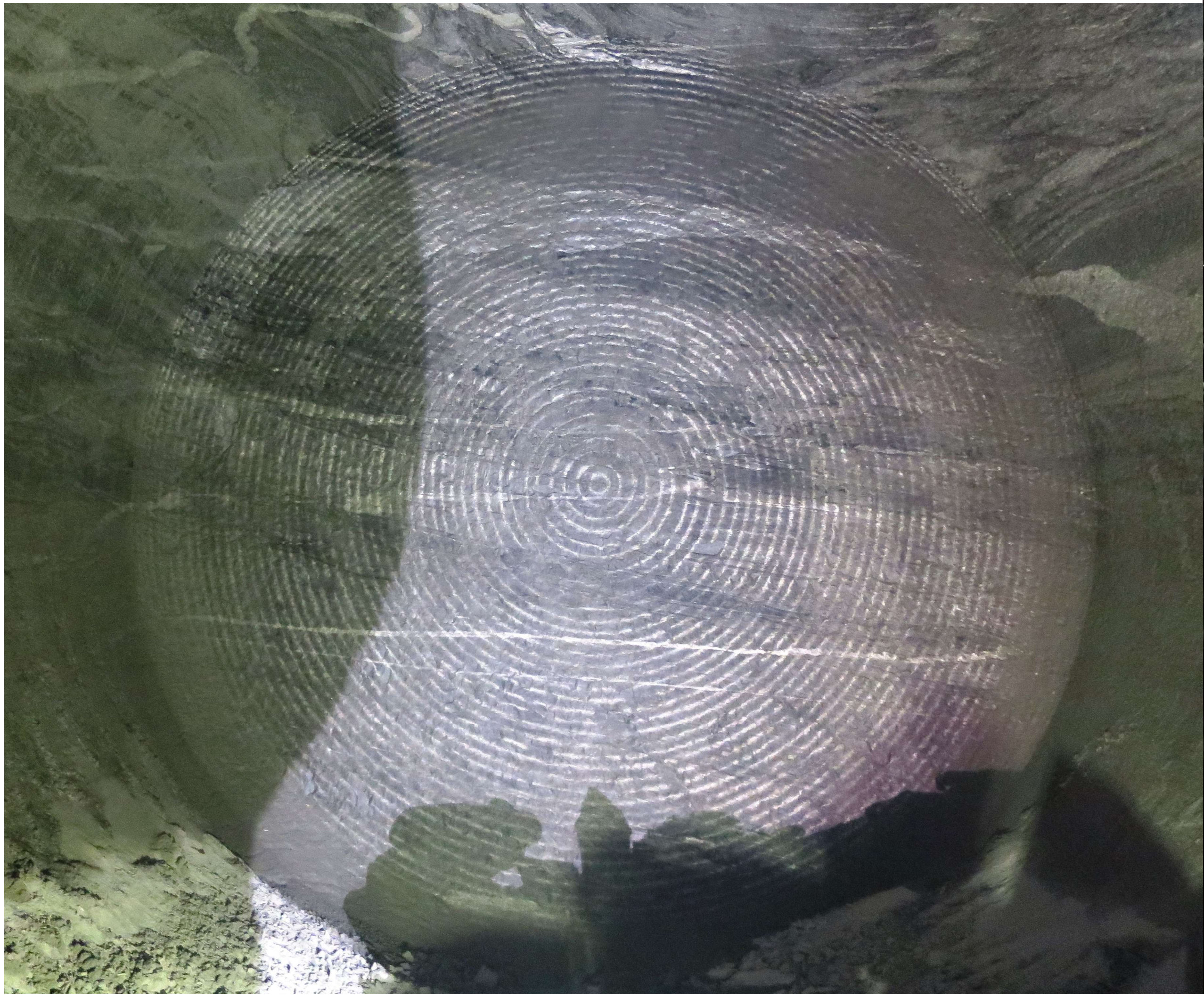
Rock boreability

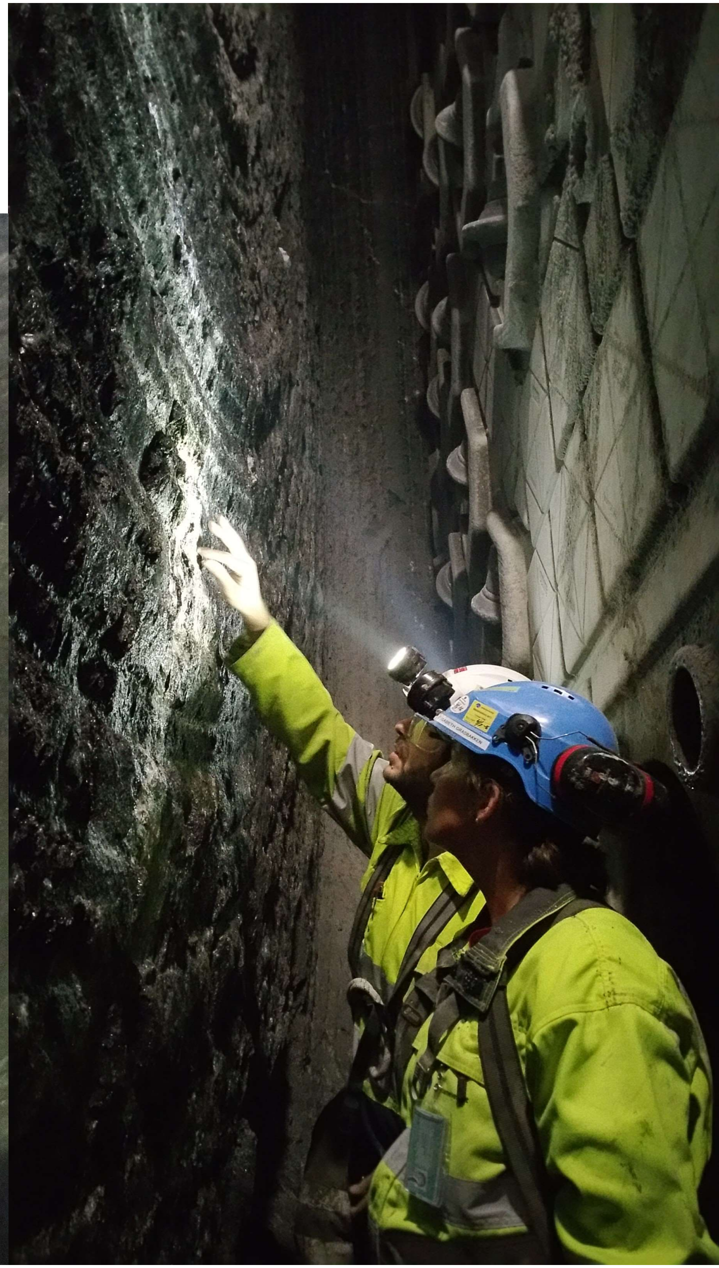
Rock Boreability?



“Rock” boredom? ability?

Rock Boreability?





Outline

- What is rock boreability?
  - Intact Rock Boreability
  - Rock mass Boreability
- Understanding rock boreability
- Conclusive remarks

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Rock Boreability

- **What** is **‘Rock Boreability’**?

It is a comprehensive parameter of rocks under excavation and expresses the result of the interaction between a given rock mass and Tunnel Boring Machine (TBM).

- **How** can be **defined ‘Rock Boreability’**?

The resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass (intact rock containing planes of weakness)

“There is no single parameter that can fully represent the properties of jointed rock masses. Different parameters have different emphases and can only provide a satisfactory description of a rock mass in an integrated form” (Singh and Goel, 2011).

Rock Boreability

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It is a comprehensive parameter of rocks under excavation and expresses the result of the interaction between a given rock mass and Tunnel Boring Machine (TBM).

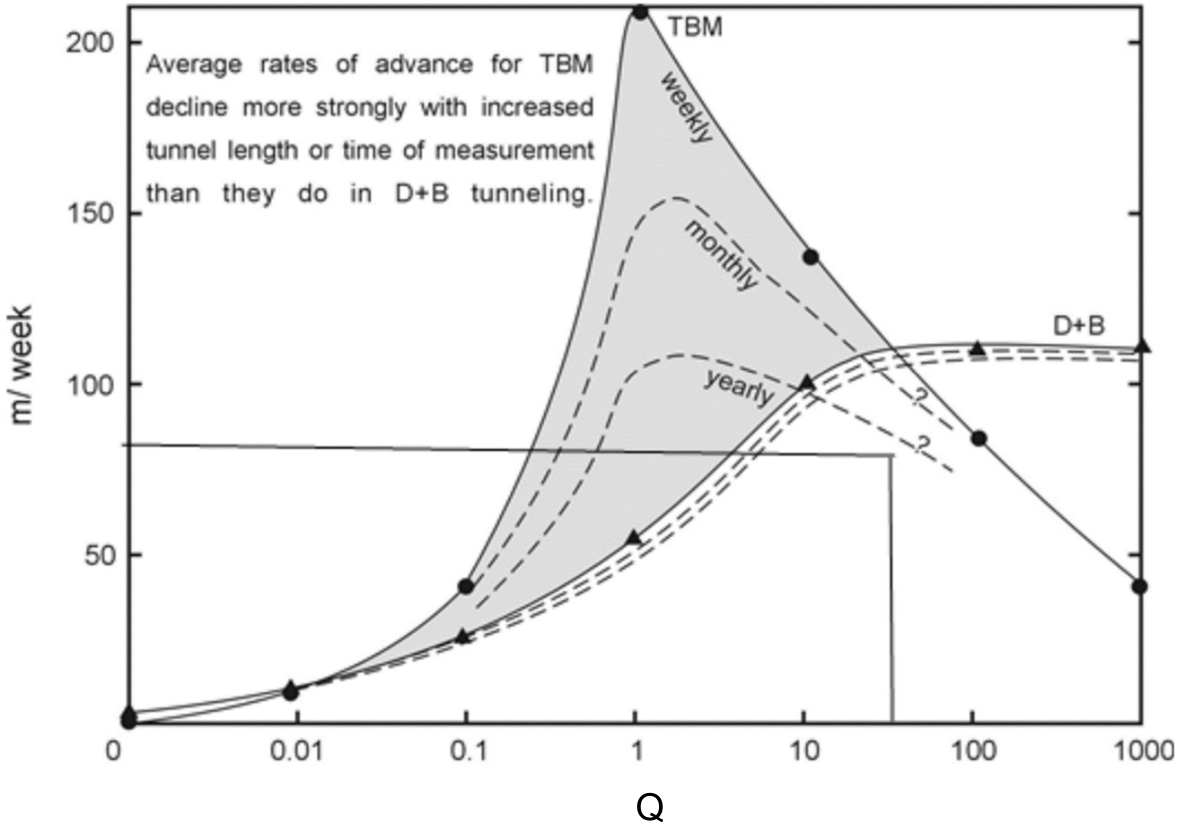
- **How** can be **defined ‘Rock Boreability’**?

The resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass (intact rock containing planes of weakness)

- **Intact rock boreability**
- **Rock mass boreability**

Rock Boreability

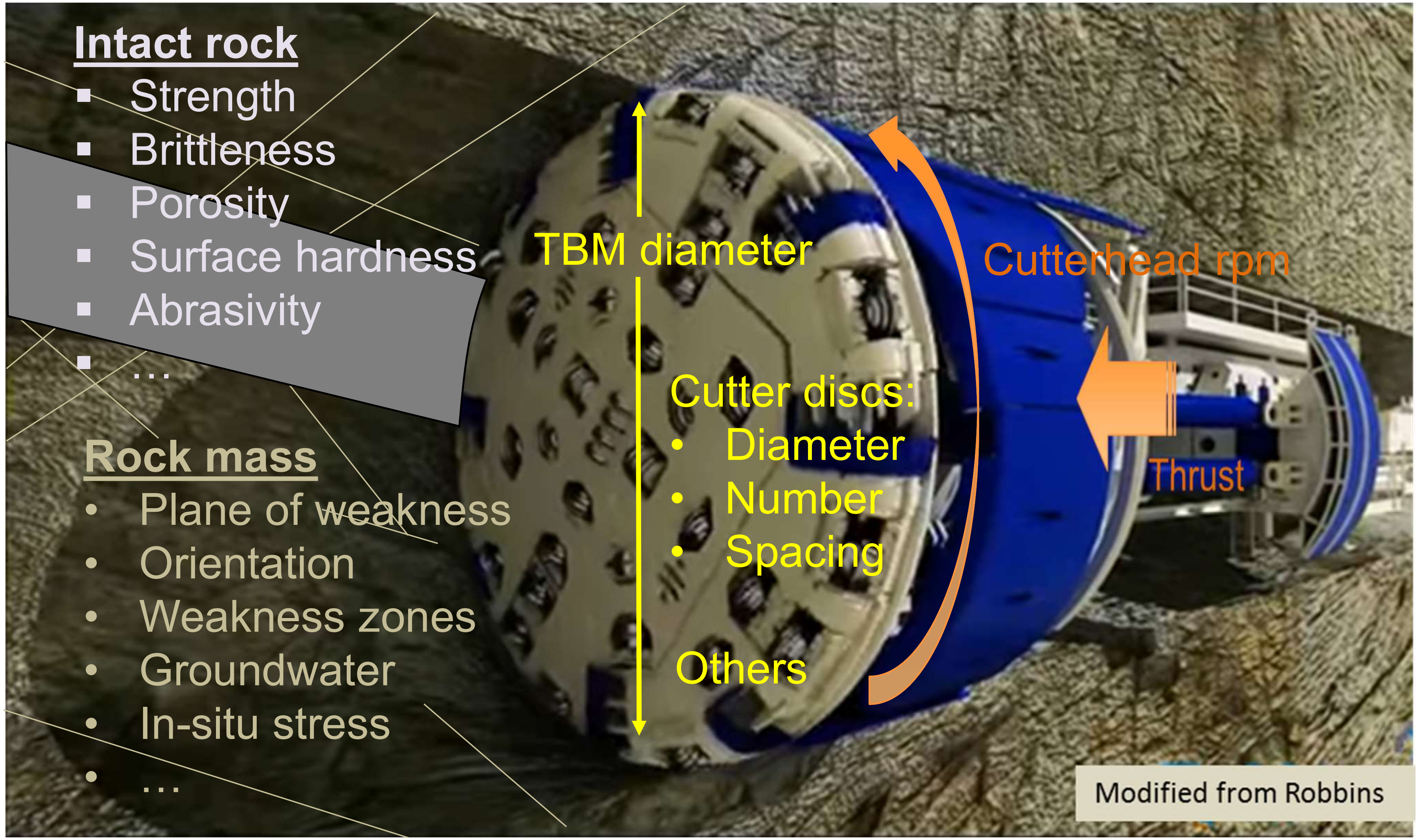
- **Why** is important **‘Rock Boreability’**?



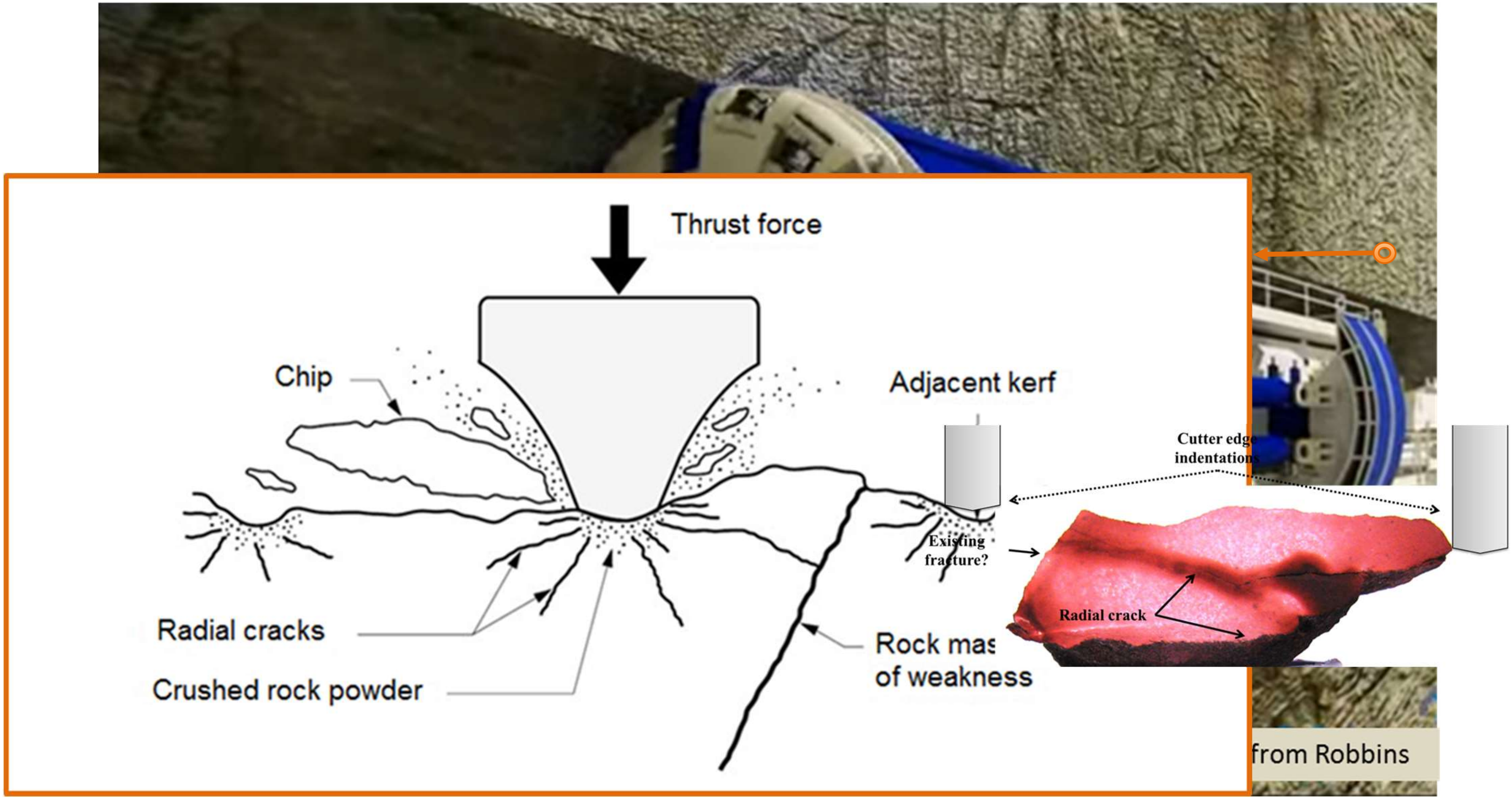
Barton (2000)

Rock Engineering

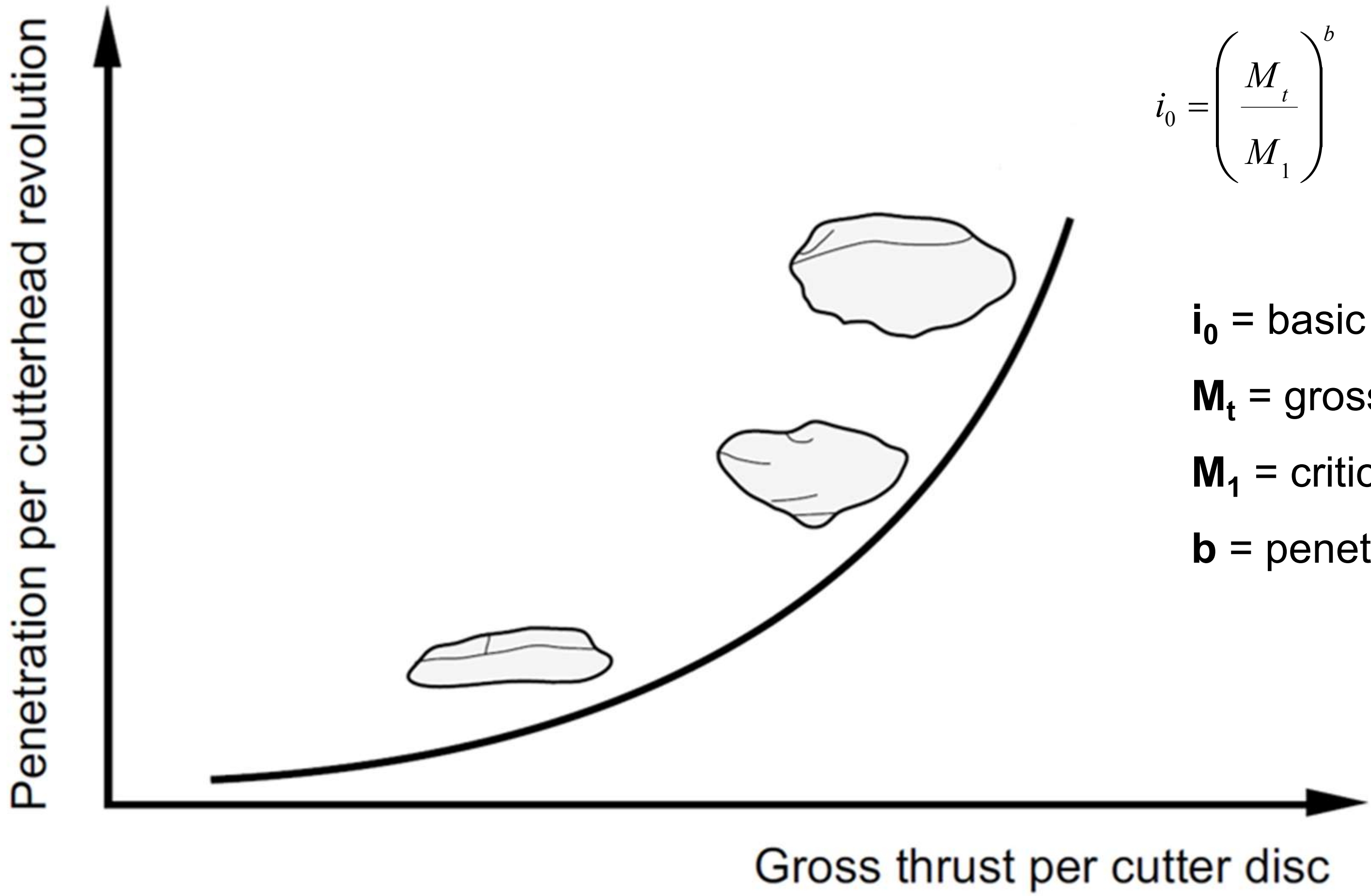
Hard rock tunnel boring



Hard rock tunnel boring



Rock boreability



$$i_0 = \left(\frac{M_t}{M_1} \right)^b \qquad \text{(mm/rev)}$$

i_0 = basic penetration rate

M_t = gross cutter thrust

M_1 = critical cutter thrust

b = penetration coefficient

Modified from Bruland (2000)

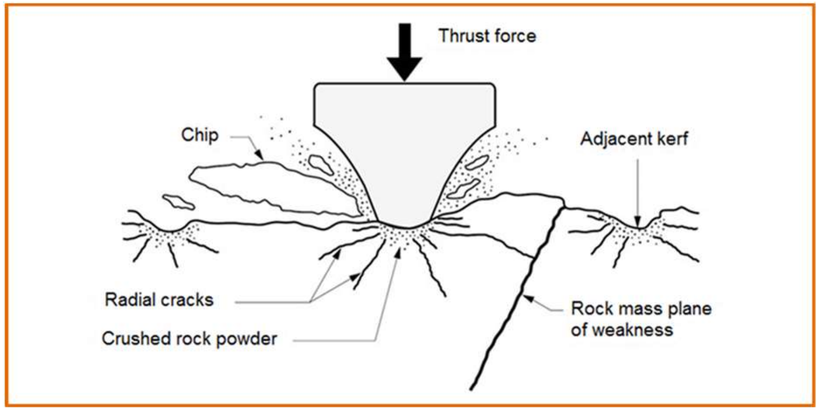
Outline

- What is rock boreability?
  - Intact Rock Boreability
  - Rock mass Boreability
- Understanding rock boreability
- Conclusive remarks

Intact Rock Boreability

- Ability of the ***intact rock*** to be bored
- Influence that intact rock properties has on machine performance and penetration rate

Breakability



Abrasivity

Intact Rock Boreability

Main intact rock properties

- ❑ Strength
- ❑ Brittleness
- ❑ Surface hardness
- ❑ Wear capacity

Intact Rock Boreability

Main intact rock properties

- ❑ Strength
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Intact Rock Boreability

Main intact rock properties

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JMC
Rock Engineering

Intact Rock Boreability

Main intact rock properties

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Intact Rock Boreability

Main intact rock properties

- ❑ Strength
- ❑ Brittleness
- ❑ Surface hardness
- ❑ Wear capacity

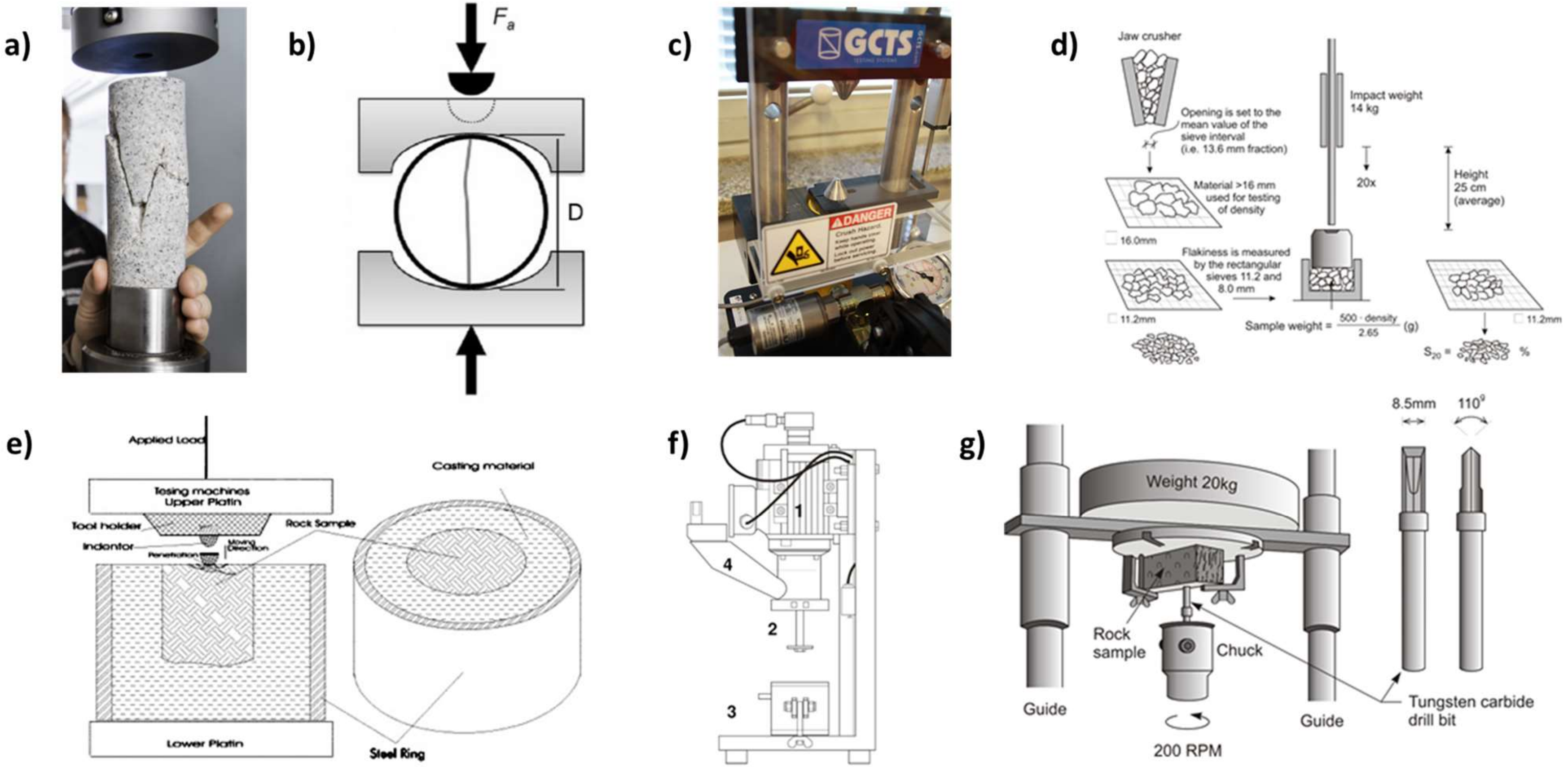
JMC Rock Engineering

Intact Rock Boreability

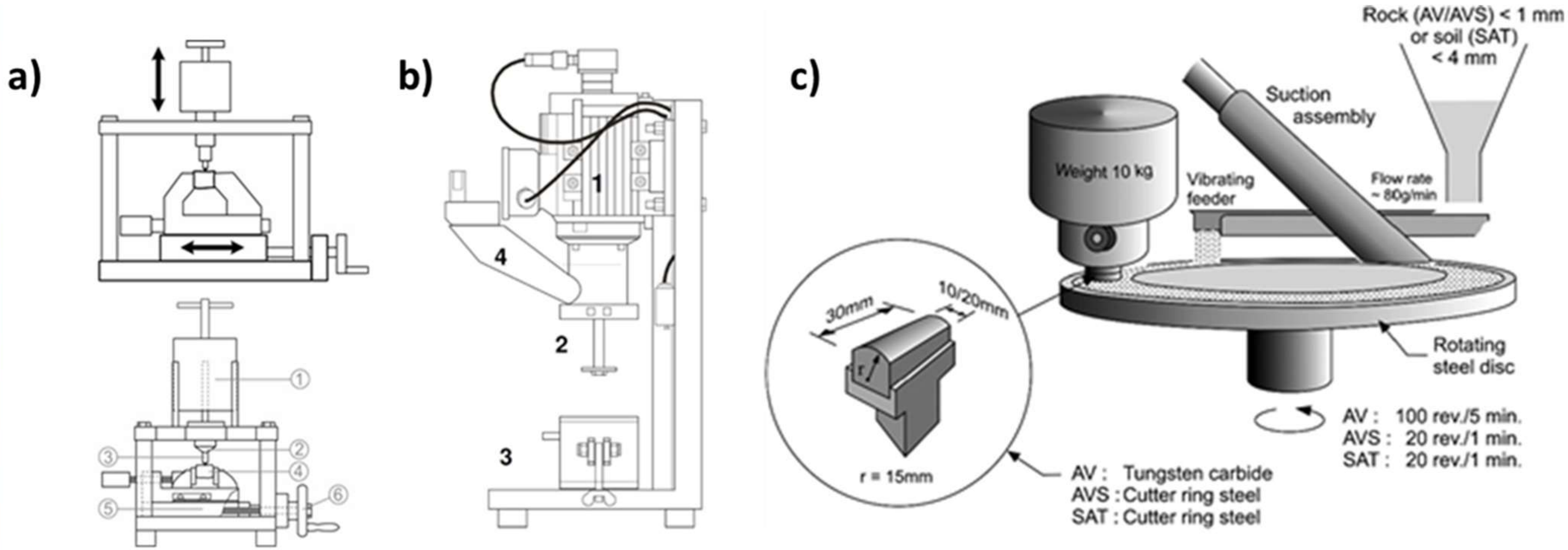
Lab assessments for Intact Rock Boreability:

- Uniaxial Compressive Strength (UCS)
- Rock Toughness
- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)
- Cerchar (CAI)

Intact Rock Boreability
Laboratory test methods: "Breakability"



Intact Rock Boreability
Laboratory test methods: “Abrasivity"



Outline

- What is rock boreability?
  - Intact Rock Boreability
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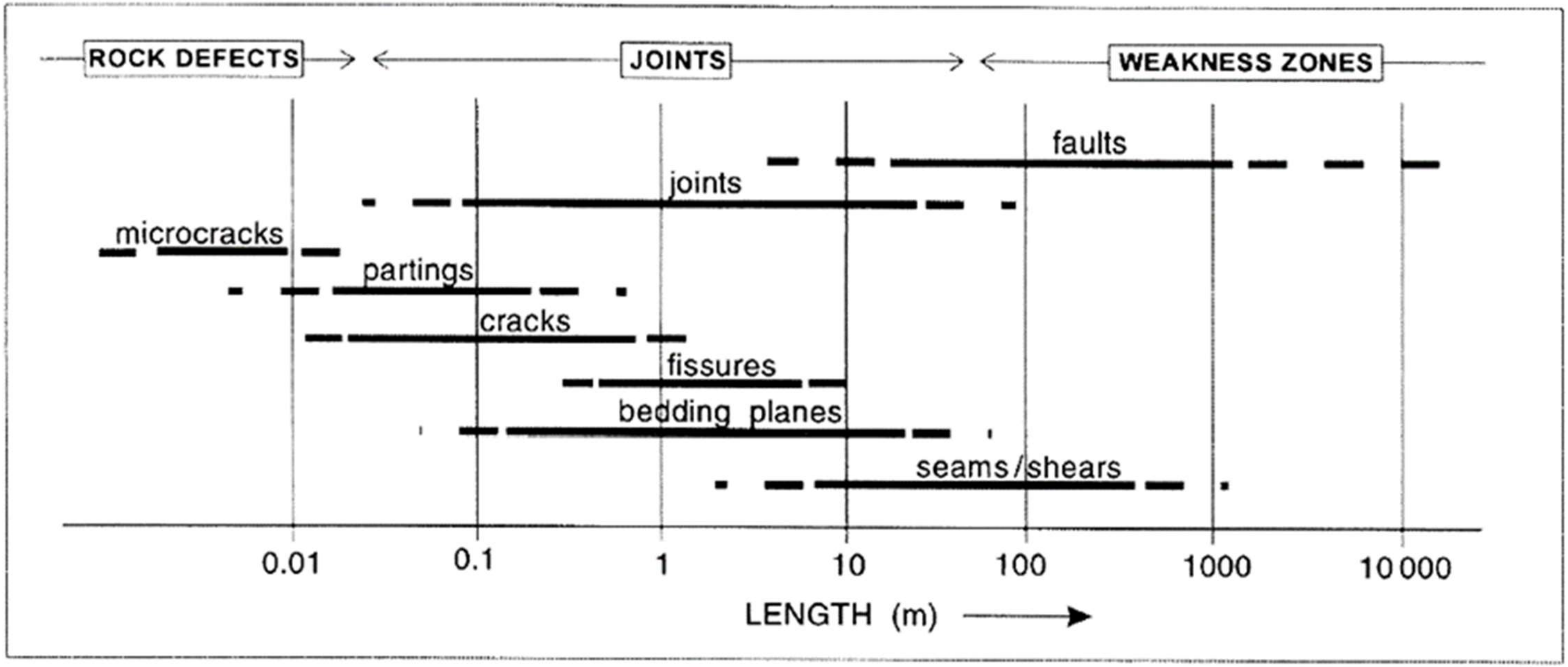
Rock Mass Boreability

- In hard rock tunnel boring, discontinuities or planes of weakness in a rock mass contribute considerably to net penetration rate and cutter wear

Rock Mass Boreability

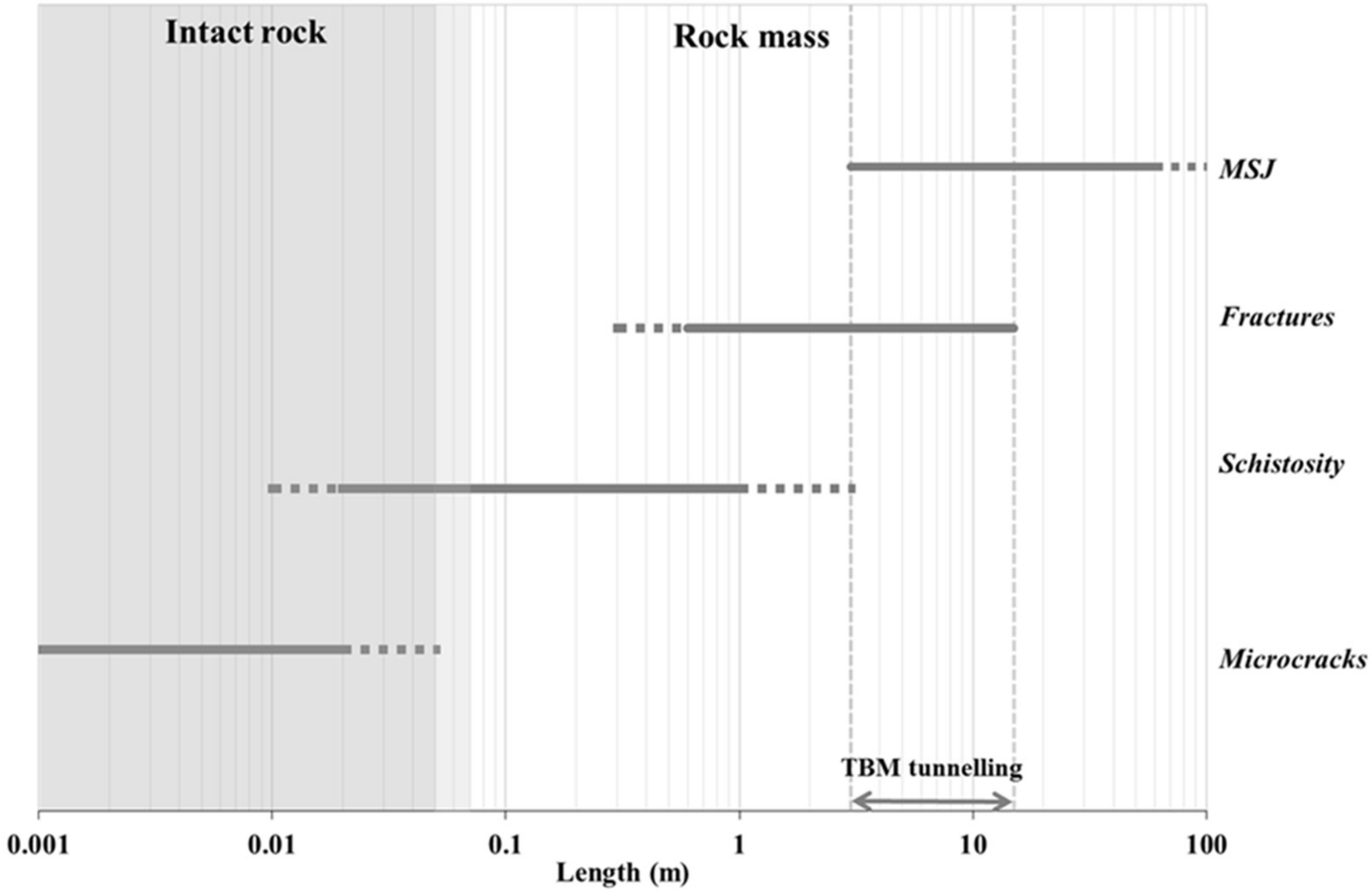
- Type of Discontinuities
- Degree of fracturing
- Fracture/joint orientation
- Number of fracture/joint sets
- Fracture/joint characteristics (e.g., persistence, aperture, filling…)
- Fabric anisotropy (e.g., Schistosity…)
- Rock mass classification methods (RQD, RMR, Q, k_{ekv}…)
- Others:
    - Rock Stress
    - Mixed Face Conditions (MFC)
    - Blocky Ground
    - …

Rock Mass Boreability



Palmström (1995)

Rock Mass Boreability



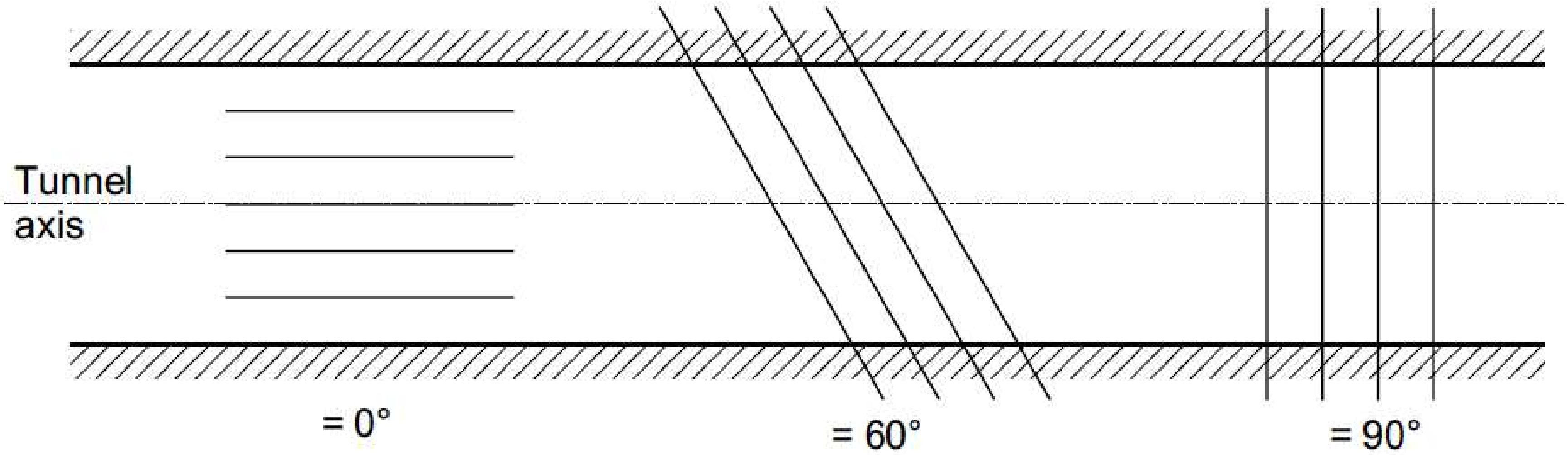
Macias (2016)

Degree of fracturing

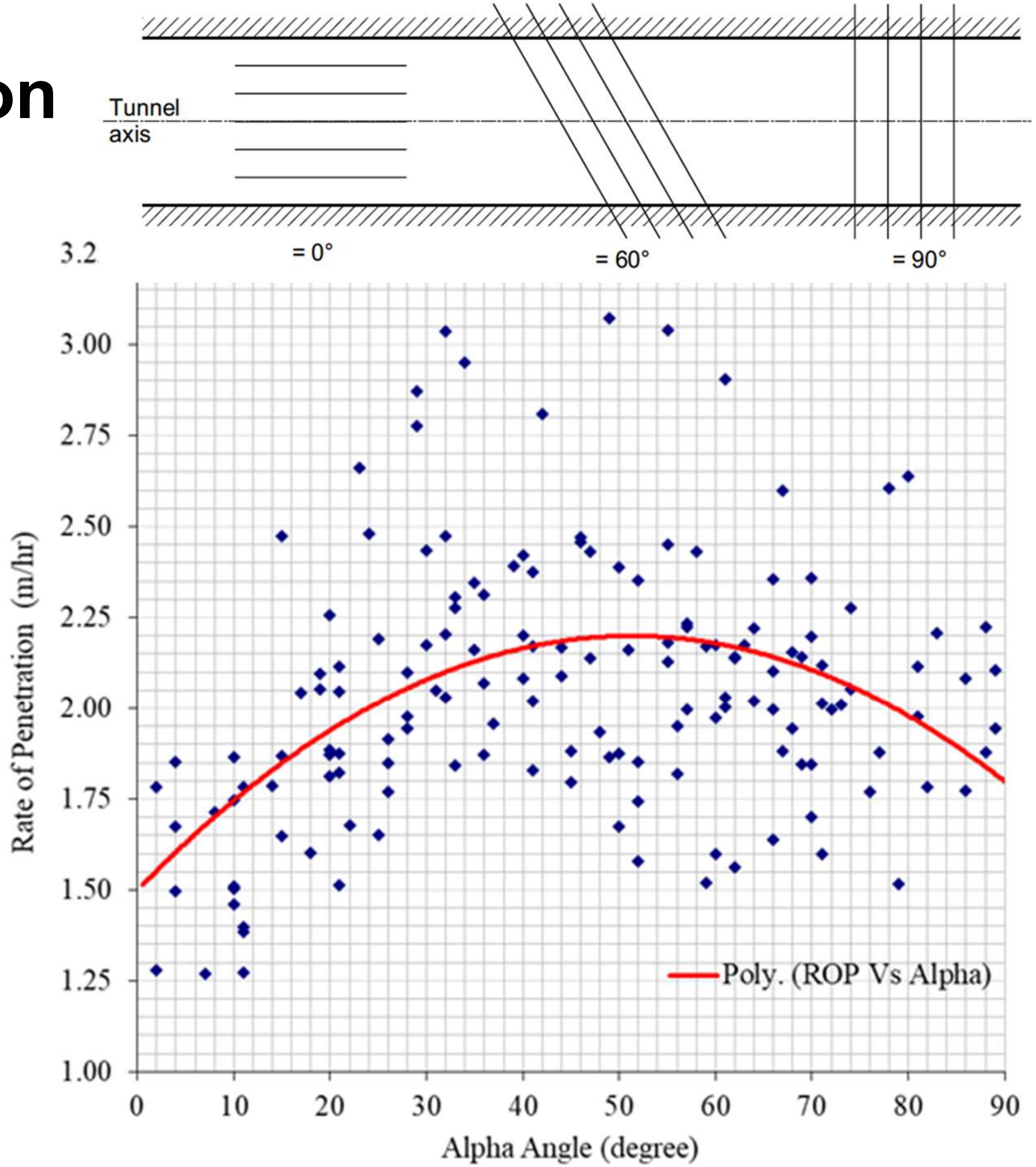
Fracture Class (Sf)	Average spacing between fractures a_f (cm)	Range class (cm)	Degree of fracturing
0	∞	480 – ∞	Non-fractured
1	320	240 – 480	Extremely low
2	160	120 – 240	Very low
3	80	60 – 120	Low
4	40	30 – 60	Medium
5	20	15 – 30	High
6	10	7.5 – 15	Very high
7	5	4 – 7.5	Extremely high

Macias (2016)

Orientation

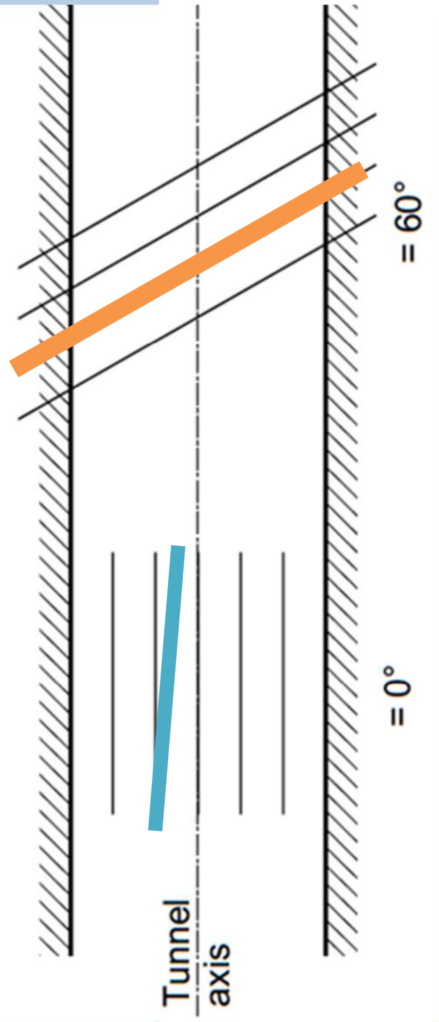


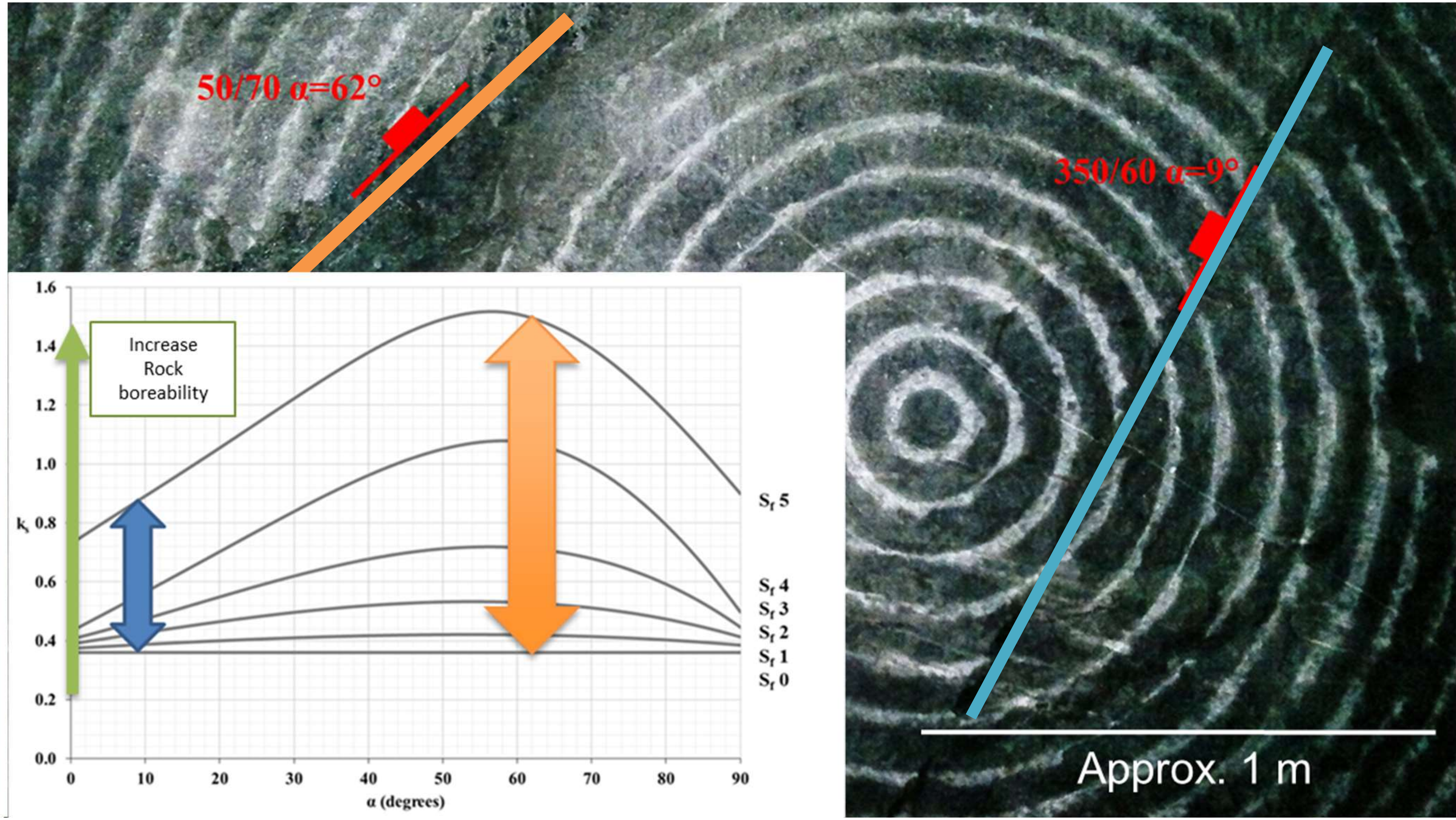
Orientation



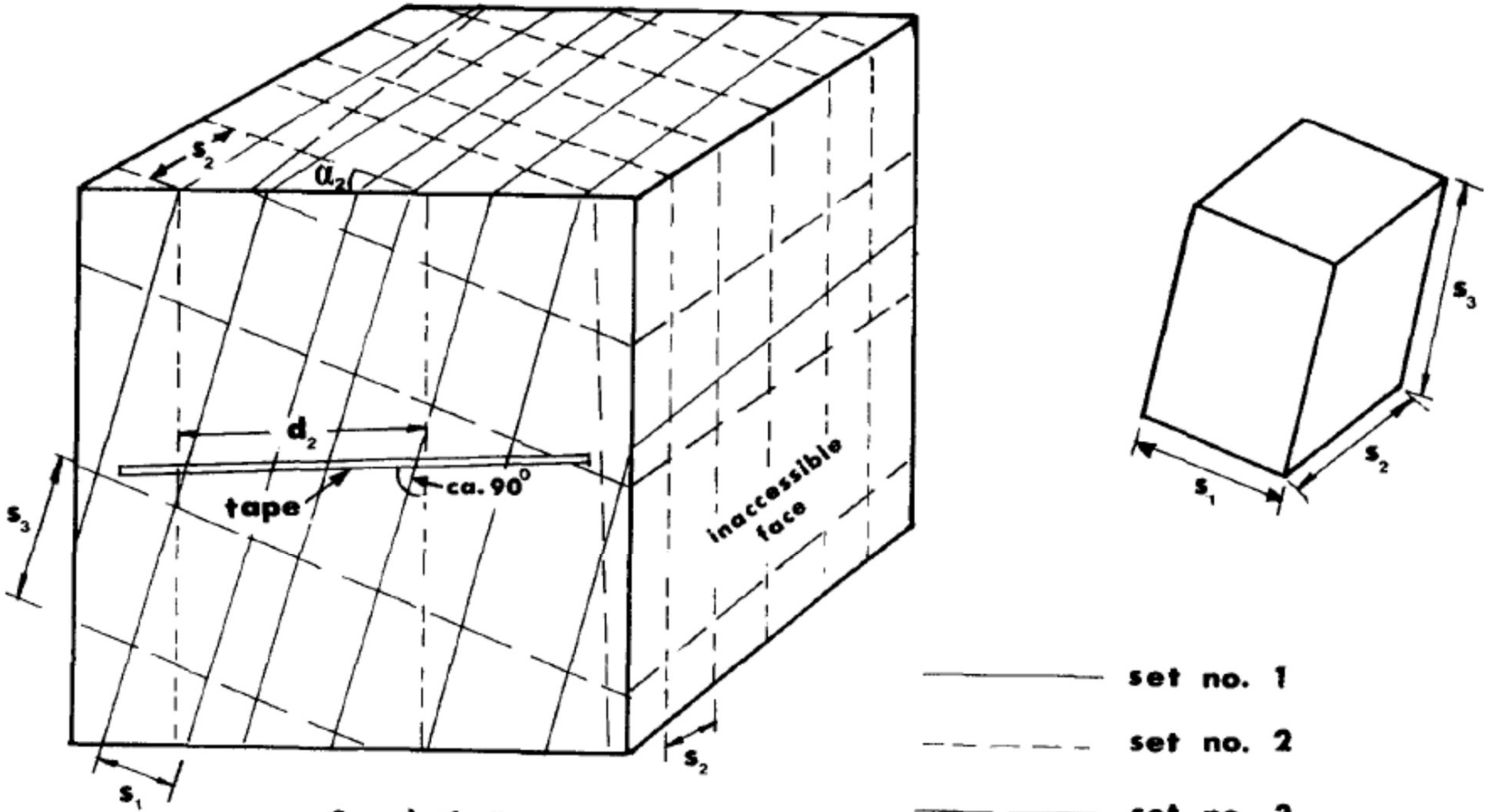
Yagiz (2008)

Rock Mass Boreability





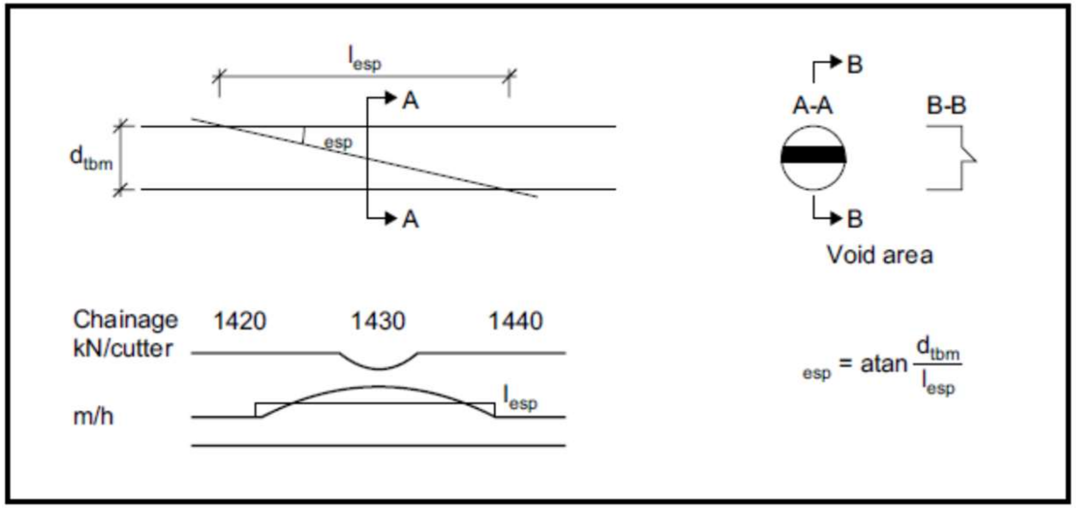
Rock Mass Boreability – Joint sets

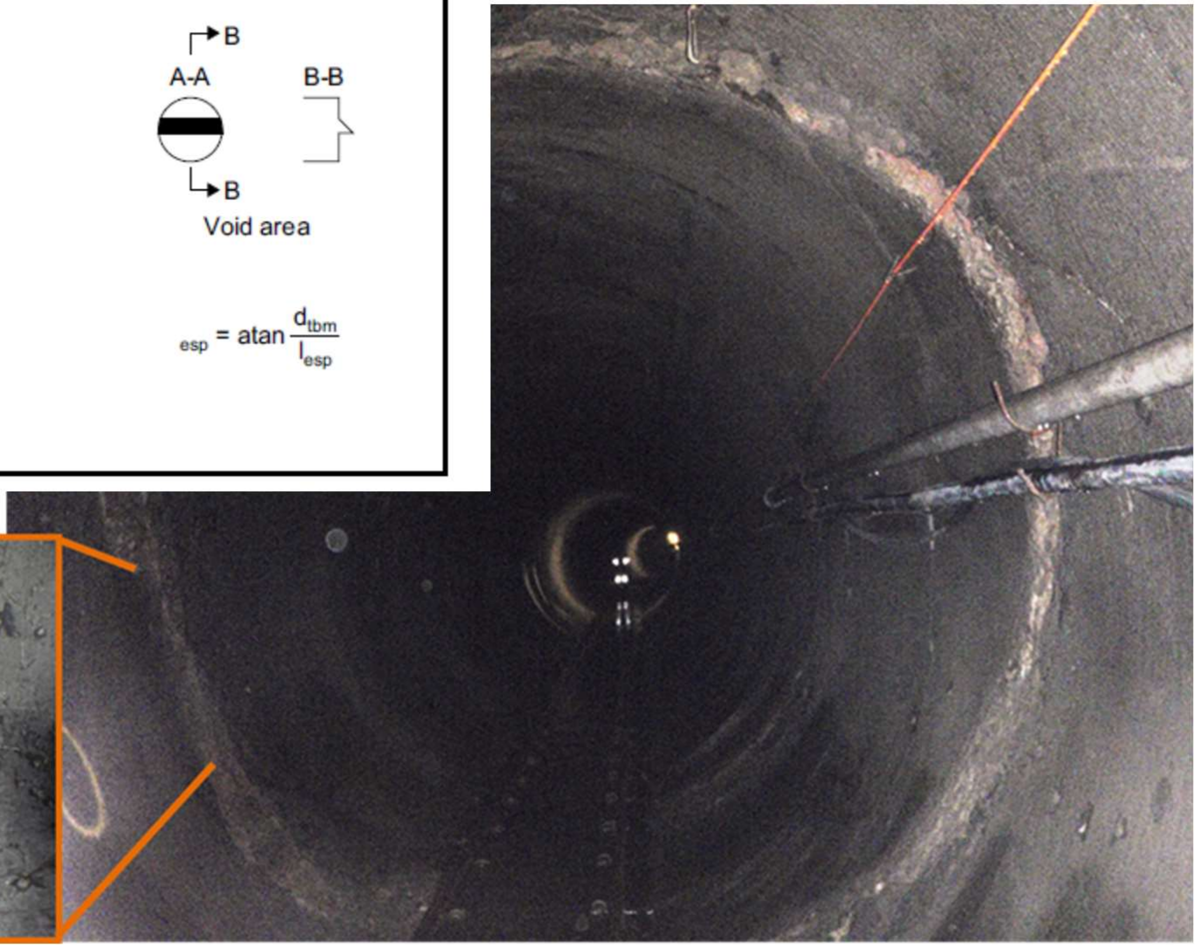


$S_2 = d_2 \sin \alpha_2$

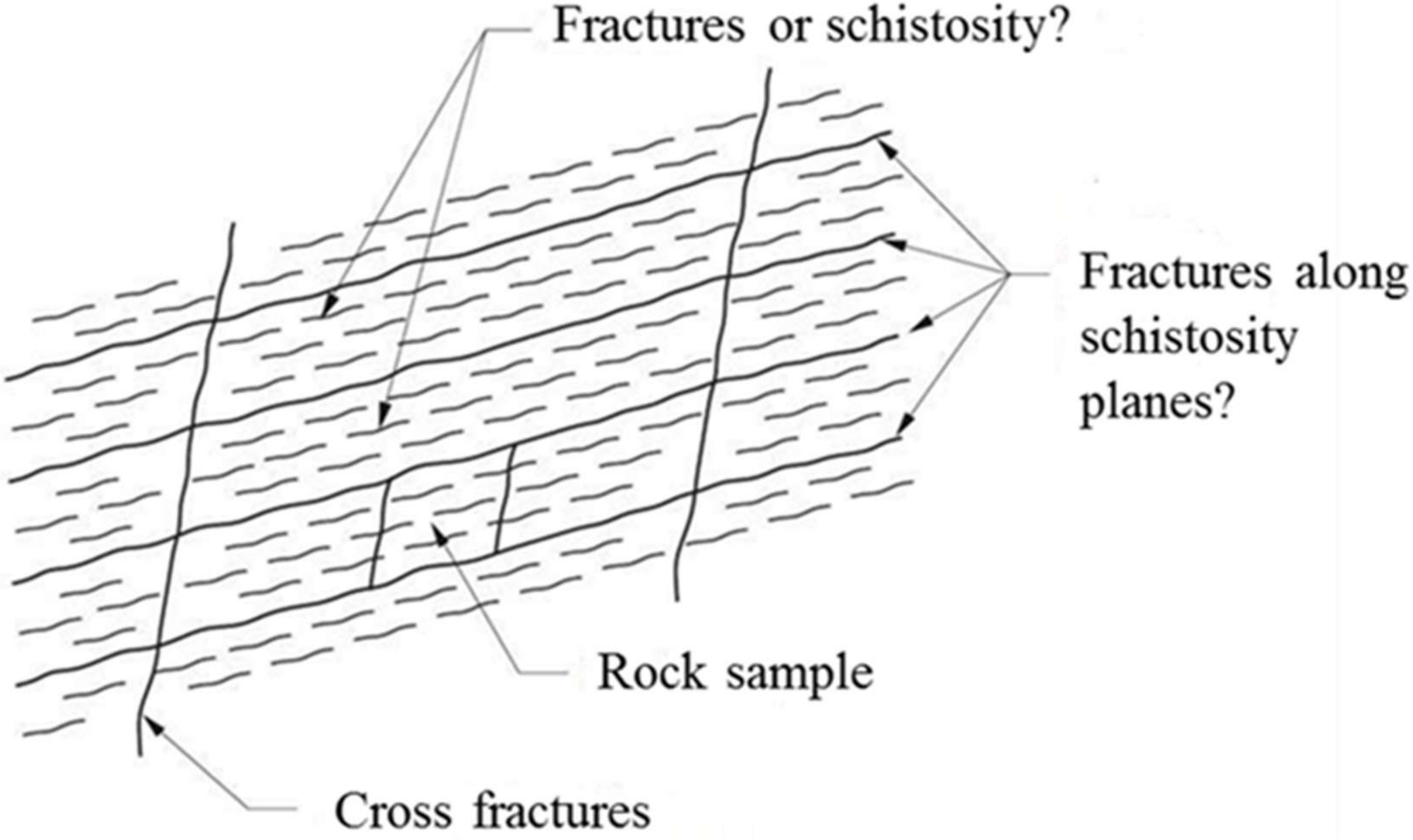
ISRM (1978)

Rock Mass Boreability

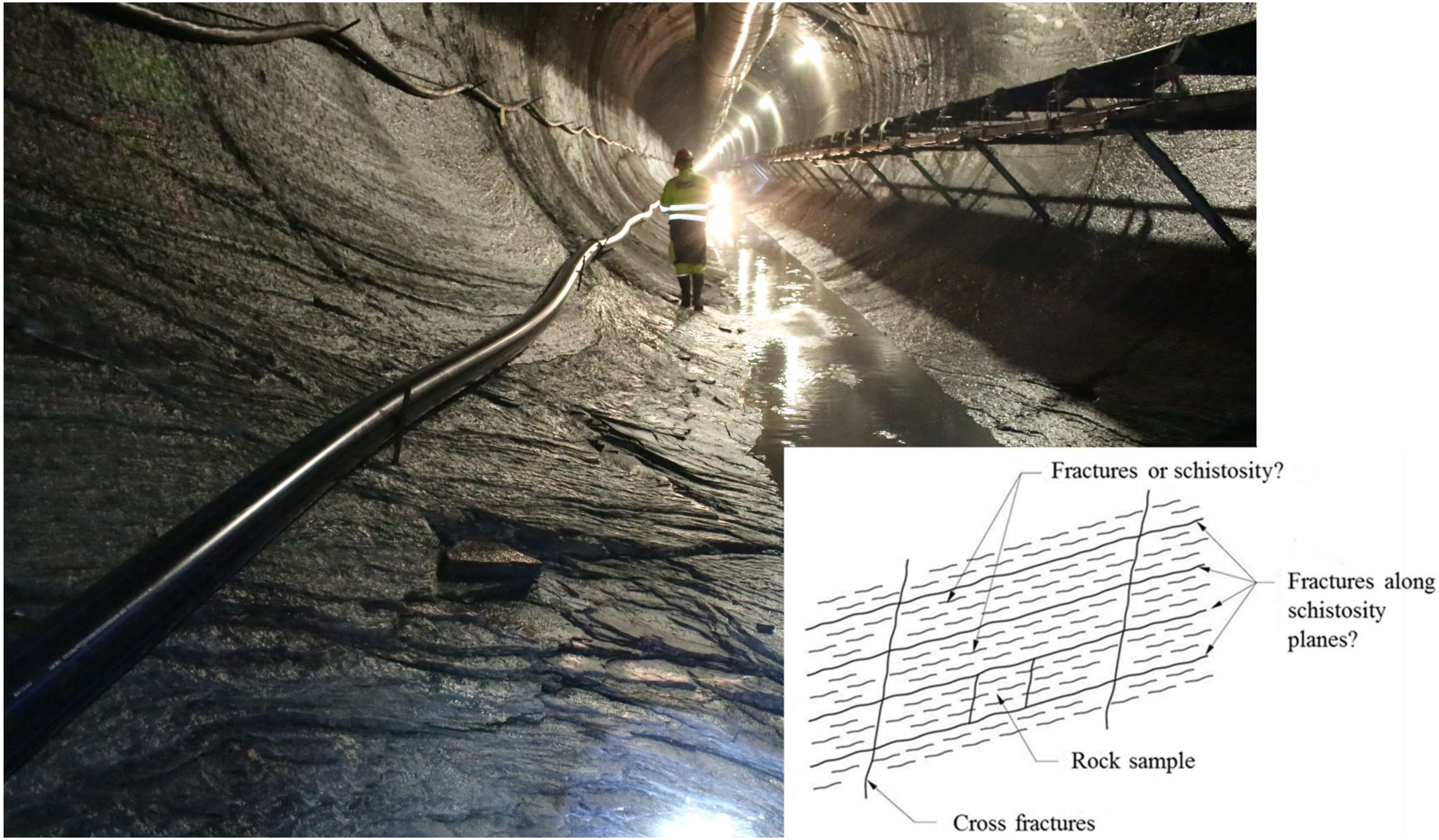




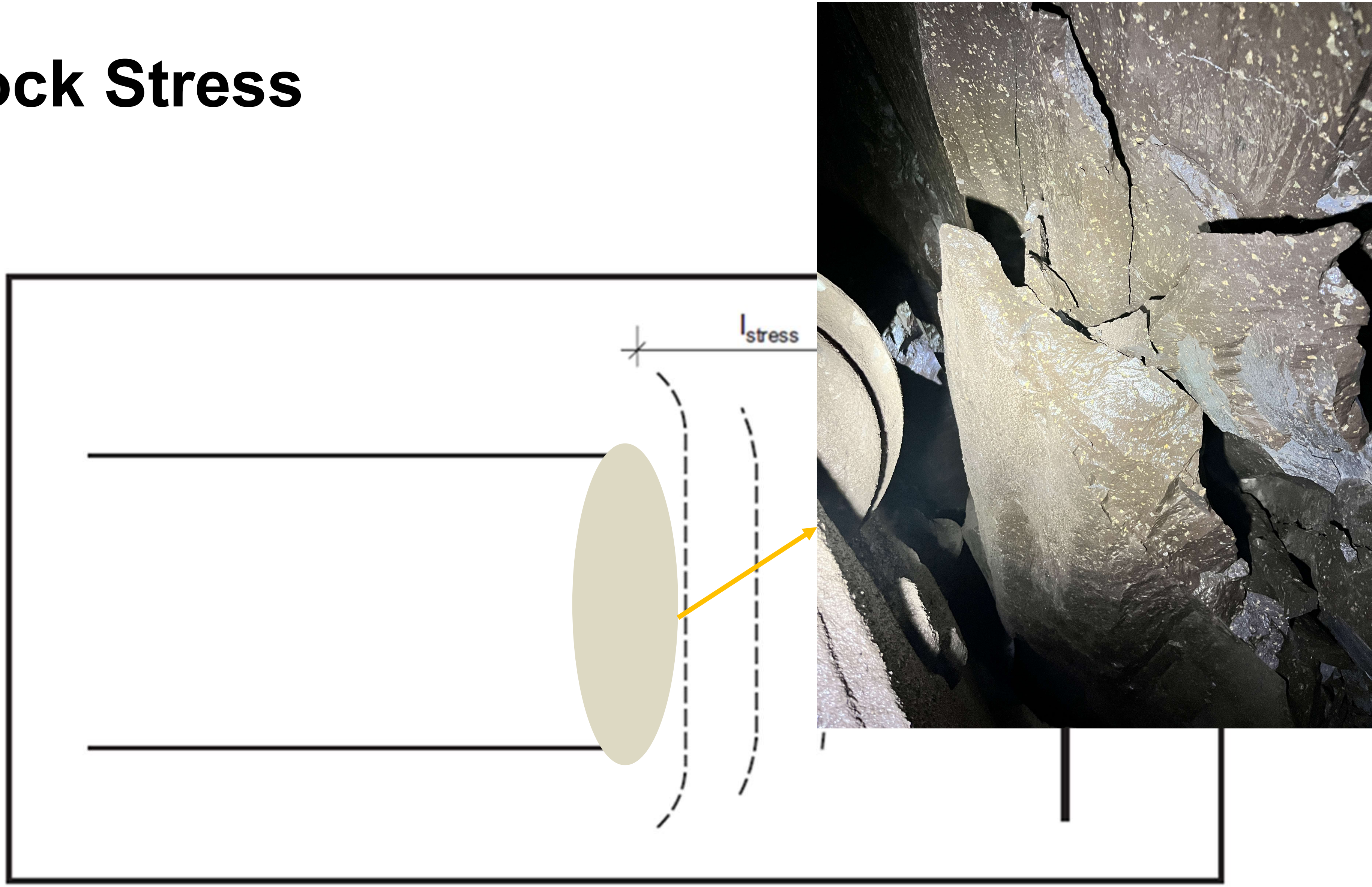
Fabric Anisotropy



Fabric Anisotropy



Rock Stress



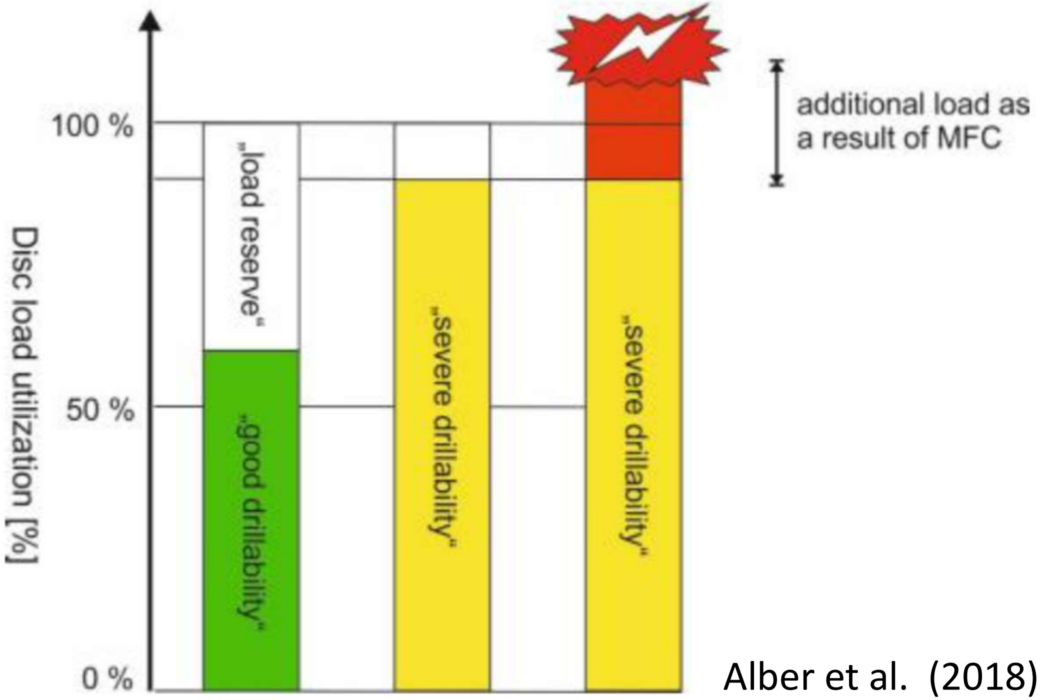
Bruland (2000)

Blocky ground

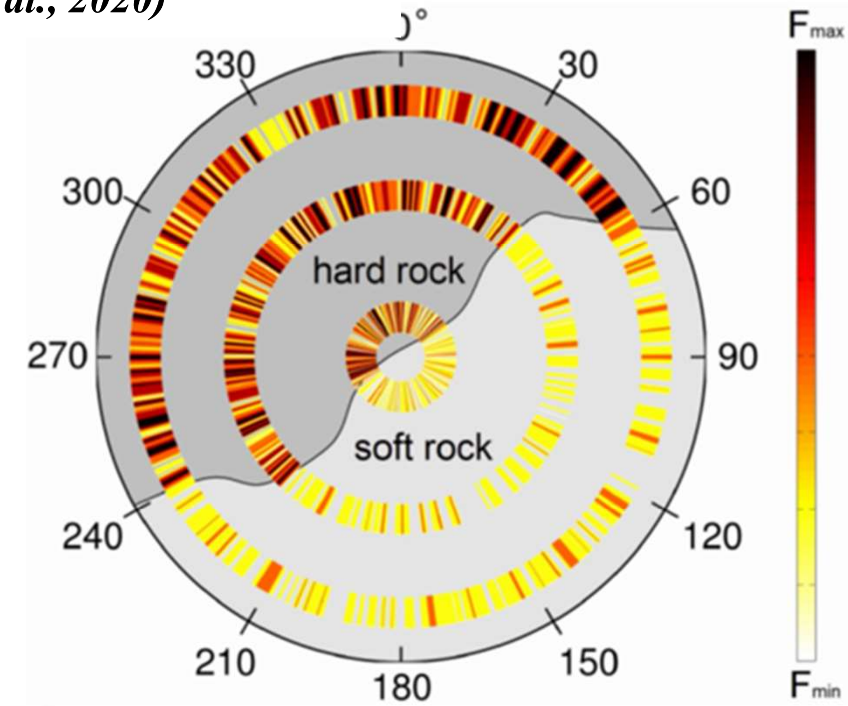


MFC/Blocky rock mass

"MFC in hard rock tunnelling occurs in case of the existence of two or more rock mass bodies with significantly different boreability parameters encountered at the tunnel face and occurs at the interaction of the cutterhead and rock mass while cutting the rock. MFC is a handicap for TBM tunnelling which affects the operational parameters, penetration rate and/or affects the cutter consumption and/or affects the TBM cutterhead or main body" (Macias et al., 2020)



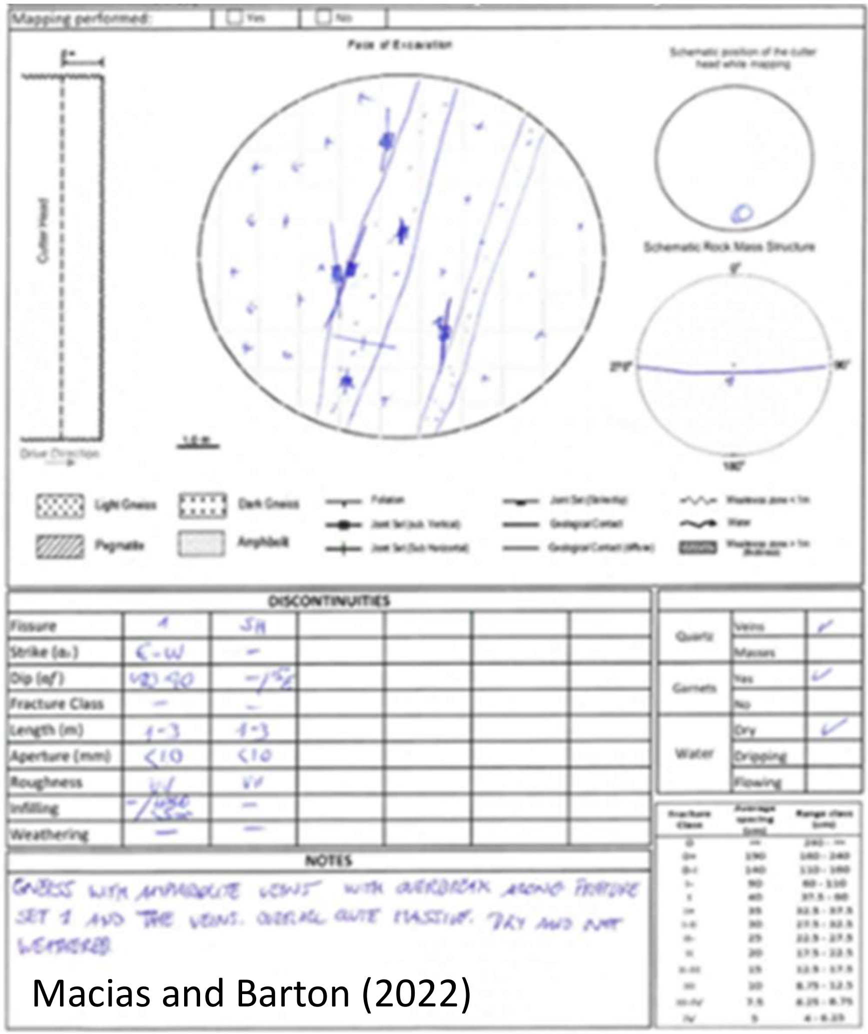
Alber et al. (2018)



Entacher (2013)

JMC Rock Engineering

Hard Rock Mixed Face Conditions (MFC)



Macias and Barton (2022)

Outline

- What is rock boreability?
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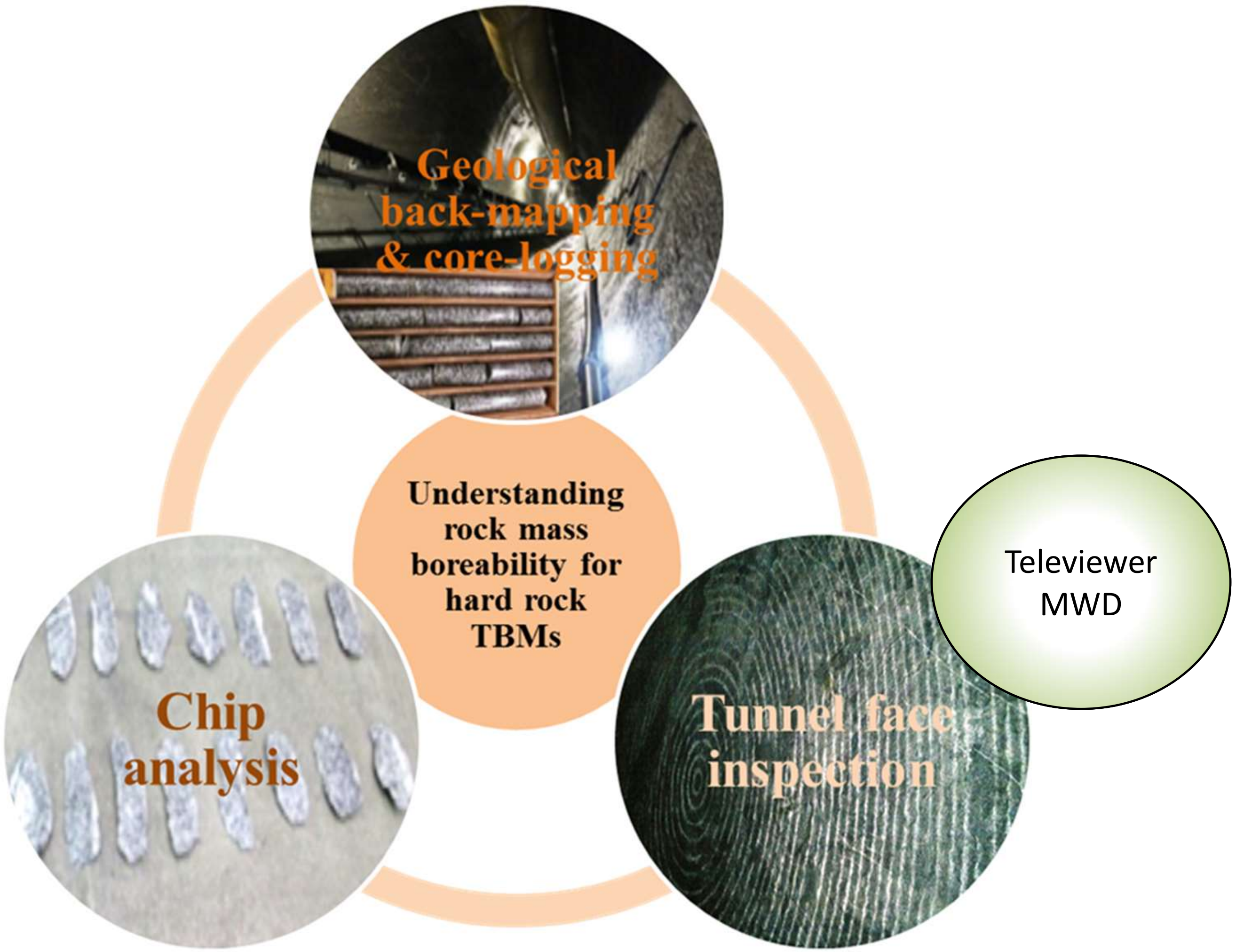
Understanding Rock Boreability



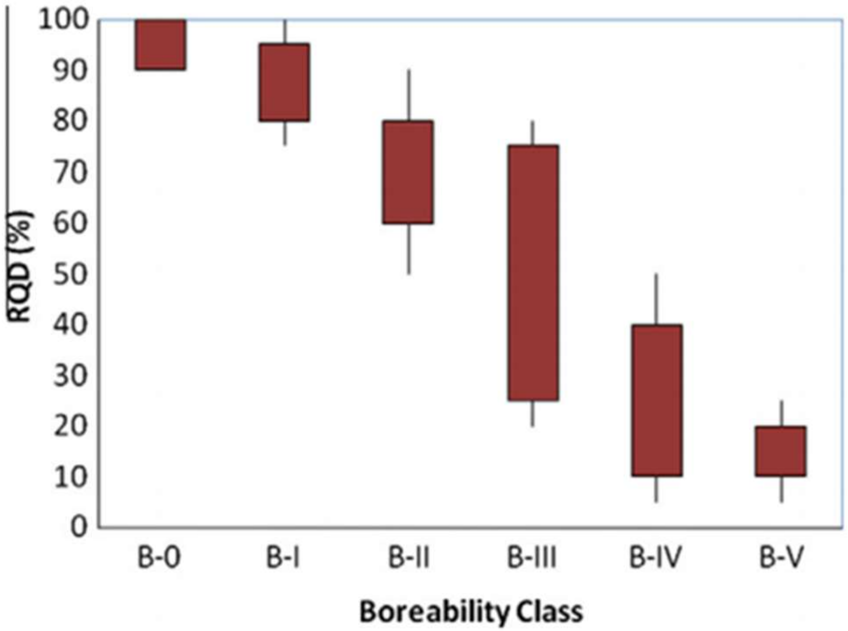
Macias (2016)

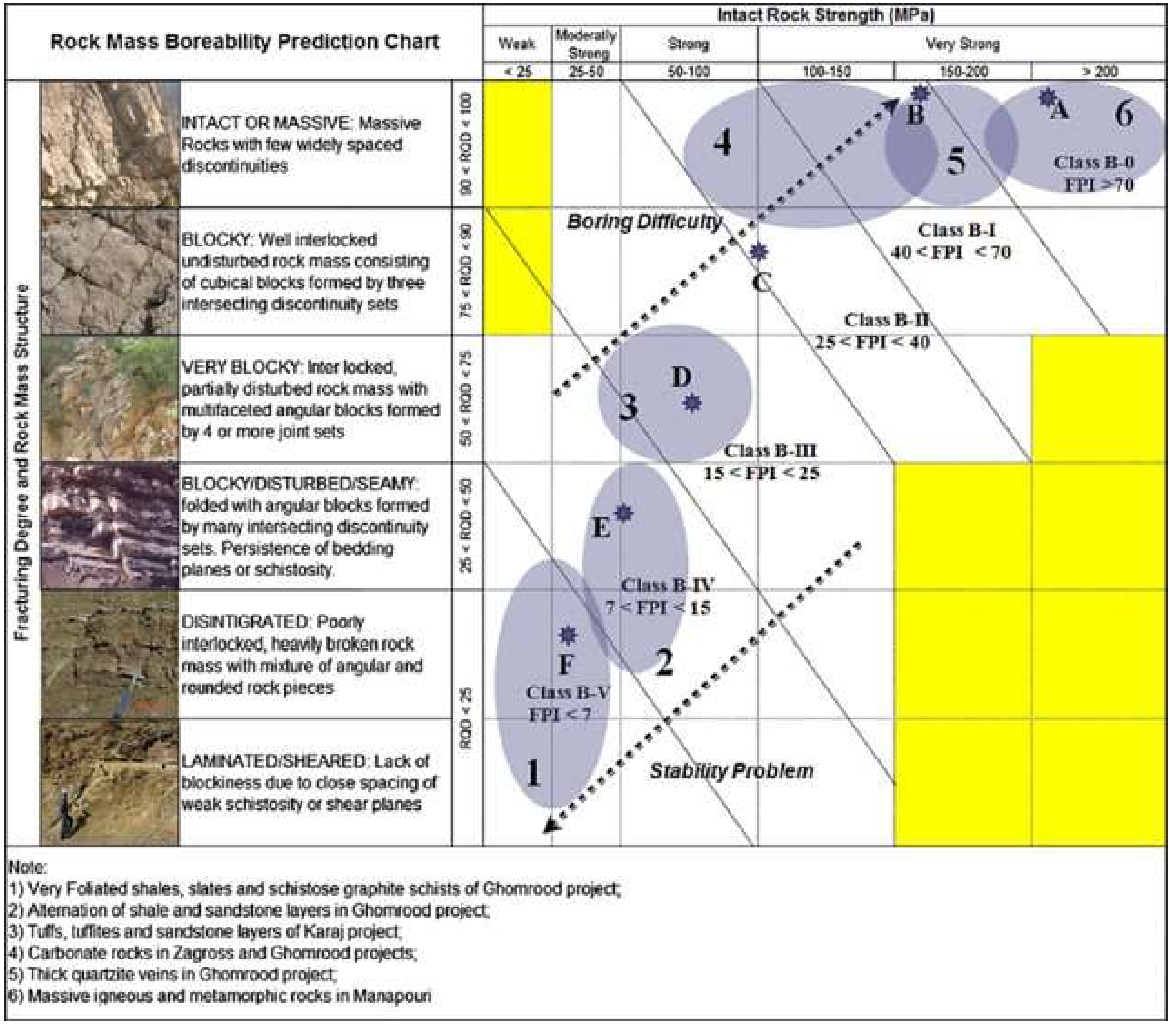
Understanding Rock Boreability

- There is no single parameter that can fully represent the properties of jointed rock masses

Rock mass classification	**Author**	**Year**
Rock Quality Designation (RQD)	D.U. Deere	1964
Rock Mass Rating (RMR)	Z.T. Bieniawki	1973
Rock Tunnelling Quality Index (Q)	N. Barton, R. Lien and J. Lunde	1974
Degree of fracturing (k_s factor)	NTNU (NTH)	1981
Rock Mass Index (RMi)	A. Palmström	1995
Geological Strength Index (GSI)	E. Hoek and E.T. Brown	1997

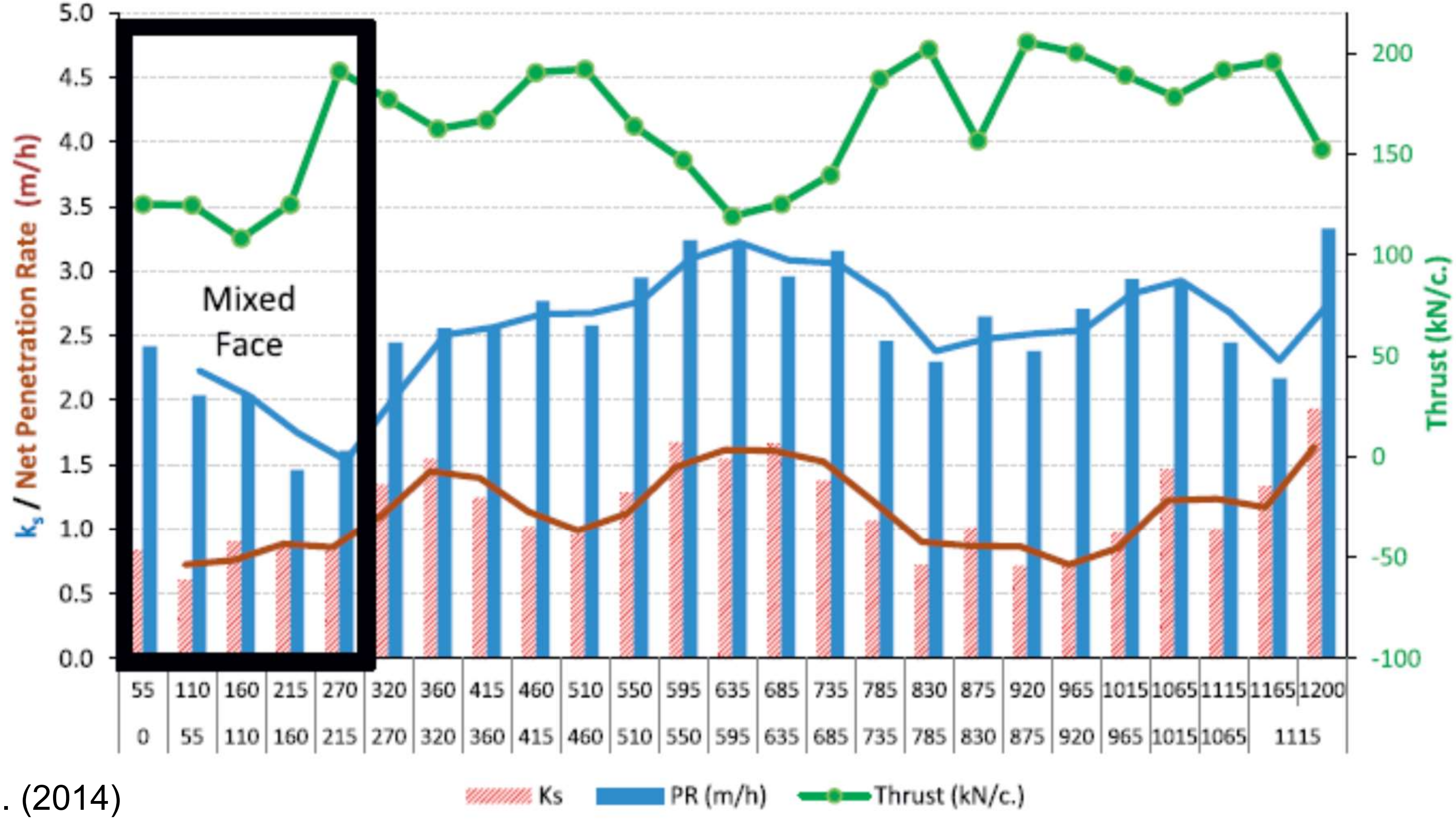
Understanding Rock Boreability





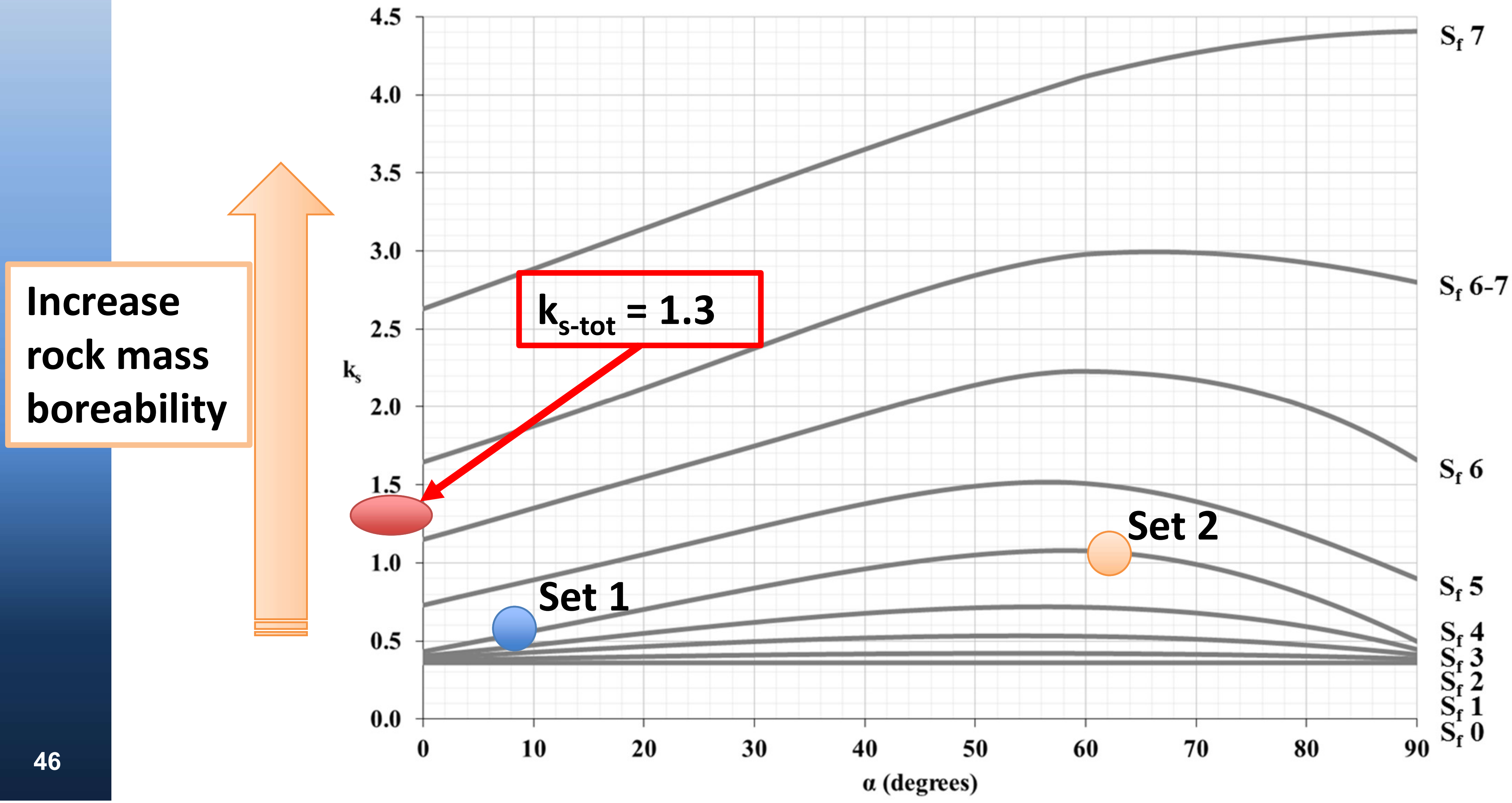
Hassanpour et al. (2014)

Understanding Rock Boreability



Macias et al. (2014)

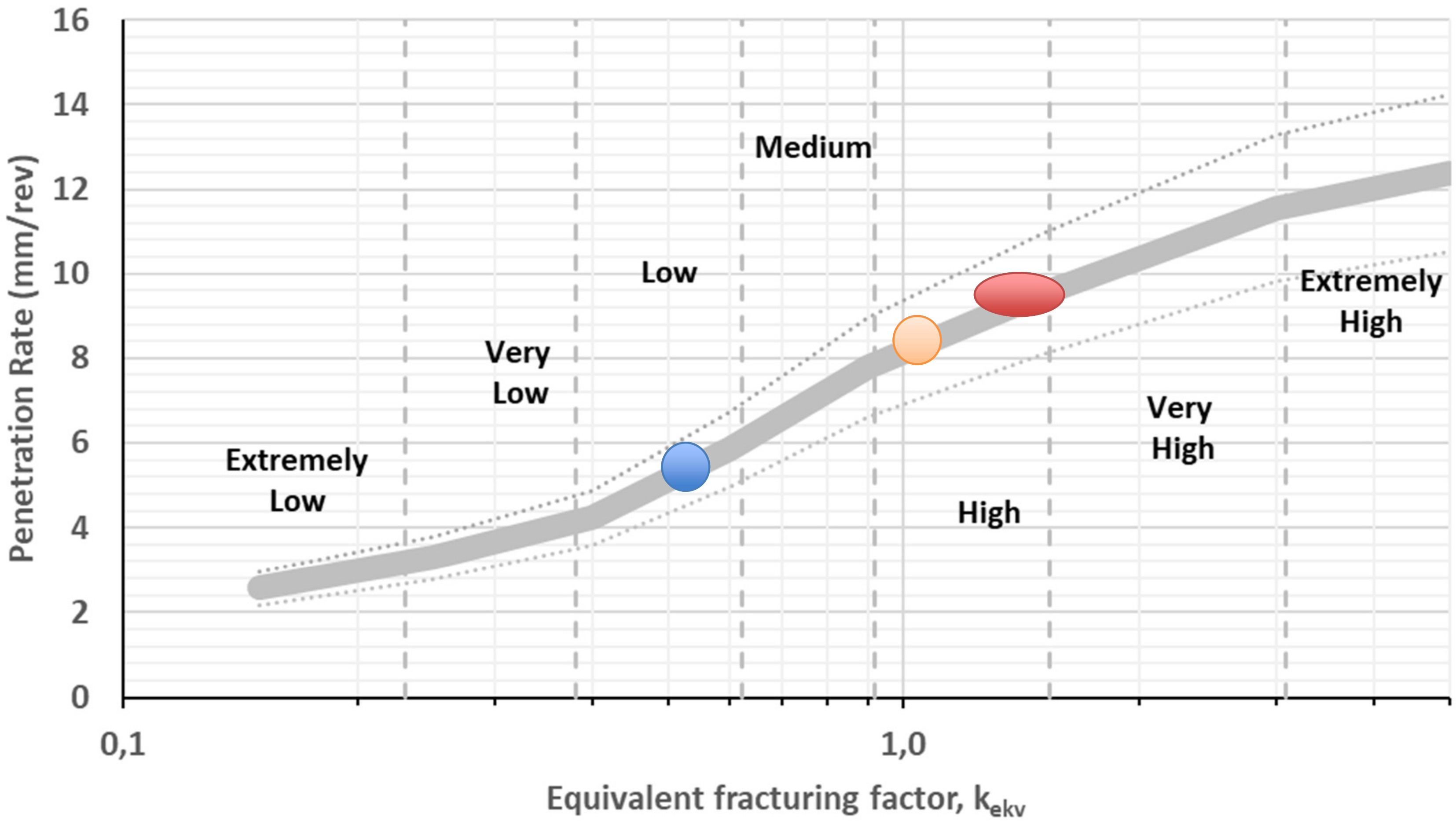
Rock Mass Boreability



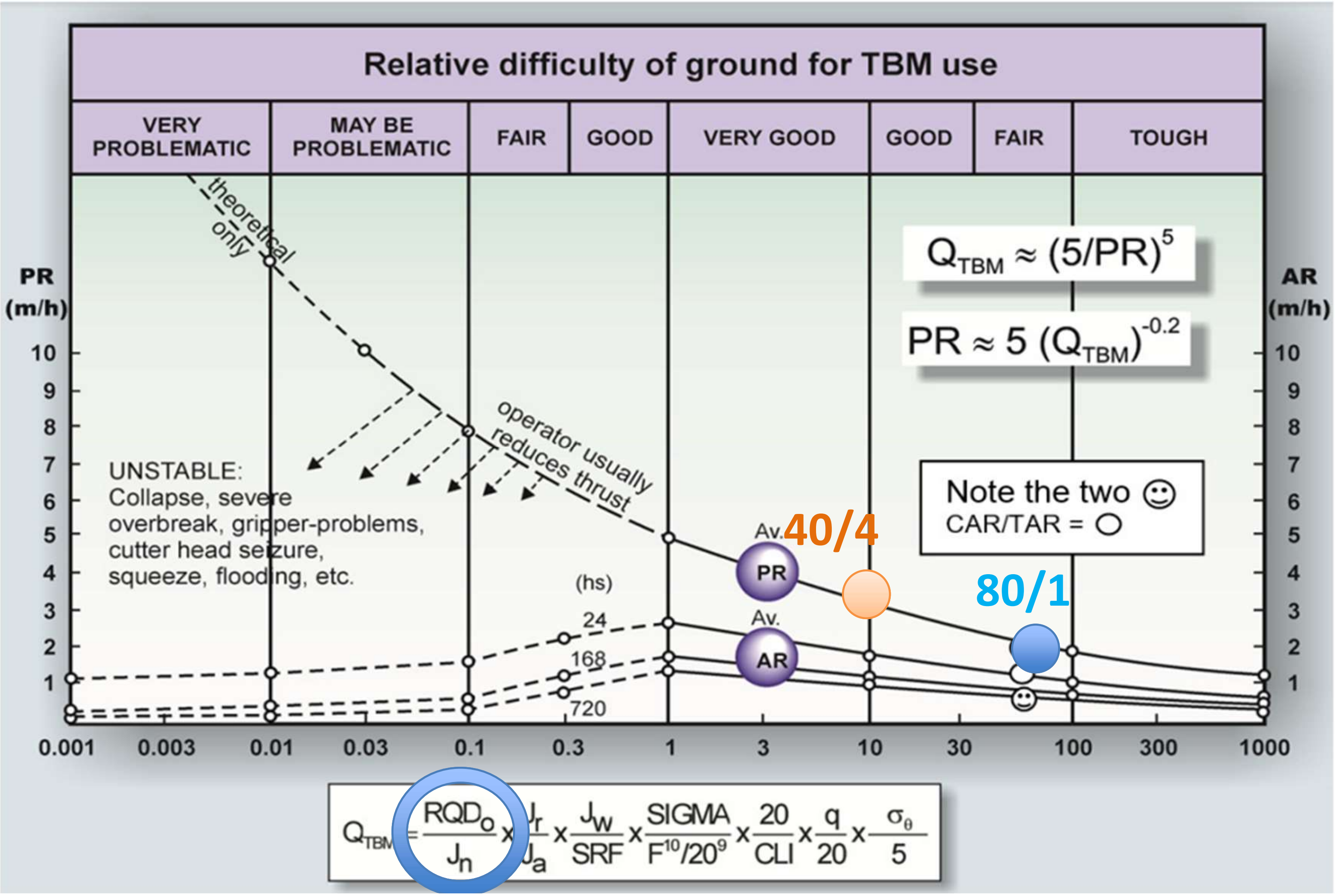
Macias (2016)

Understanding Rock Boreability

NTNU model 2016,
recommended thrust/RPM

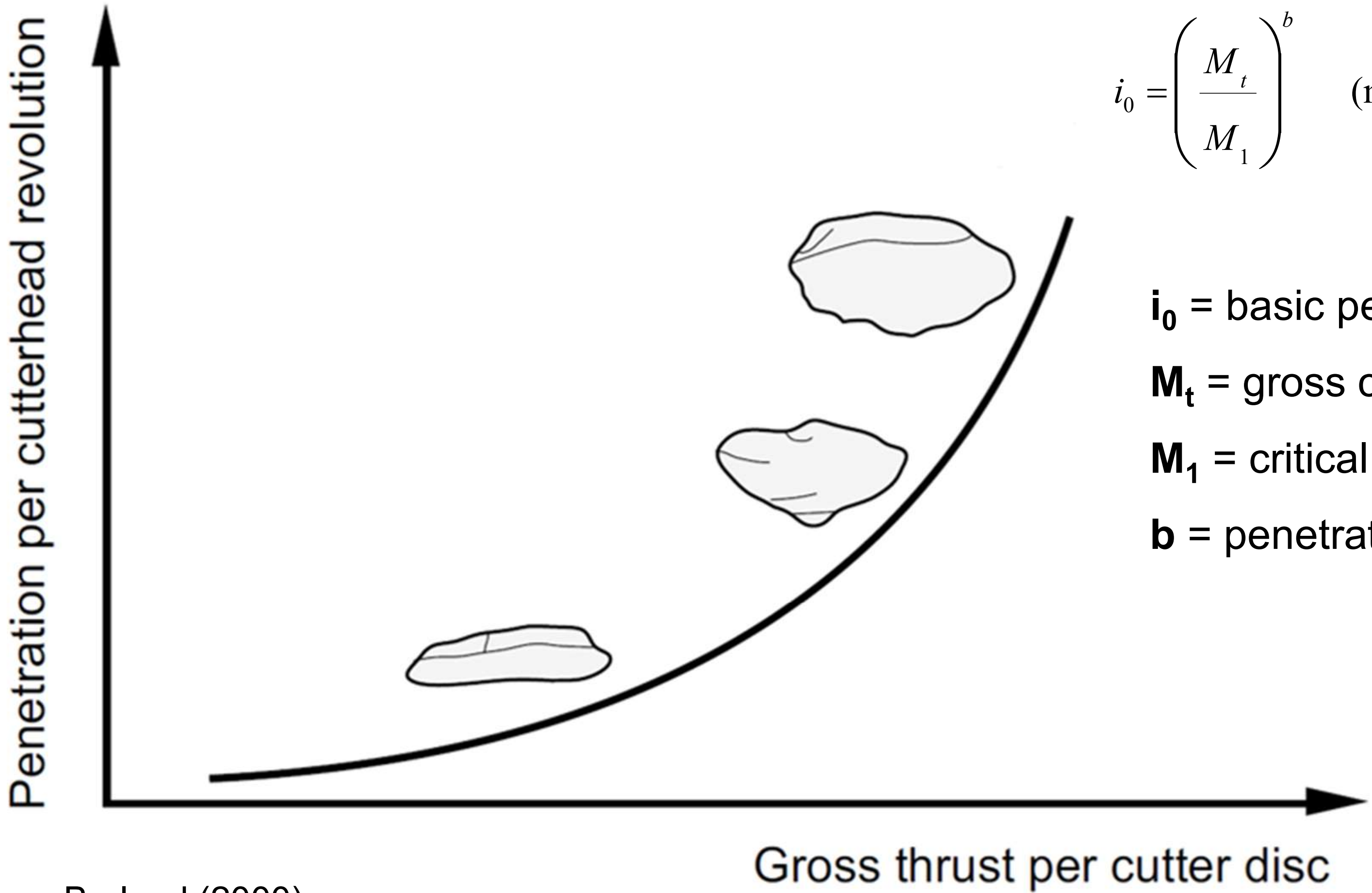


Rock Mass Boreability



Barton (2000)

Understanding Rock Boreability



$$i_0 = \left(\frac{M_t}{M_1} \right)^b \quad \text{(mm/rev)}$$

i_0 = basic penetration rate

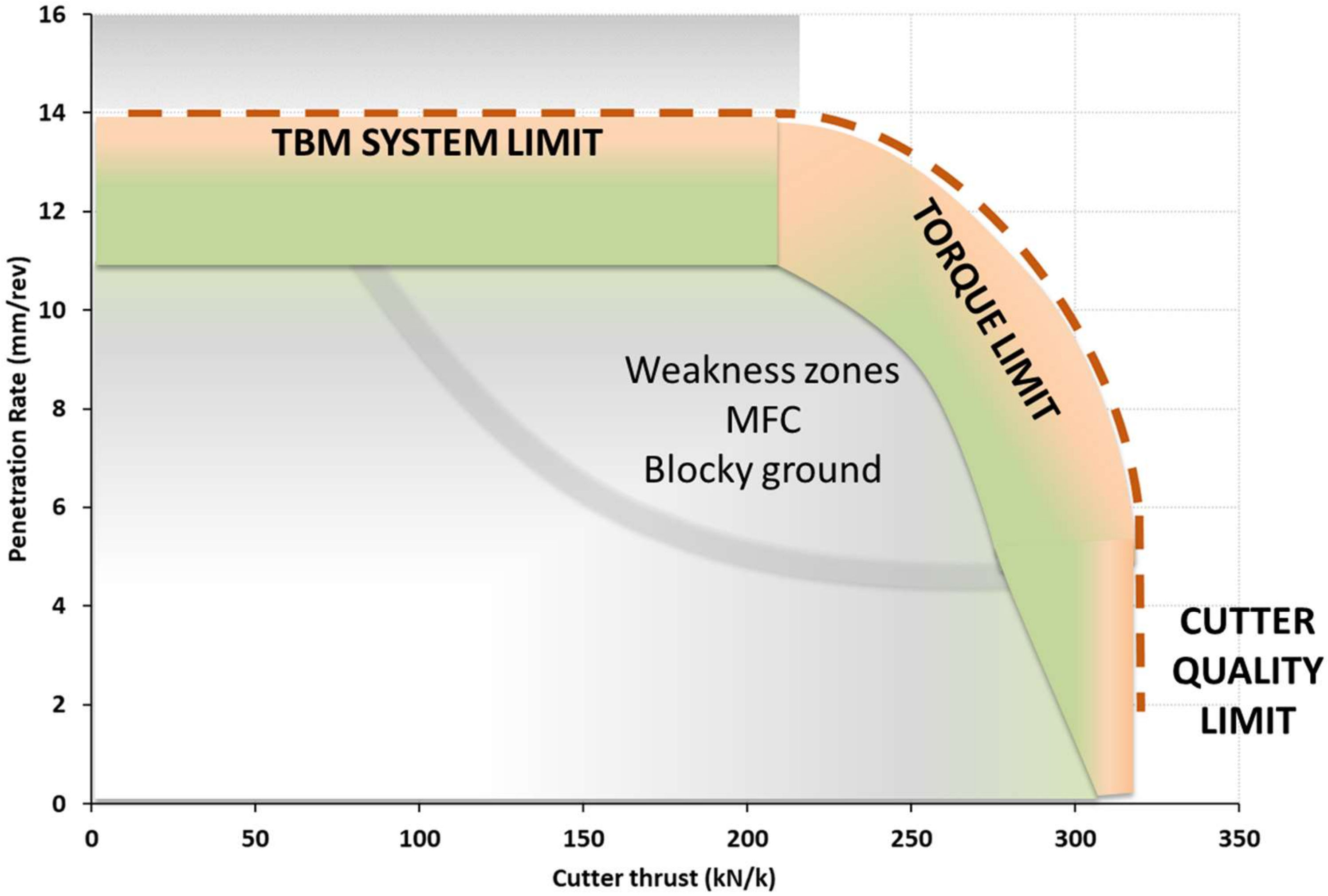
M_t = gross cutter thrust

M_1 = critical cutter thrust

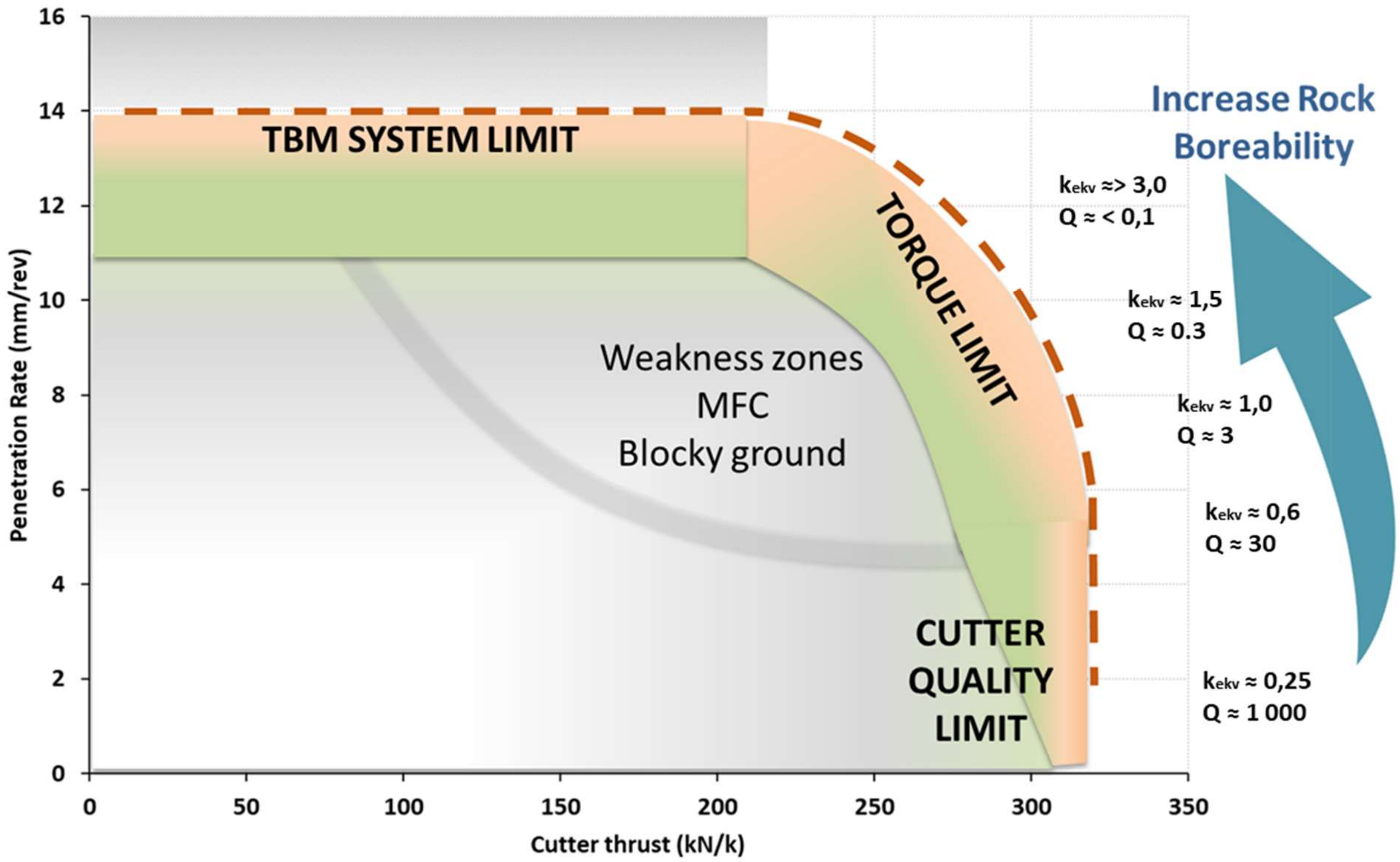
b = penetration coefficient

Modified from Bruland (2000)

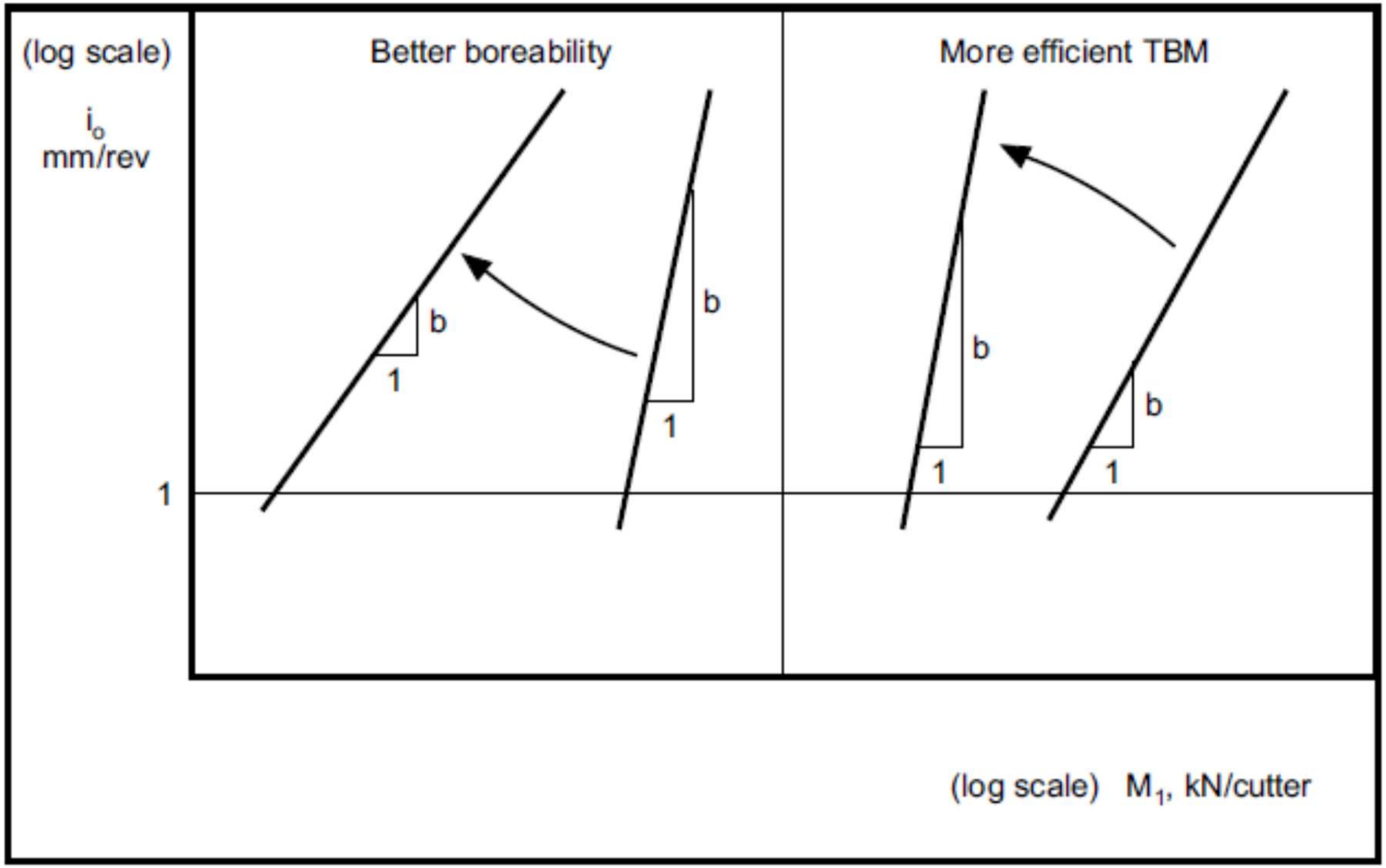
Understanding Rock Boreability



Understanding Rock Boreability

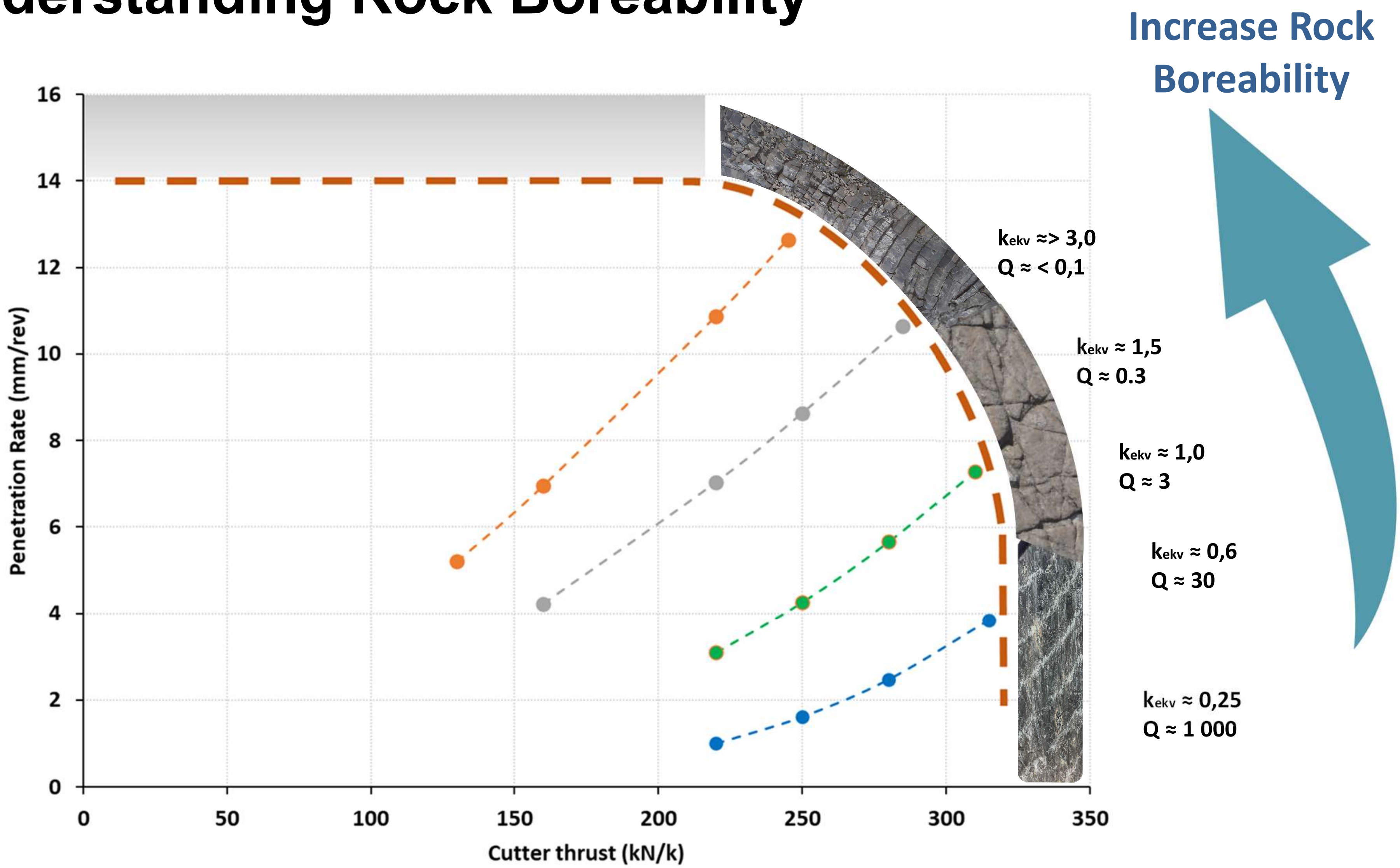


Understanding Rock Boreability



Bruland (2000)

Understanding Rock Boreability



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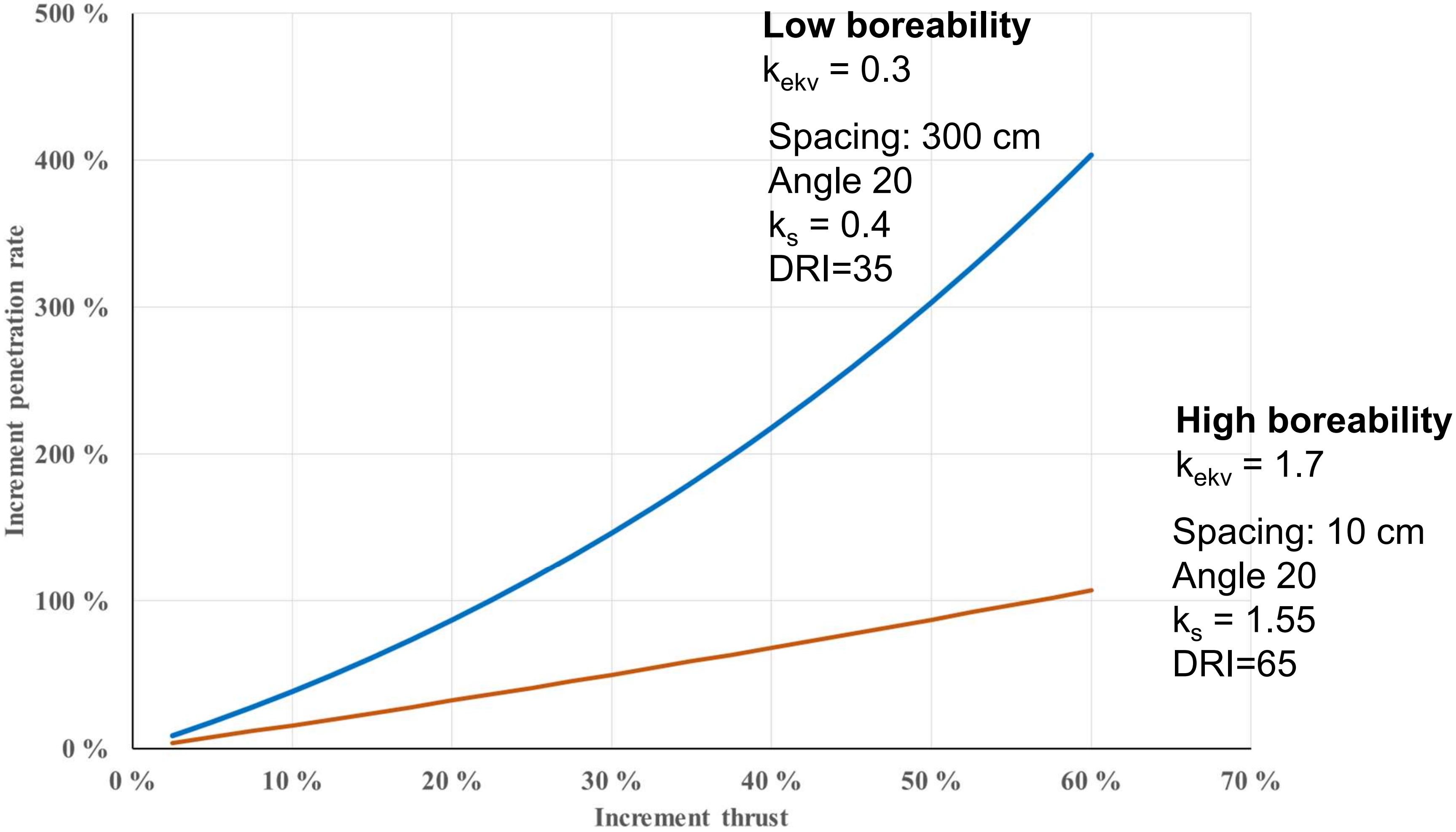
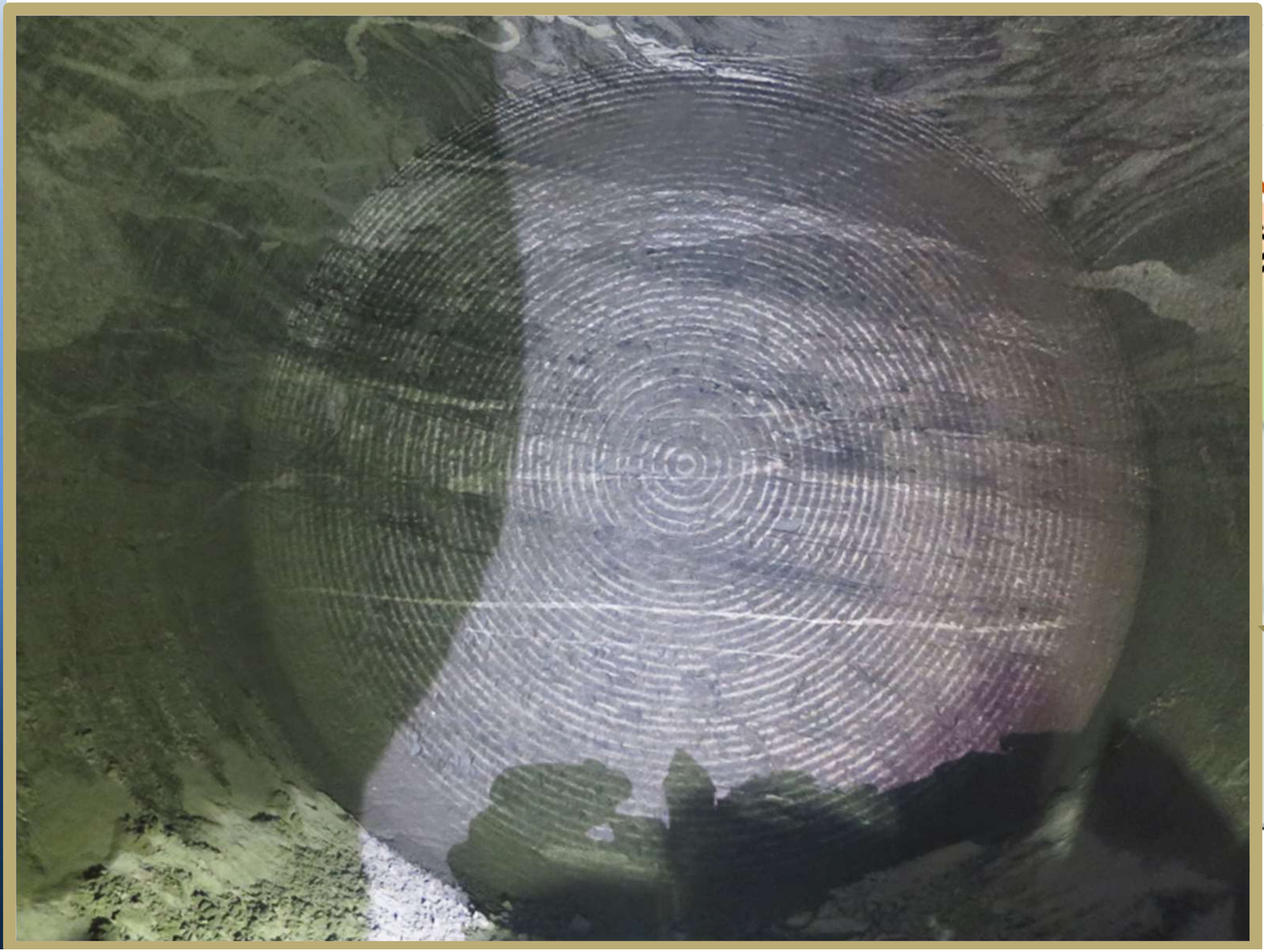
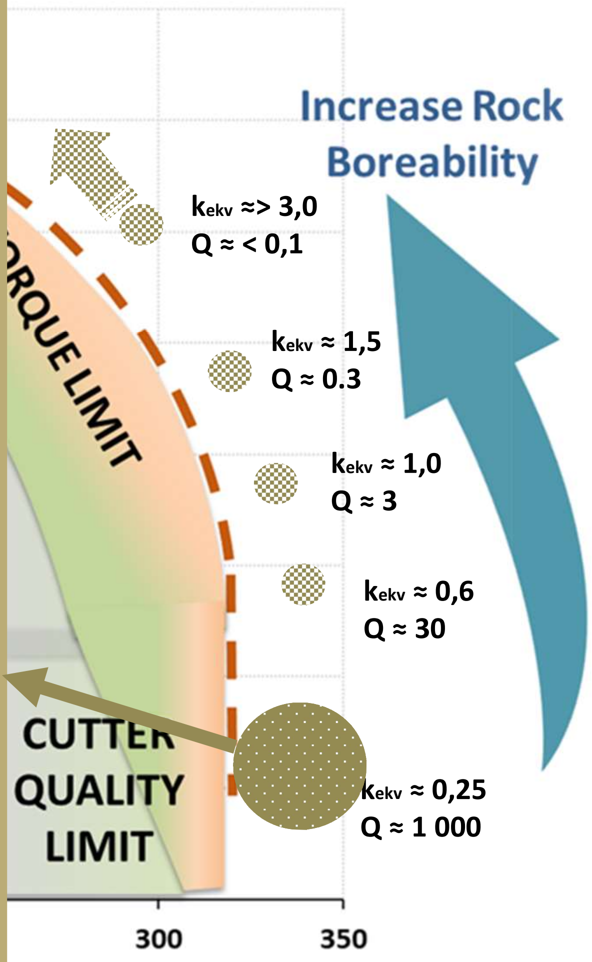
Understanding Rock Boreability

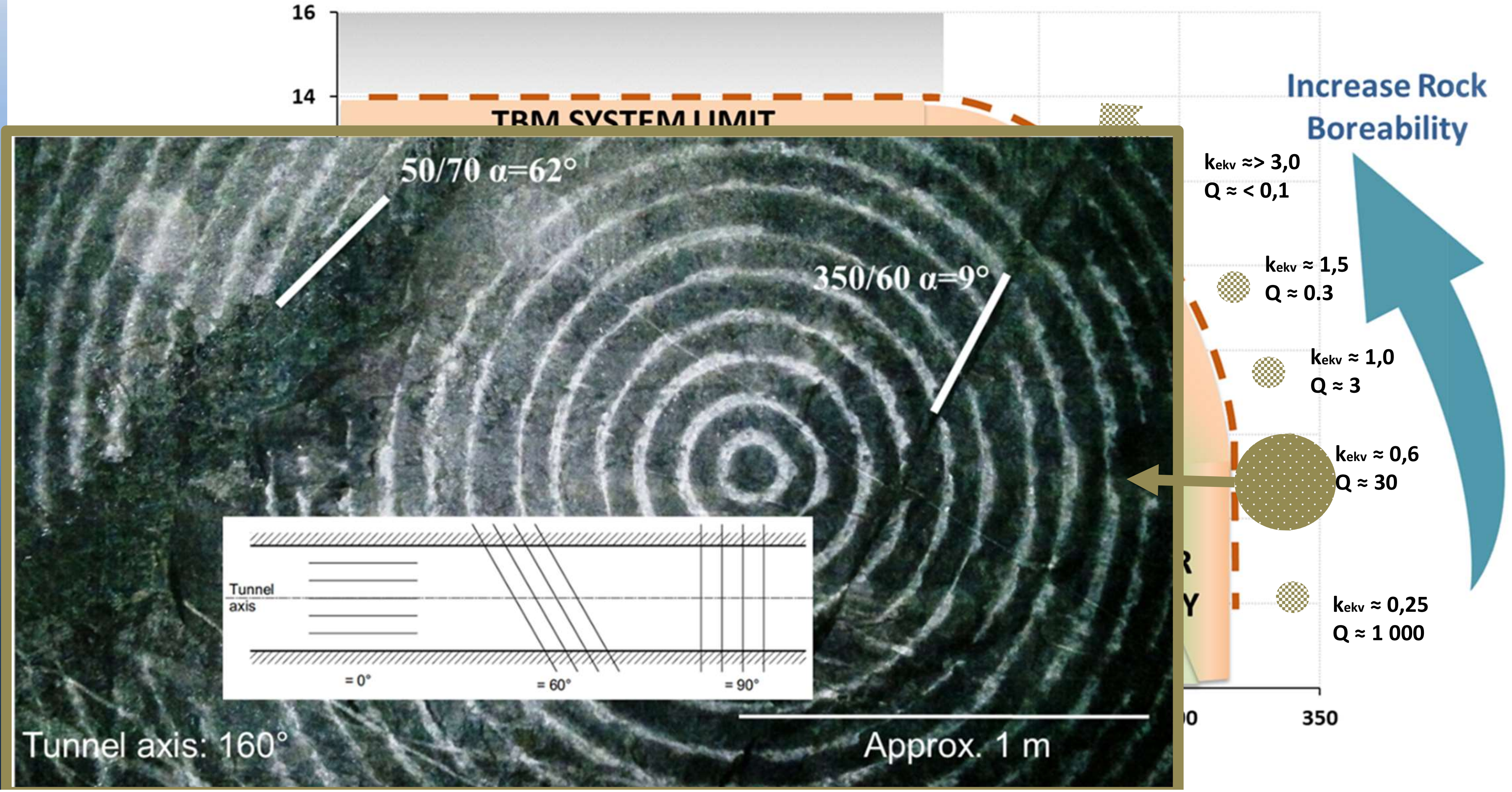


Understanding Rock Boreability

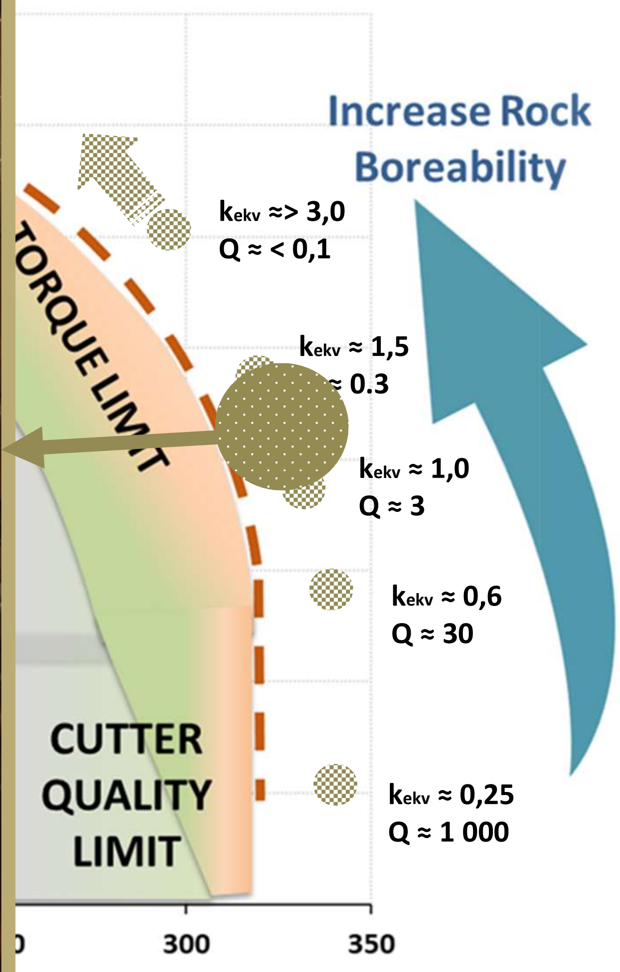




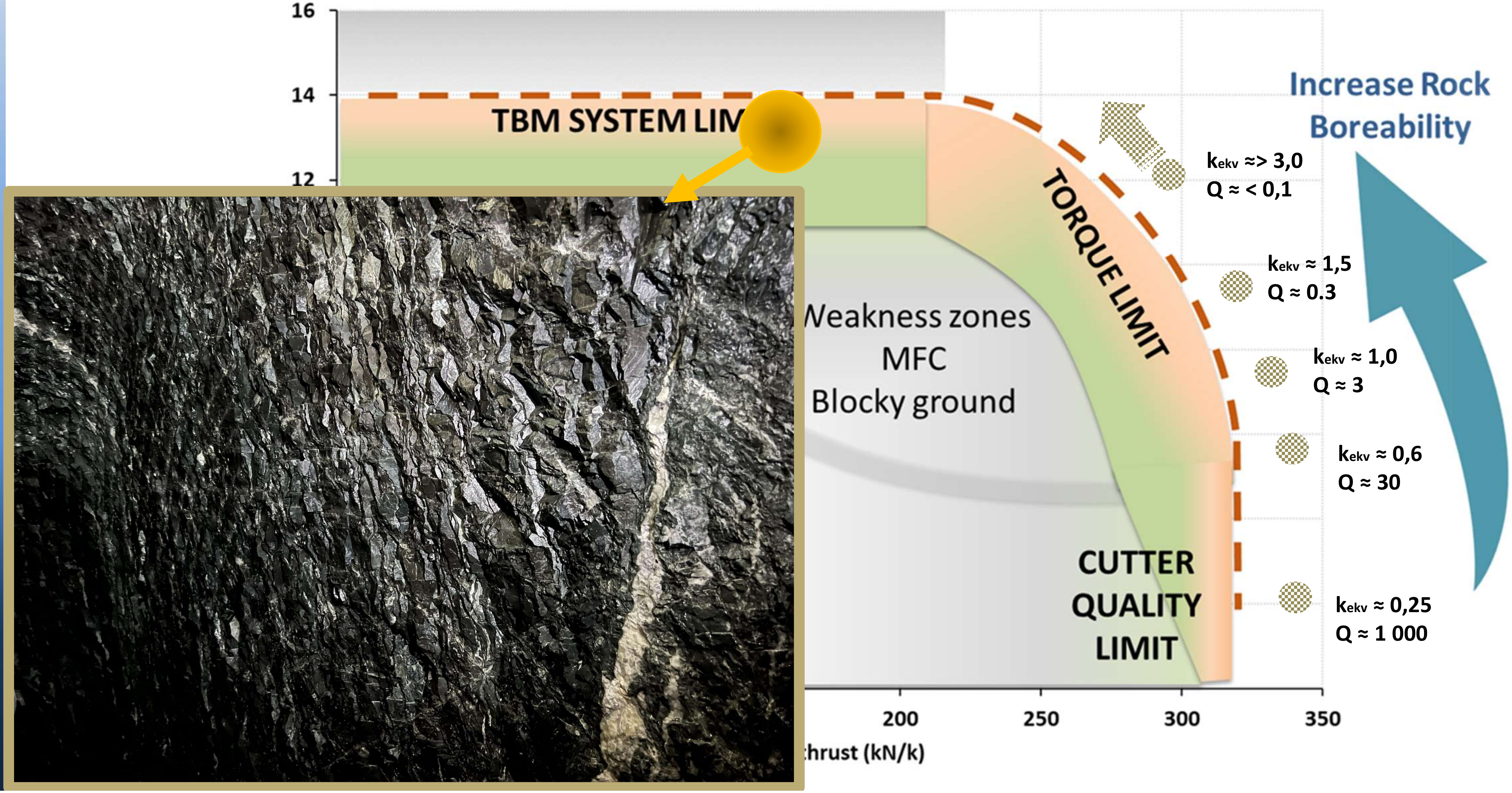
Understanding Rock Boreability



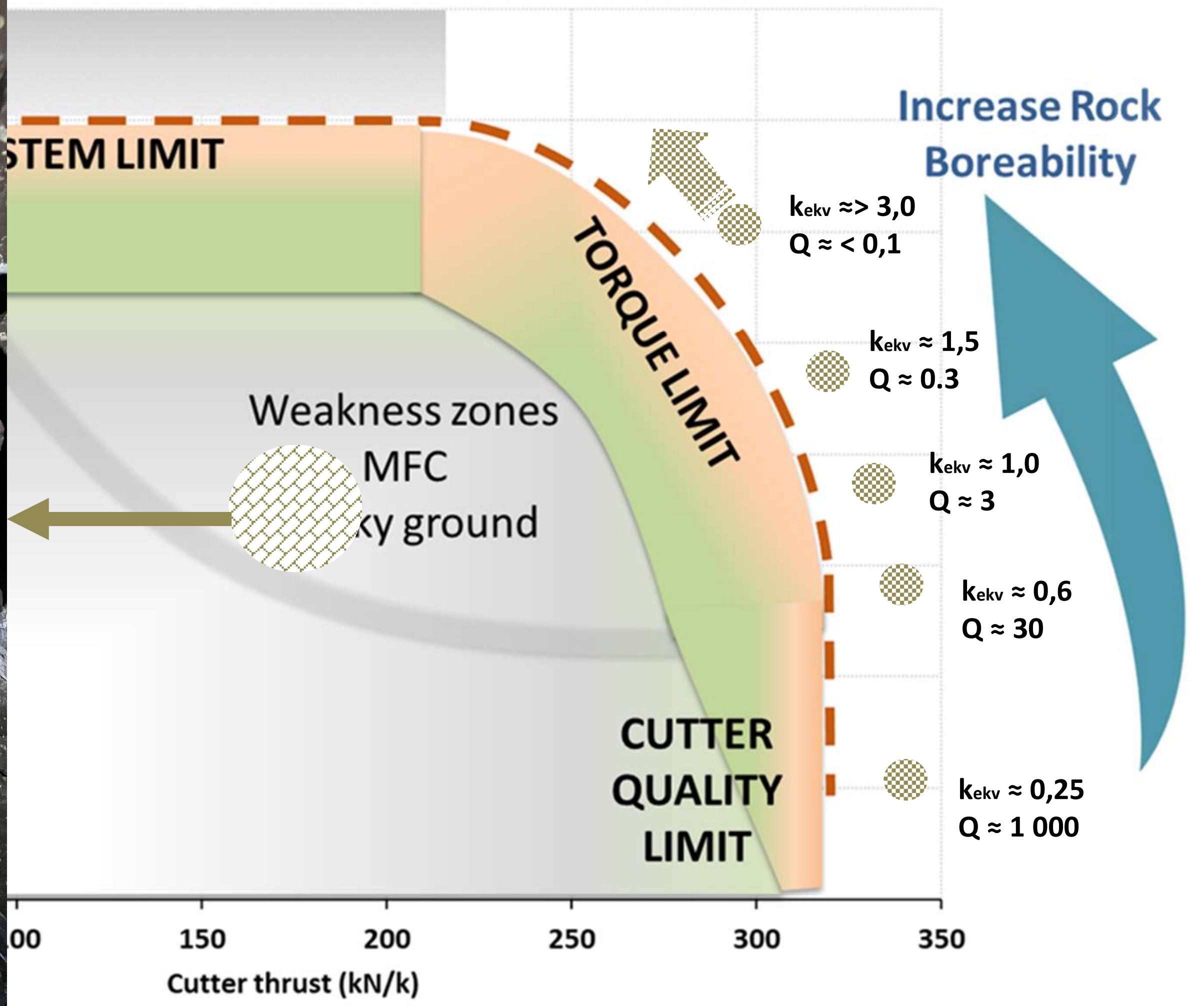
Understanding Rock Boreability



Understanding Rock Boreability



Understanding Rock Boreability



Rock boreability and cutter wear

DRI = 20
CLI=5
Abrasive minerals = 60%

Increase rock boreability

ks	Hh (h/c)	Hm (m/c)	Hf (m^3/c)
0,36	0,72	1,0	38
0,5		1,4	52
1		2,9	112
1,5		4,6	177
2		4,8	185
2,5		5,6	215
3		6,1	236

Over 500%!

DRI = 60
CLI=20
Abrasive minerals = 10%

Increase rock boreability

ks	Hh (h/c)	Hm (m/c)	Hf (m^3/c)
0,36	2,60	4,5	172
0,5		6,3	241
1		8,8	337
1,5		10,9	420
2		12,3	473
2,5		13,3	511
3		14,3	552

Over 200%!

Outline

- What is Rock Boreability?
  - Intact Rock Boreability
  - Rock Mass Boreability
- Understanding Rock Boreability
- Conclusive remarks

Conclusive remarks

- 'Rock Boreability' is the resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass (intact rock containing planes of weakness)
- 'Rock boreability' is a comprehensive parameter:
  - Intact rock properties
  - Rock mass parameters
- Rock mass fracturing is found to be the geological factor that exerts the greatest influence on net penetration rate and cutter wear

Takeways

- There is no single parameter that can fully represent the properties of jointed rock masses
  - Rock mass assessments
- Recognize the significance of rock mass on TBM performances
- Understand the influence of rock boreability on tunnel boring operation and TBM performances


Tusen Takk!
Spørsmål?
Javier.Macias@JMC-RockEng.com

Oslo

Foreløpige erfaringer fra Ny vannforsyning Oslo - Råvannstunnelen (E5)

Til NBG-kurs 09-10 januar 2024
Bergteknikk for TBM - Boring i hardt fjell

Martin Stormoen
Geolog, VAV Oslo Kommune

Med bidrag fra flere kolleger i VAV og Skanska

Agenda

- Kort om prosjektet
- Geologi
- Fremdrift og status
- Sonderboring og forinjeksjon fra TBM
- Svakhetssoner
- Oppsummering og videre arbeider

Råvannstunnelen – E5

- Utførelsesentreprise (NS 8405)
- Entreprenør: Skanska Norge
  Prosjekterende: Multiconsult, COWI, Asplan Viak
- Byggherrestyrt forinjeksjon

Betzy og Anne Brit

TBM:

- 2 stk TBM - 5,2 m diameter dobbeltskjold
- 320m lang TBM

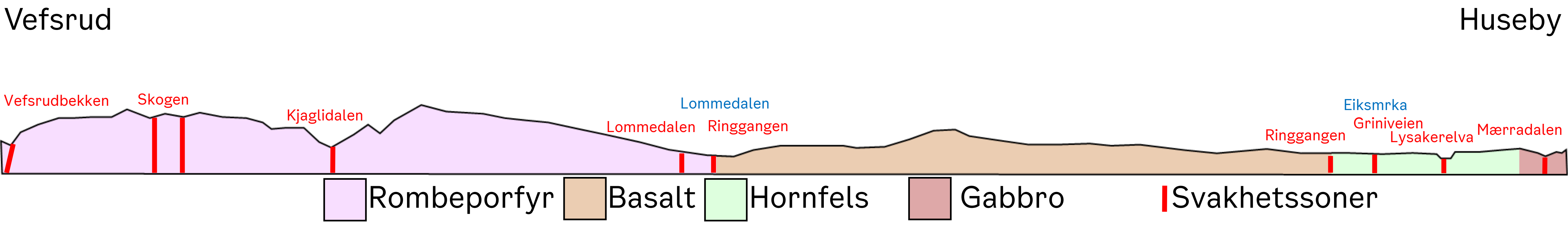
Tunnel:

- 19 km TBM-driving
- Ferdig tunnel vil ha en diameter på 4,3m

Tunnelkledning:

- Betongsegmenter, med bakfyll av ertegrus og industrisement

Geologi - råvannstunnel



- Høye vanntrykk og stor vannledningsevne, spesielt mellom lavastrømmer
- Flattliggende geologiske lag
  - Økt usikkerhet på tunnelnivå
  - Flattliggende svake og permeable lag over lengre strekker
- Enkelte urbane områder med høy setningsømfintlighet

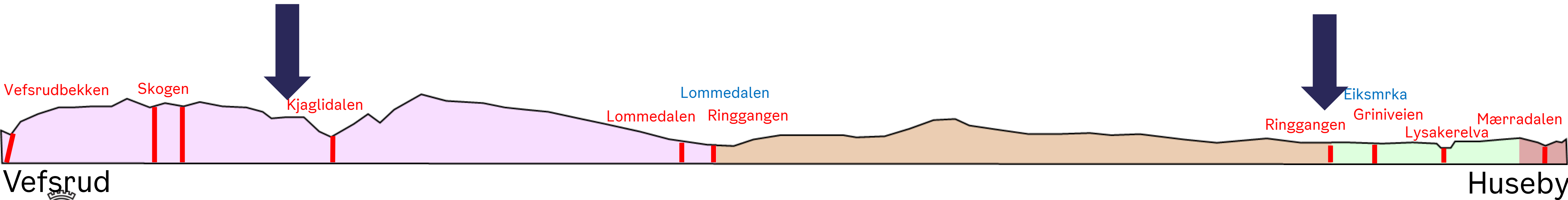
Fremdrift og status – E5 TBM

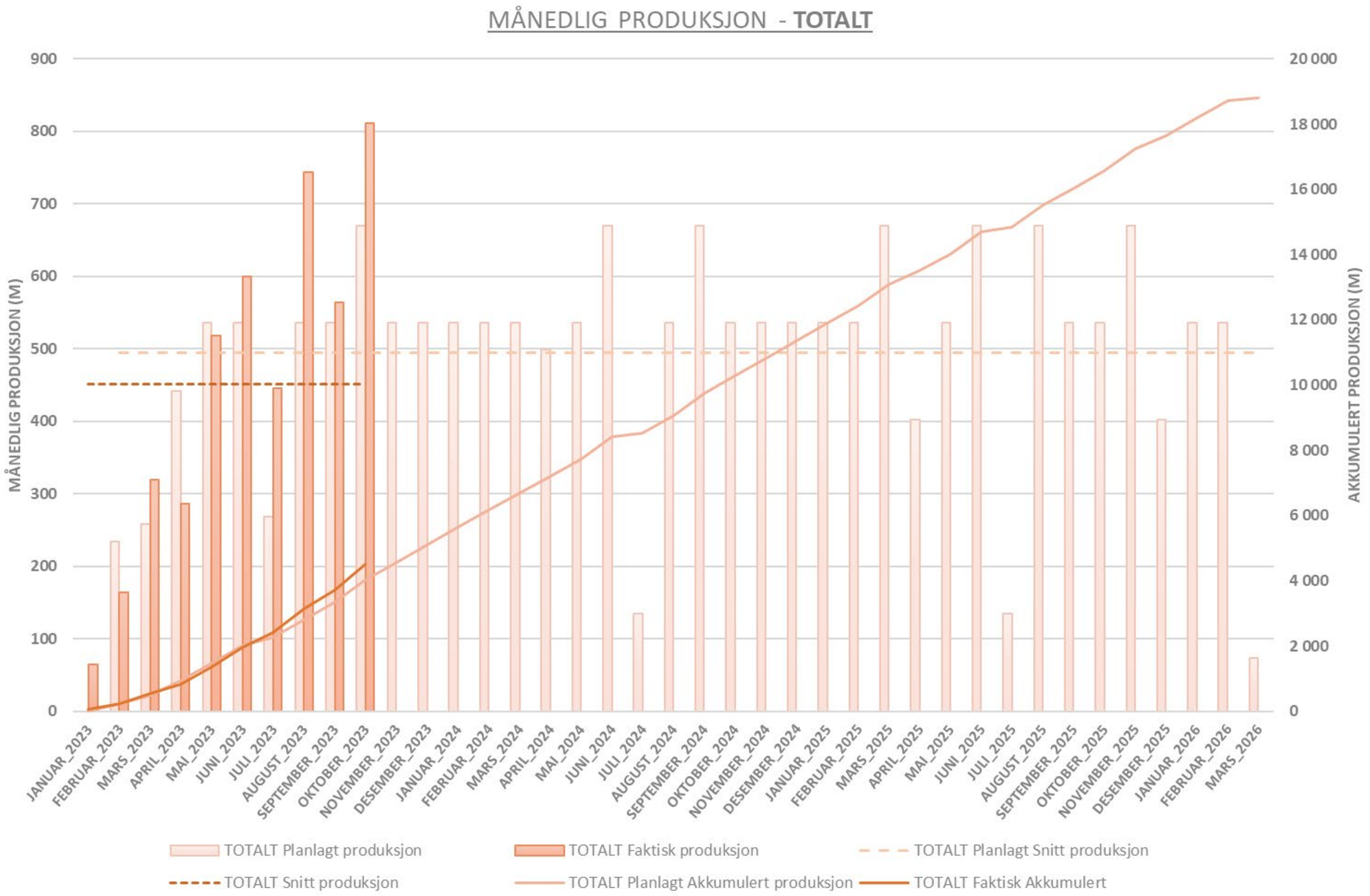
Betzy (fra Vefsrud):

- Drevet 3410m, satt 2274ringer
- Pumpet 1255294 kg microsement
  - snitt per skjerm 10729kg
- Boret 1317 langhull, snitt 36,8m
- Maks ukesproduksjon TBM: 164m

Anne Brit (fra Huseby):

- Drevet 2852m, satt 1902 ringer
- Pumpet 888690 kg microsement
  - snitt per skjerm 11849kg
- Boret 1272 langhull, snitt 37,4m
- Maks ukesproduksjon TBM 115m

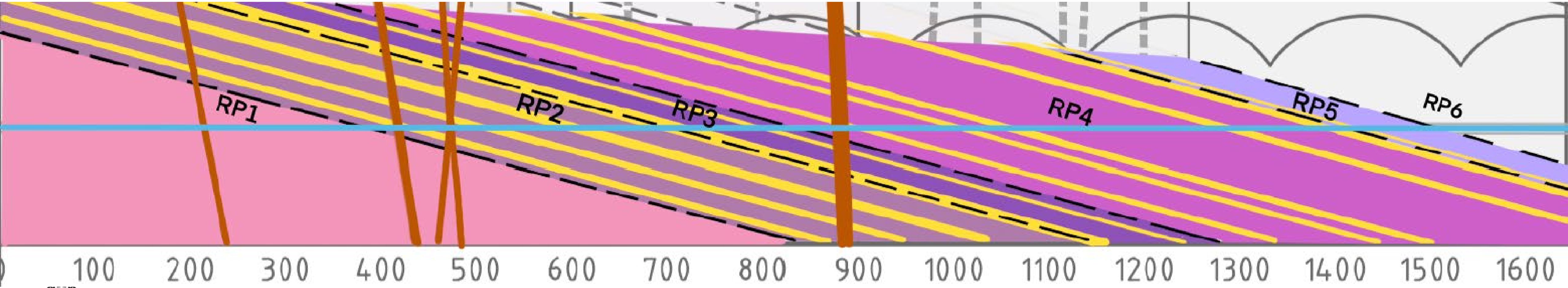



MÅNEDLIG PRODUKSJON - TOTALT
MÅNEDLIG PRODUKSJON (M)
AKKUMULERT PRODUKSJON (M)
0
100
200
300
400
500
600
700
800
900
0
2 000
4 000
6 000
8 000
10 000
12 000
14 000
16 000
18 000
20 000
JANUAR_2023
FEBRUAR_2023
MARS_2023
APRIL_2023
MAI_2023
JUNI_2023
JULI_2023
AUGUST_2023
SEPTEMBER_2023
OKTOBER_2023
NOVEMBER_2023
DESEMBER_2023
JANUAR_2024
FEBRUAR_2024
MARS_2024
APRIL_2024
MAI_2024
JUNI_2024
JULI_2024
AUGUST_2024
SEPTEMBER_2024
OKTOBER_2024
NOVEMBER_2024
DESEMBER_2024
JANUAR_2025
FEBRUAR_2025
MARS_2025
APRIL_2025
MAI_2025
JUNI_2025
JULI_2025
AUGUST_2025
SEPTEMBER_2025
OKTOBER_2025
NOVEMBER_2025
DESEMBER_2025
JANUAR_2026
FEBRUAR_2026
MARS_2026
TOTALT Planlagt produksjon
TOTALT Faktisk produksjon
TOTALT Planlagt Snitt produksjon
TOTALT Snitt produksjon
TOTALT Planlagt Akkumulert produksjon
TOTALT Faktisk Akkumulert

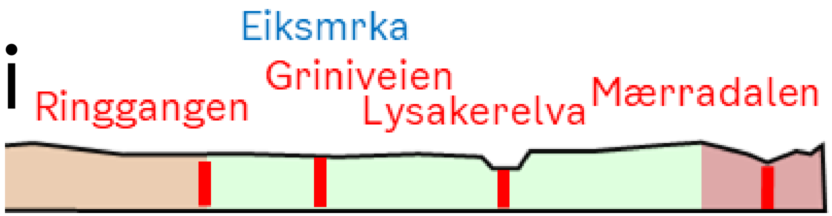
Oslo

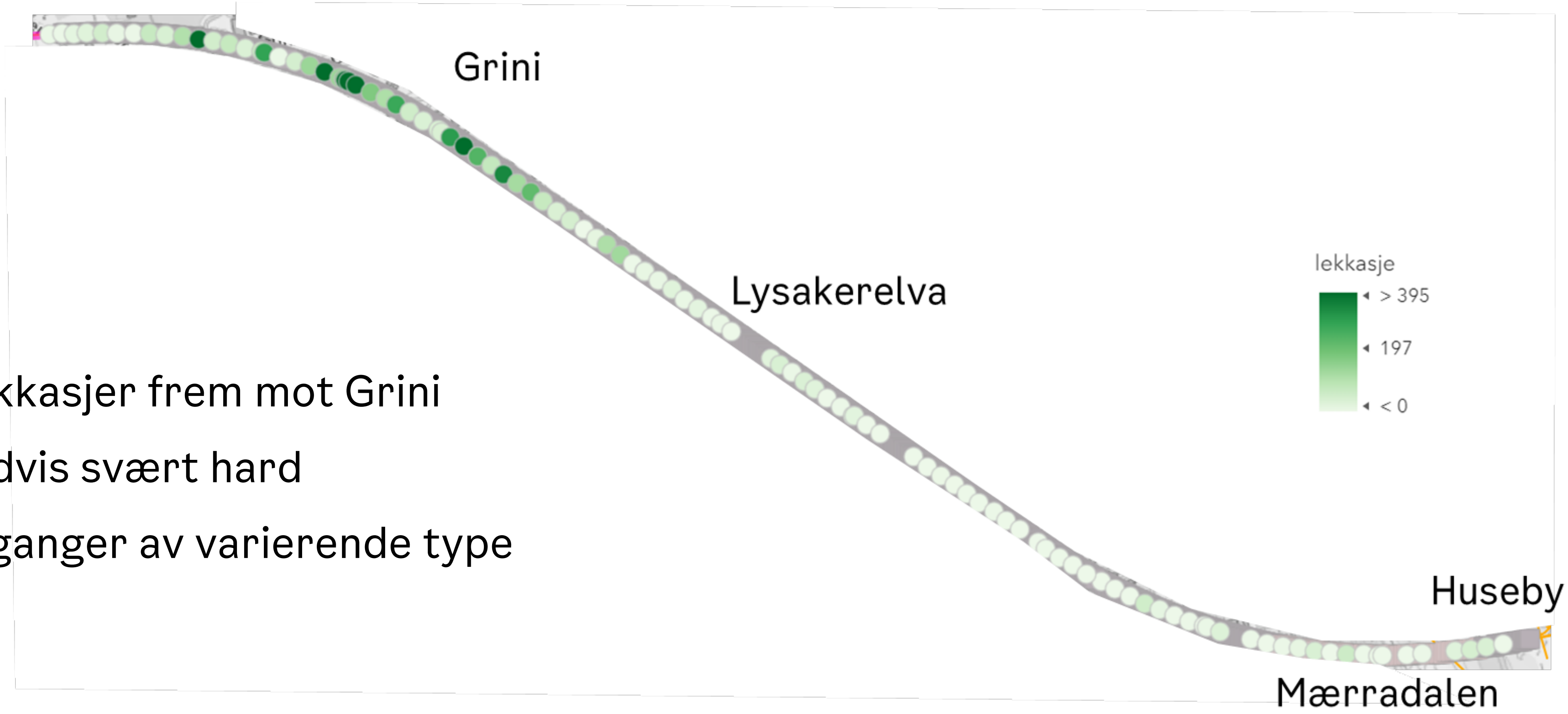
Påtruffede grunnforhold Krokskogen

- Geologien har i stor grad vært i tråd med forventningene
- Krevende vannforhold i rombeporfyren, også lengre tørre strekker
- Store lekkasjer i tilknytning til «lavatopper»



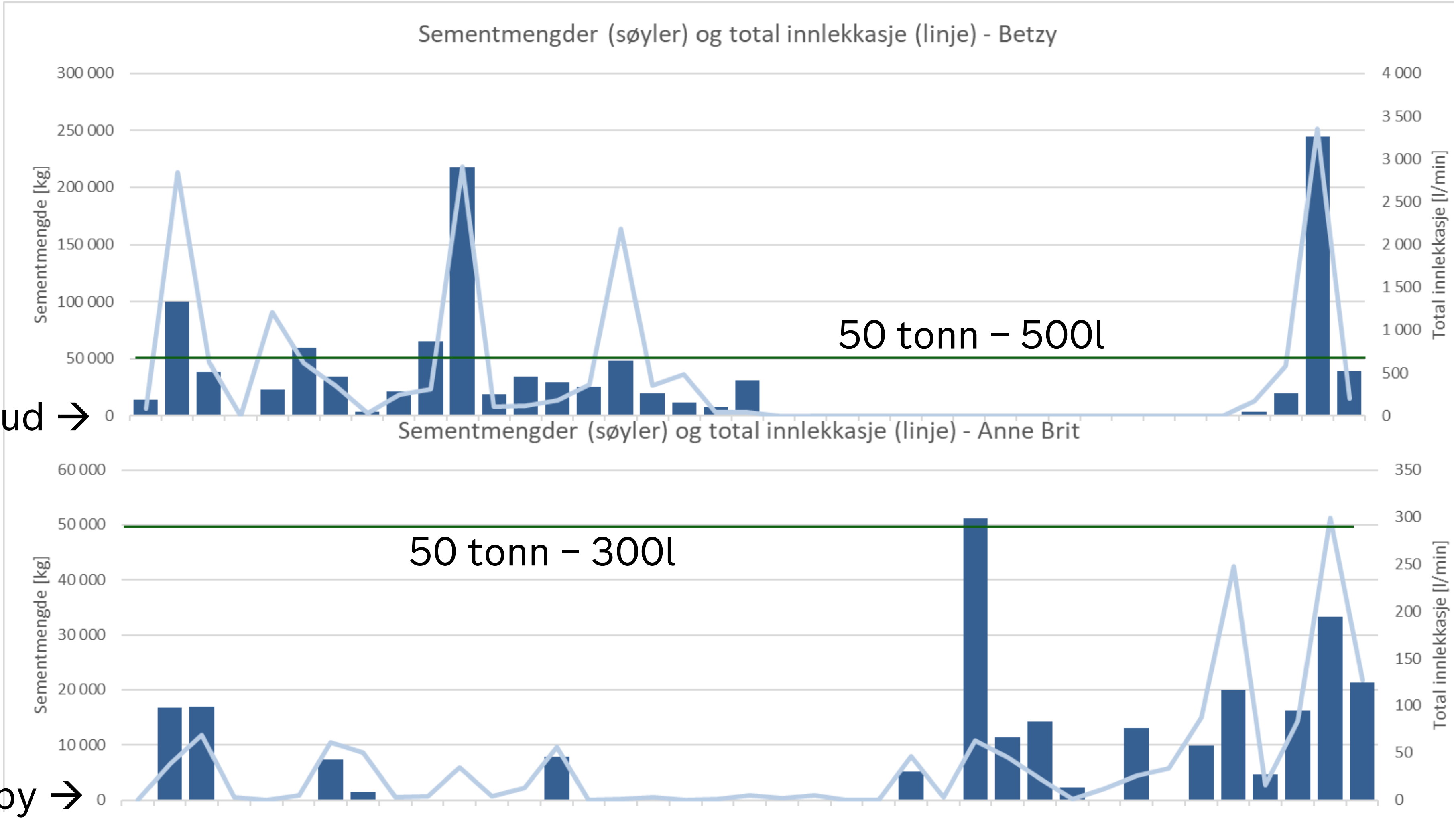
Påtruffede grunnforhold Huseby-Grini





- Svært lite lekkasjer frem mot Grini
- Hornfels stedvis svært hard
- Mye intrusivganger av varierende type

Innlekkasje og sementforbruk (nov 2023)



Vefsrud →

Huseby →

Oslo

Påtruffede grunnforhold

- Sprakefjell i rombeporfyren
  - Kan være relatert til diabasganger
- Kartlagte svakhetssoner
  - Generelt bedre bergmassekvalitet enn fryktet
  - Lite problemer med å bore gjennom med TBM
- Innlekkasjer og injeksjon har vært det mest krevende

(Foto: I. Kvarstein)

Påtruffede grunnforhold

Hornfels

Druserom, i rombeporfyr
(Foto: I. Kvarstein)

Typisk face i rombeporfyr
(Foto: I. Kvarstein)

Påtruffede grunnforhold
(foto: Skanska)

Innlekkasje fra borehull

Sone med høye bergspenninger, Vefsrud

Langhullsboring og injeksjon -forventninger og erfaringer

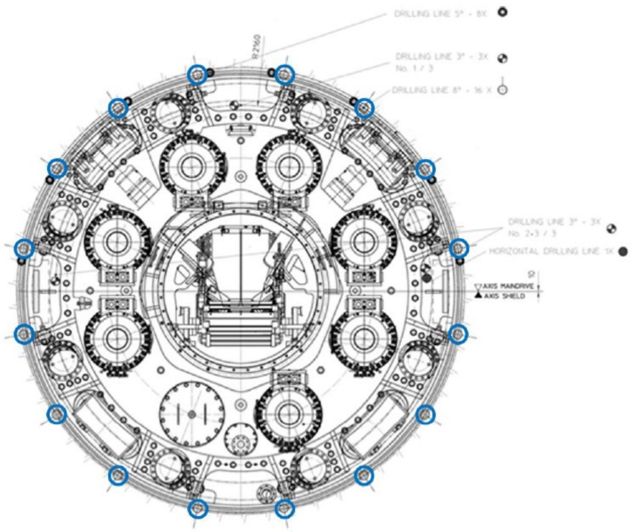
- Langhullsboring og injeksjon ofte argumentet mot TBM i krevende hydrogeologiske forhold
- Bore- og injeksjonsutstyret på TBM har historisk vært av dårligere kvalitet enn D&B.
- Strenge kontraktskrav→ AMV og Herrenknecht med innovativt TBM-design med et eget boreskjold

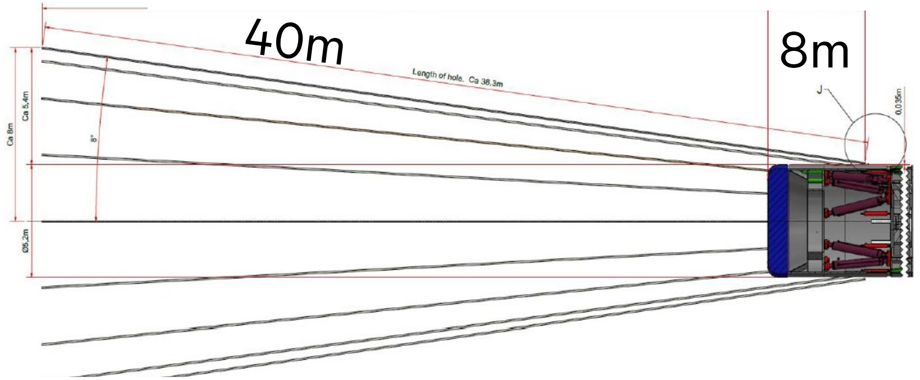
Foto: E. Larsen

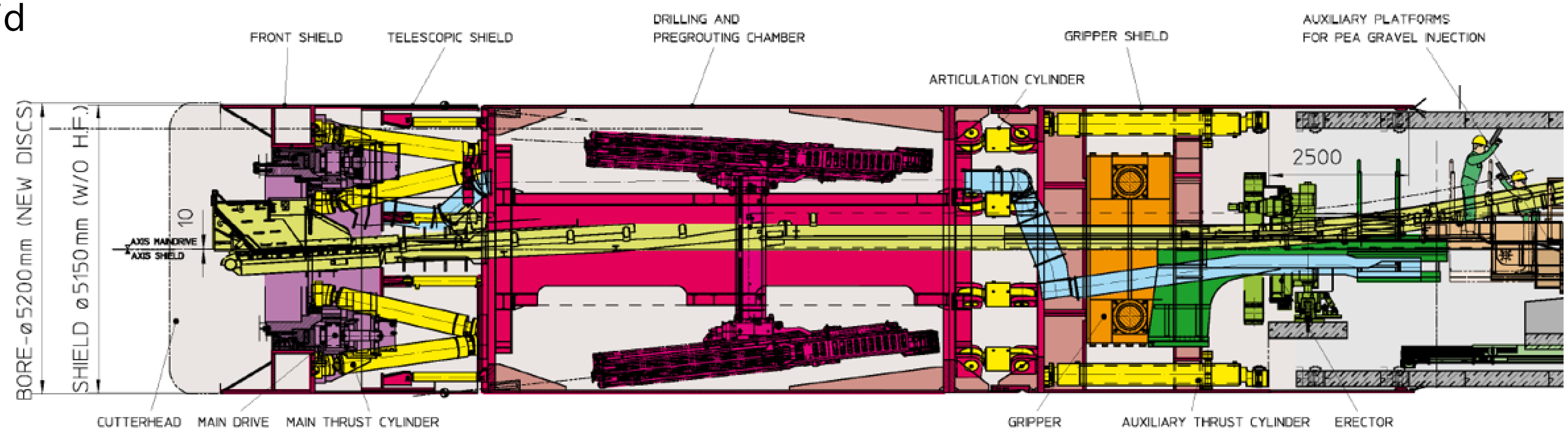
Forinjeksjon fra TBM

- 16 boreporter, 8 grader
- 8 boreporter, 5 grader
- Øvrige boremuligheter ved krevende forhold
- Borerigger tilsvarende D&B,
  lett tilgjengelig, godt tilpasset for parallelle aktiviteter

- Langhullsboring fra TBM er krevende
  - Lav vinkel og blindt arbeid



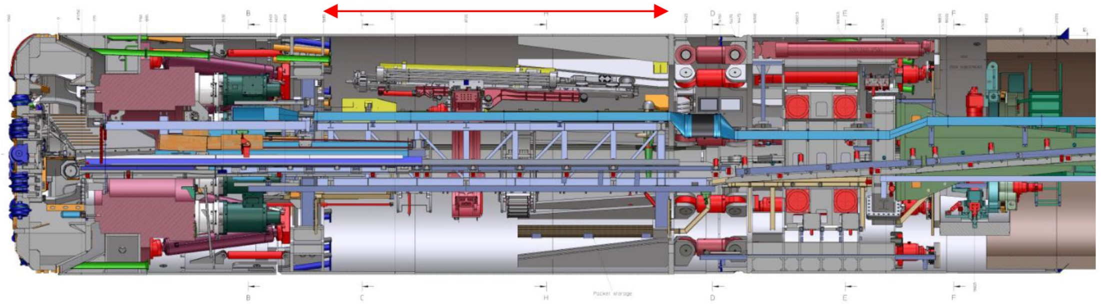




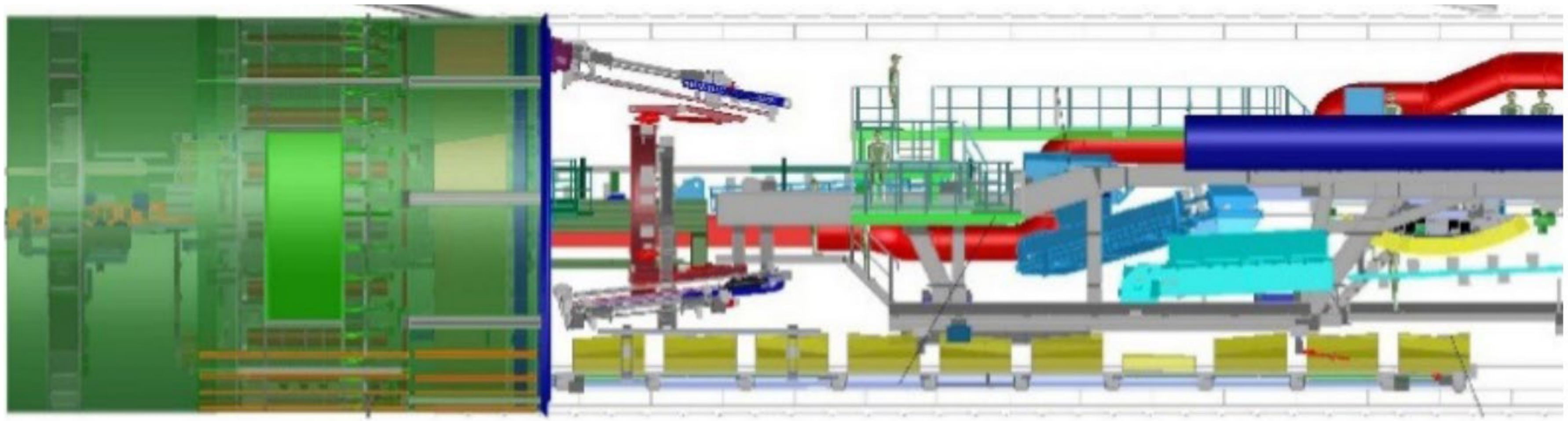
Oslo

TBM med boreskjold

- Eget boreskjold – svært langt skjold totalt
- Spesielt gunstig med eget boreskjold når TBM er såpass liten



NVO
(Skanska)



Follobanen
(Herrenknecht)

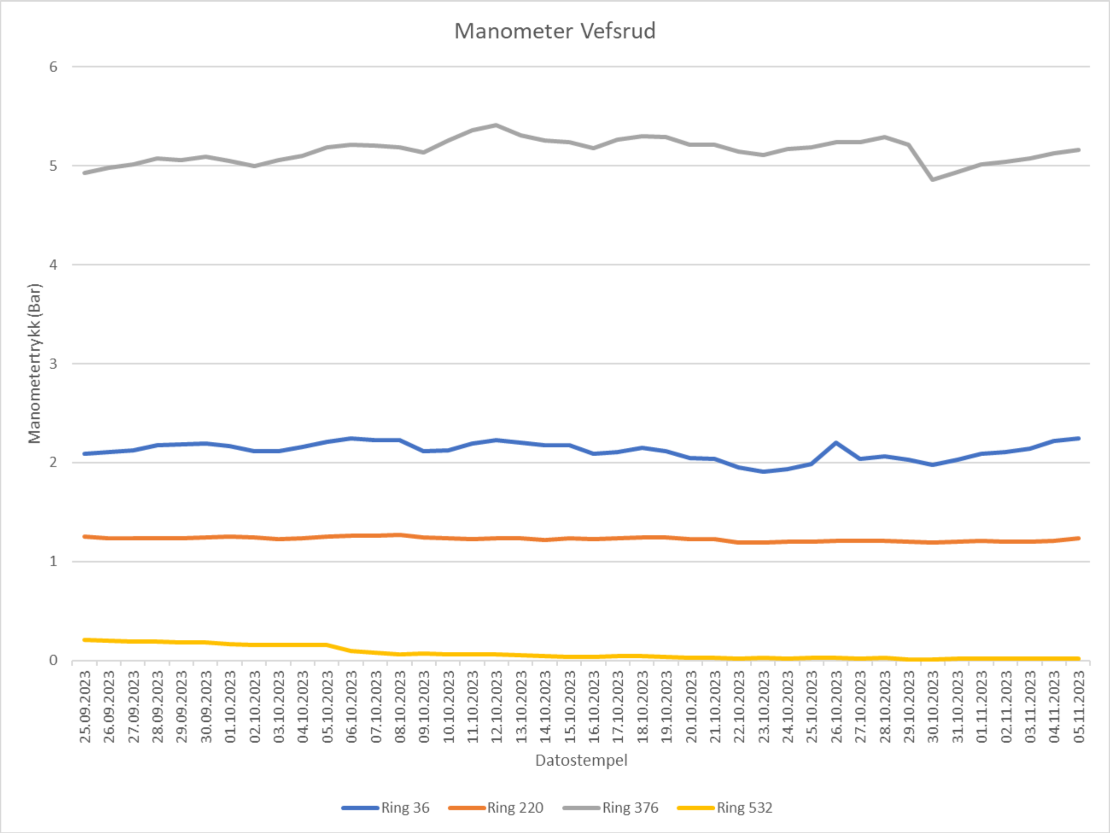
Langhullsboring og injeksjon -positive erfaringer

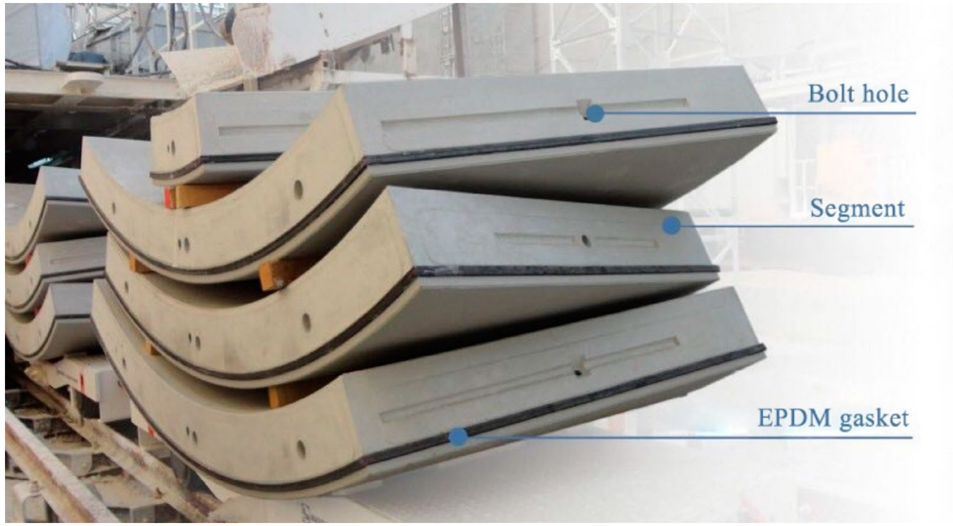
- 40 meter langhull med automatisk stanghåndtering.
- Fanger opp vanskelige soner tidligere
- Slanke hydrauliske pakkere
- MWD-data sammen med OTV gitt god informasjon om bergforhold.

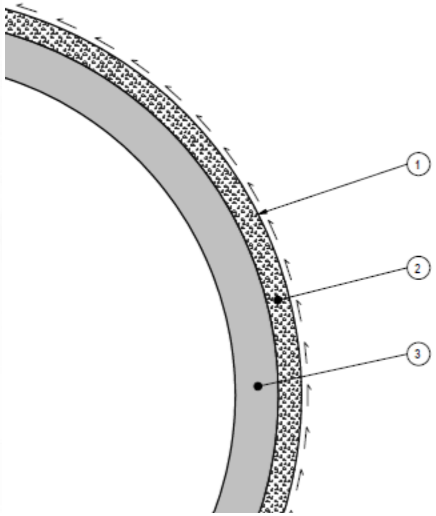
Foto: H. Enersvold

Betongkledning med backfill

- Henger sammen med injeksjonskonseptet
- EPDM-pakninger gjør at tunnelen kan bygges vanntett
- Tett løsning ved vanntrykk under 120m







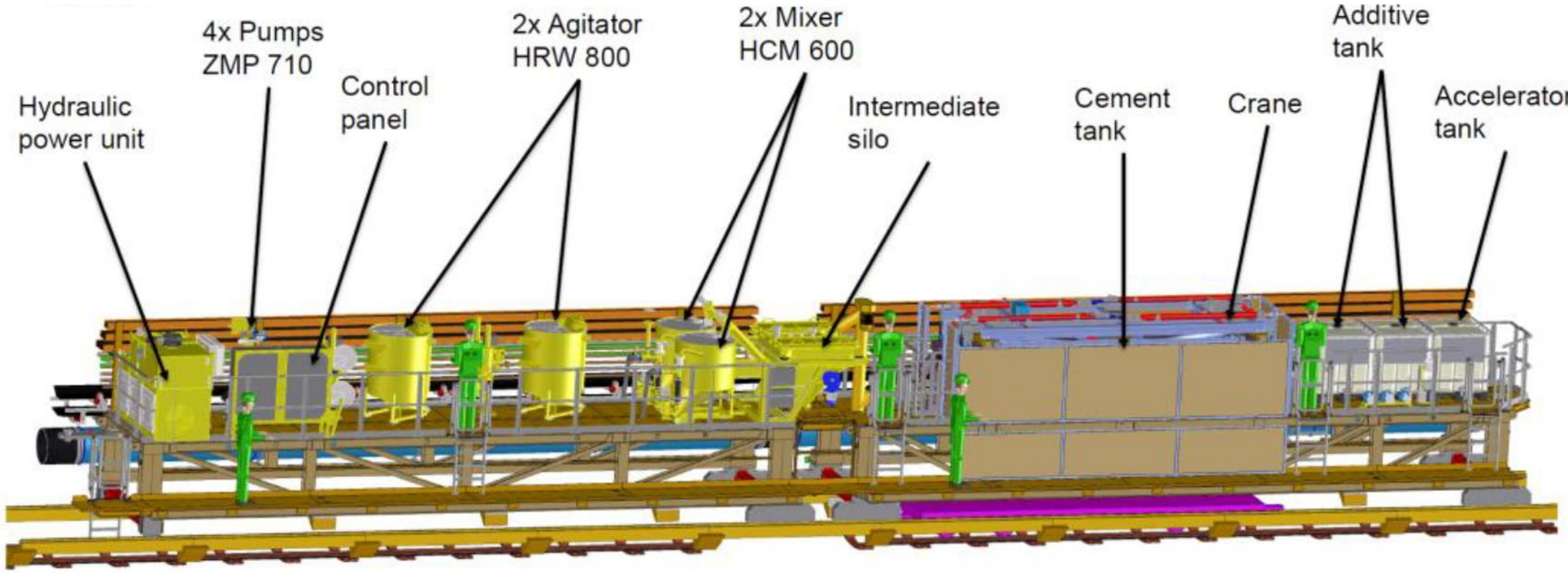
Barrierer

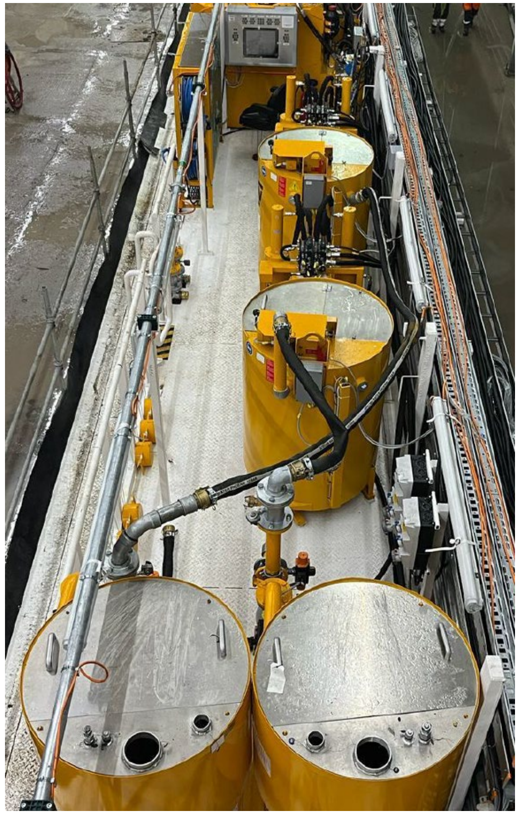
- Settes omtrent hver 200m
- Begrenser vanngjennomstrømning og lekkasjer
- Bidrar til mindre utvasking bak segmenter

- Øvrige tiltak for å redusere midlertidige lekkasjer:
  - Unngå å ha boreporter åpne over lengre tid
  - Sette pakker raskt

Forinjeksjon fra TBM

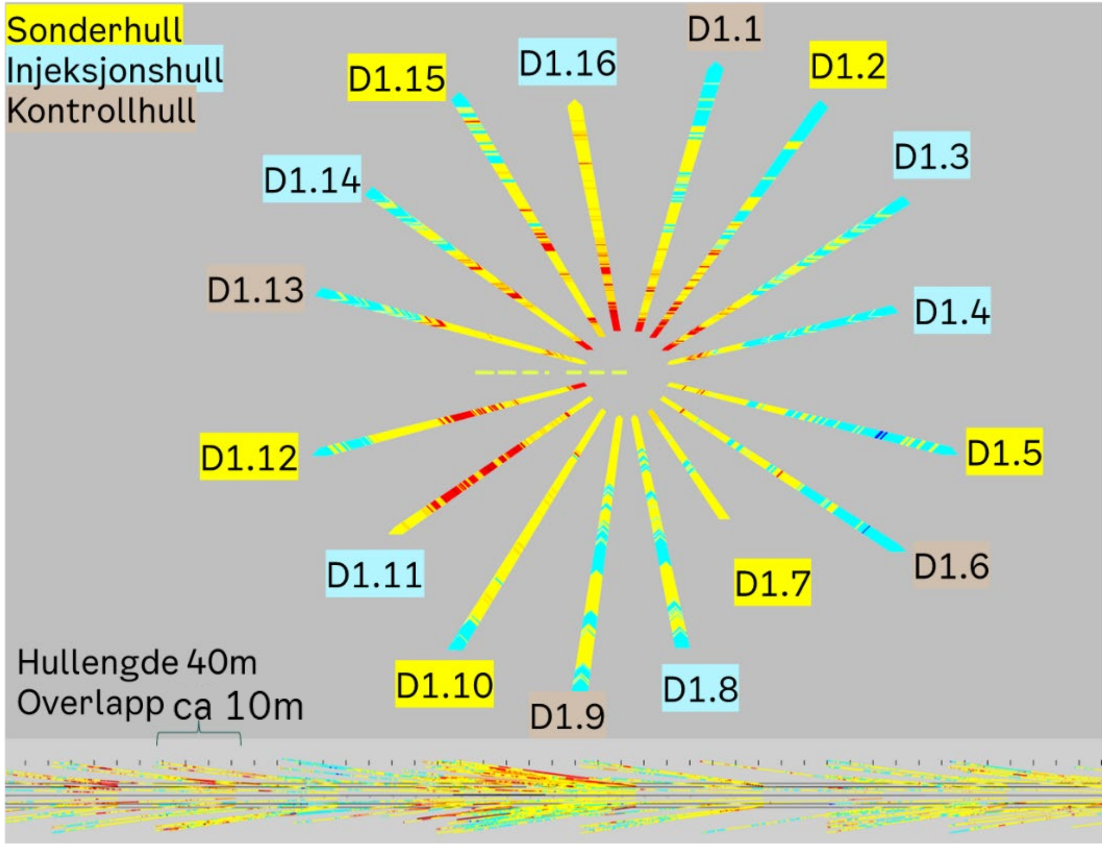
- Slangelengder 130m, 9m injeksjonsstaver, dype pakkerplasseringer
- Høy temperatur i TBM
- Omfattende logistikk
- Ventetid er kostbart





Forinjeksjon fra TBM

- Typisk oppsett av skjerm



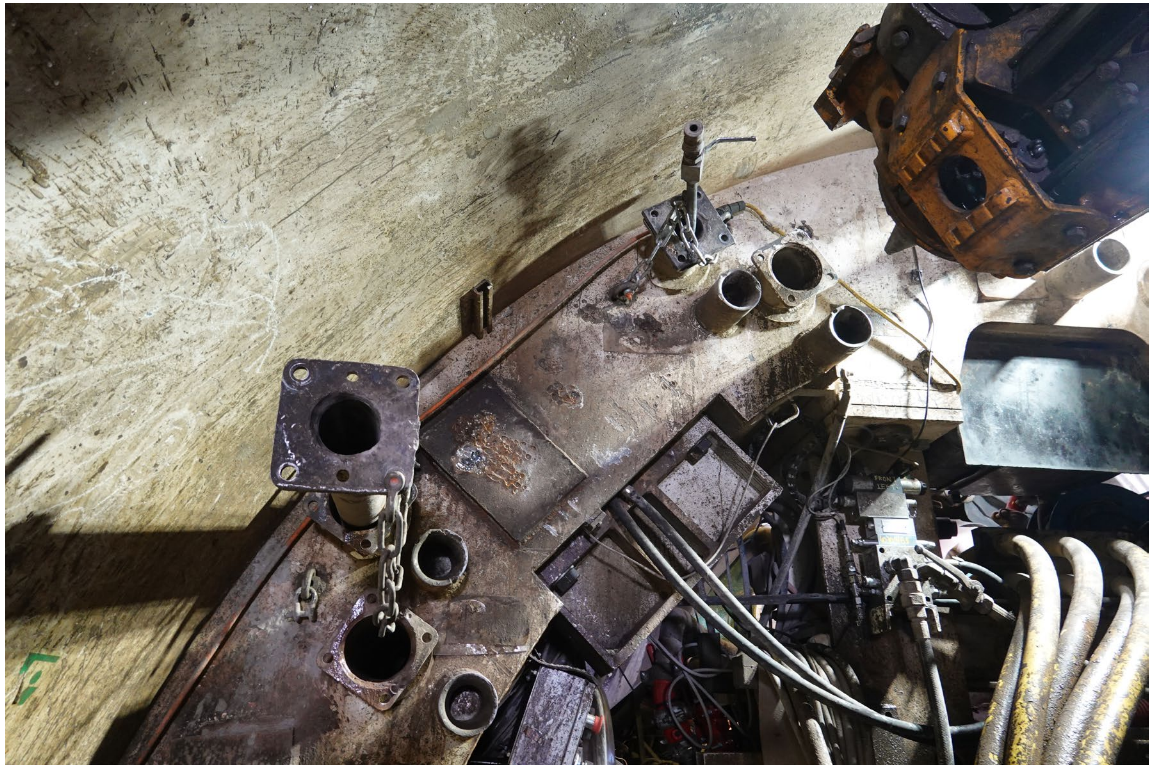
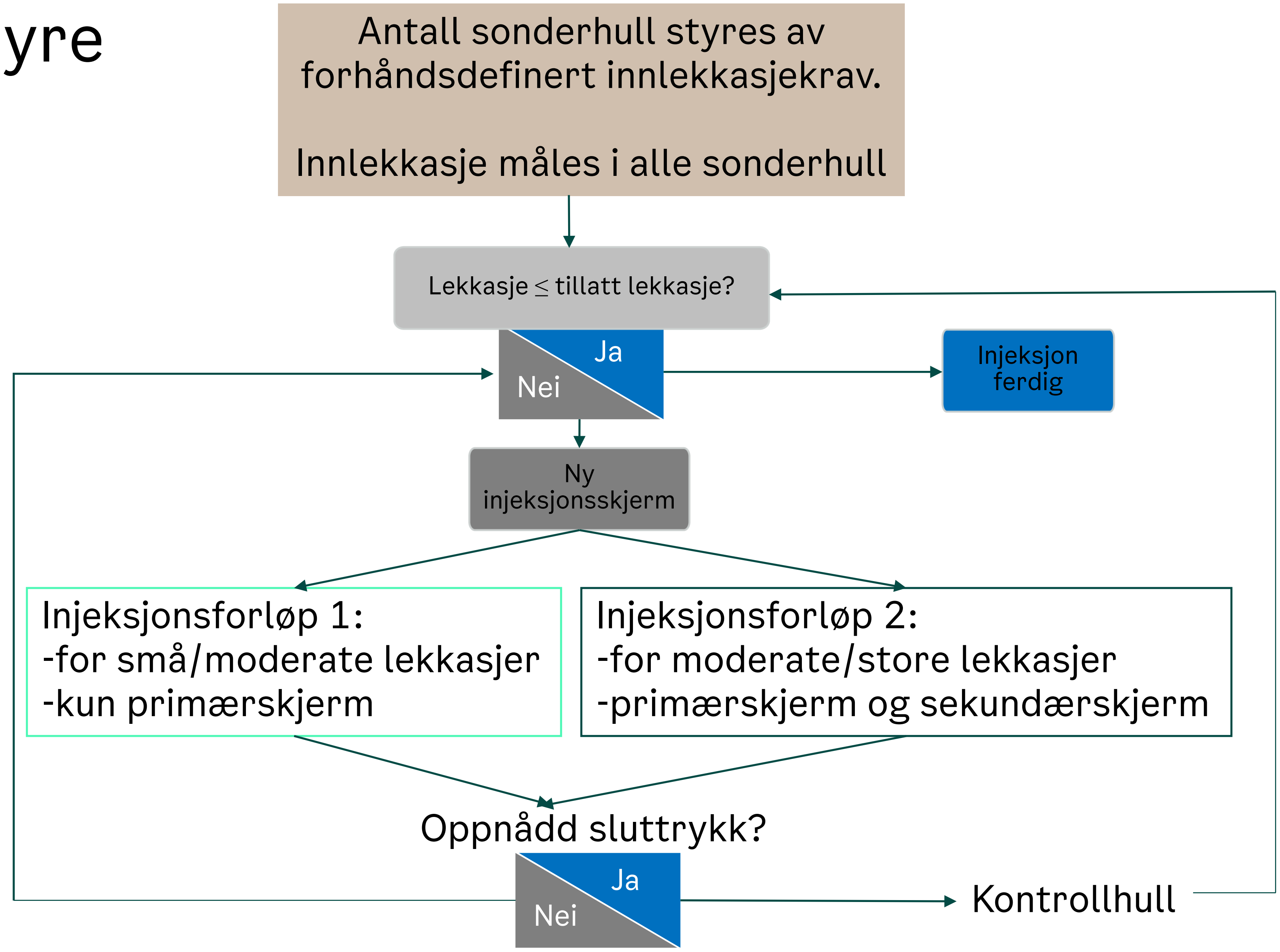


Foto: A. Hansen

Injeksjonsprosedyre

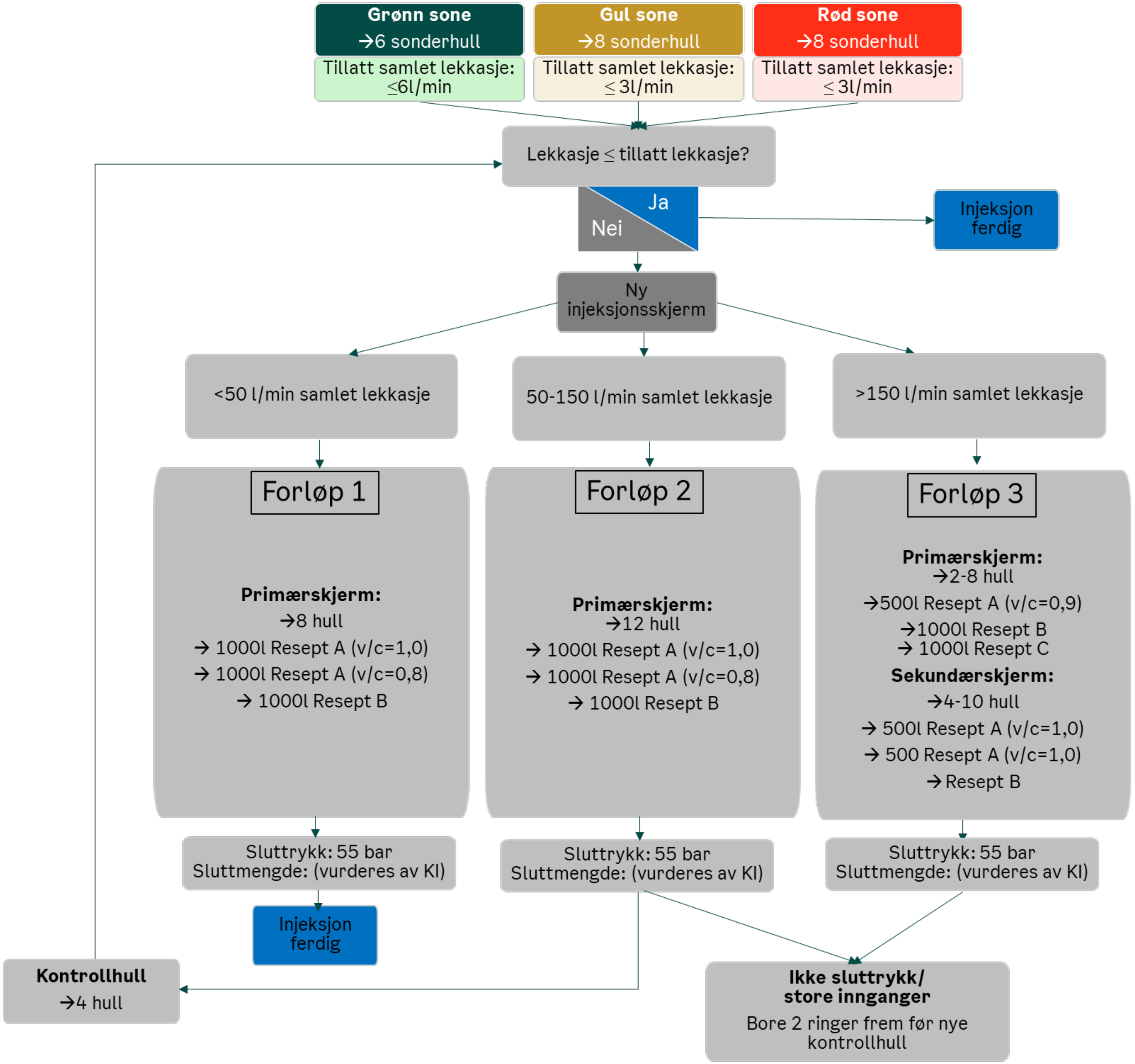
Resepter:

- Microsement
- v/c-tall 0,6-1,0
- Avbindingstid 45-120 min
- Hydratiseringsakselerator



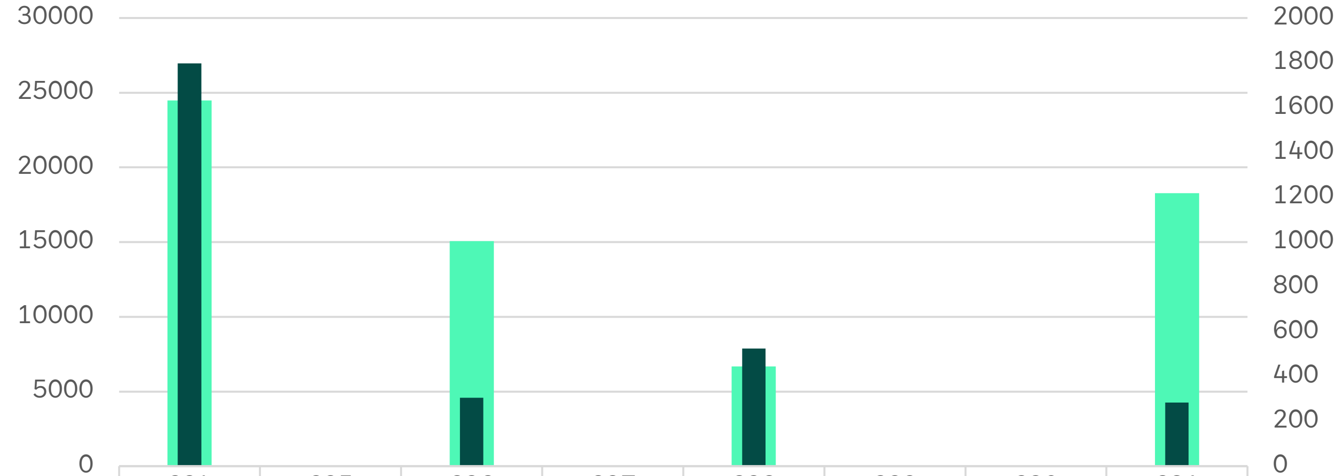
Oslo

Prosedyre for TBM-injeksjon fra Vefsrud (drenert løsning)



Generelt:
- → Mengder kan økes ved manglende trykkoppbygning
- → Stopp på mengde hvis stopptrykk ikke er nådd

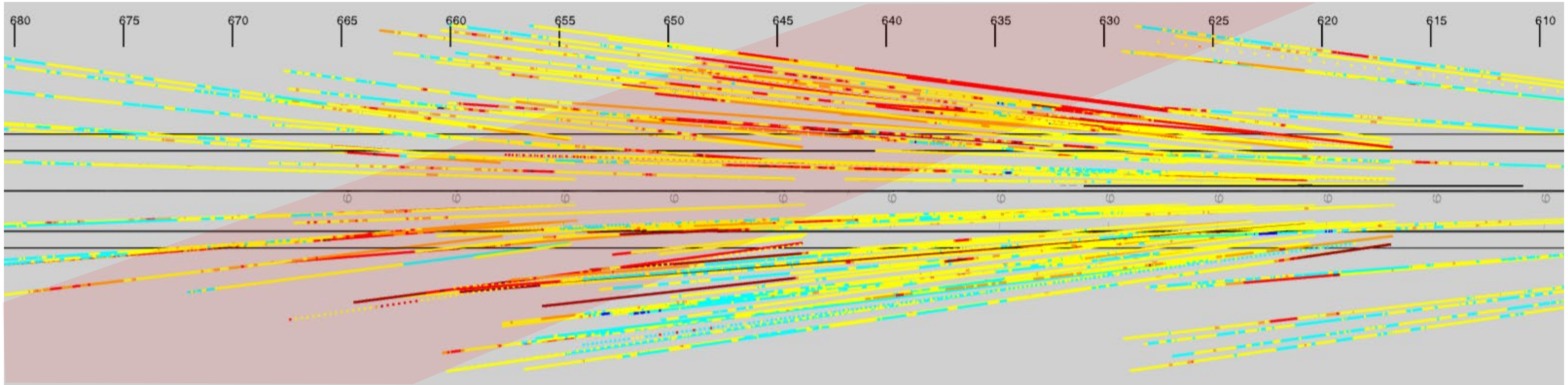
Injeksjon - lavatopp i RP2



	624	625	626	627	628	629	630	631
Injeksjon (kg tot)	24475,7	0	15074,6	0	6674,4	0	0	18279,3
Lekkasje (l tot)	1797	0	305,5	0	525	0		284,5

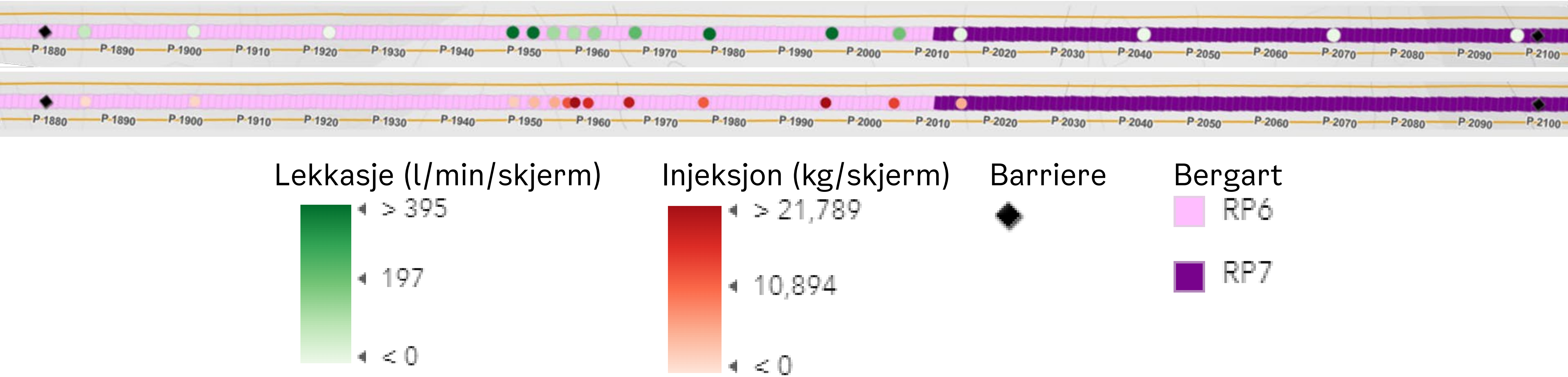
Pelnummer

Optisk televiewer



MWD (Bever)

Forinjeksjon fra TBM



Resultater og vannlekkasjer

- Noe restlekkasjer mellom pakninger og i porter
- Lekkasjeverdier i tråd med krav mht. omgivelser
- Punktvis etterinjeksjon i kledningen med PU i områder med tett kledning
- Overvåkning av trykkoppbygning bak betongkledningen
  - Vurderinger av behov for punktering av kledning i drenert del av tunnel

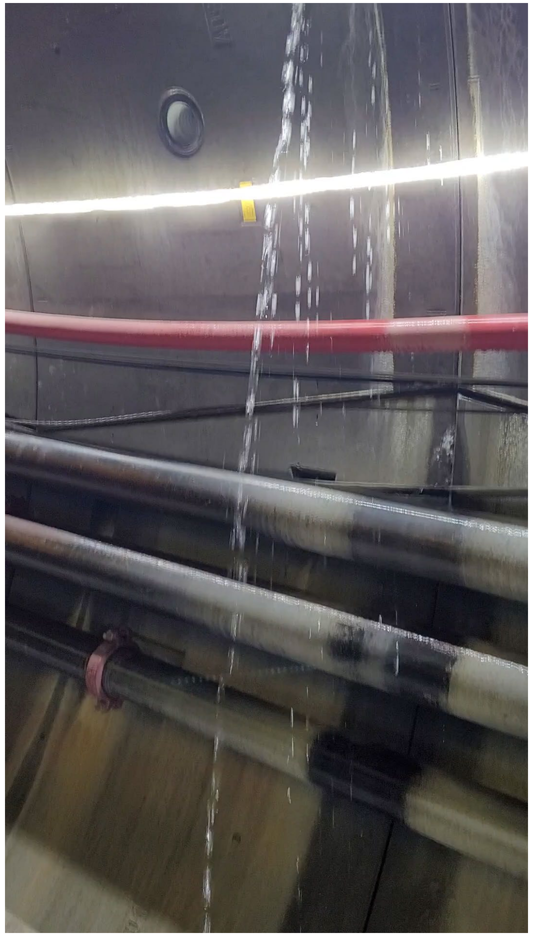
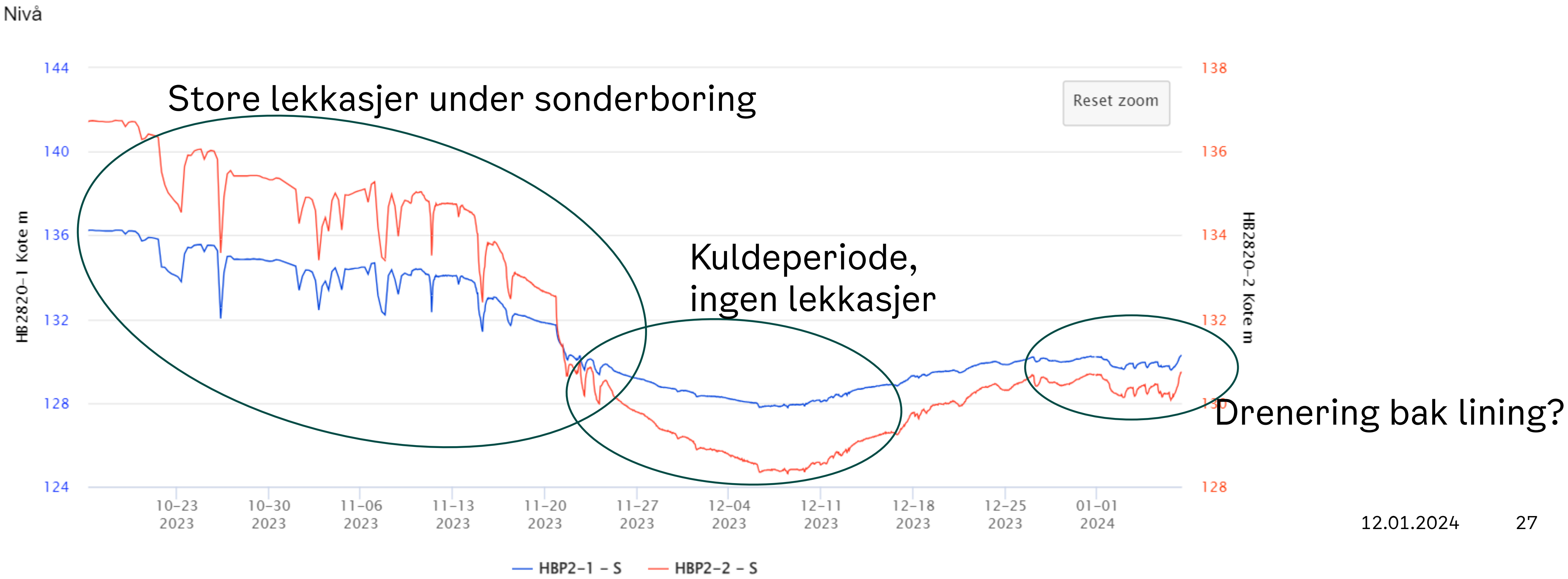


Foto: E. Larsen

Påvirkning av grunnvann

- Lekkasjer under sonderboring
- Drenering bak betonglining før bakfylling



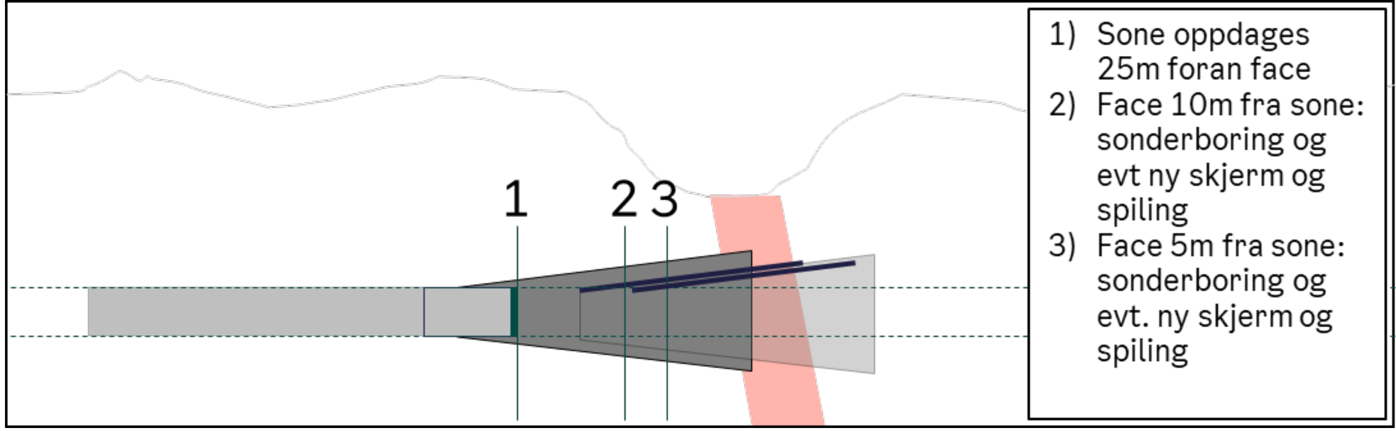
Kutterlevetid

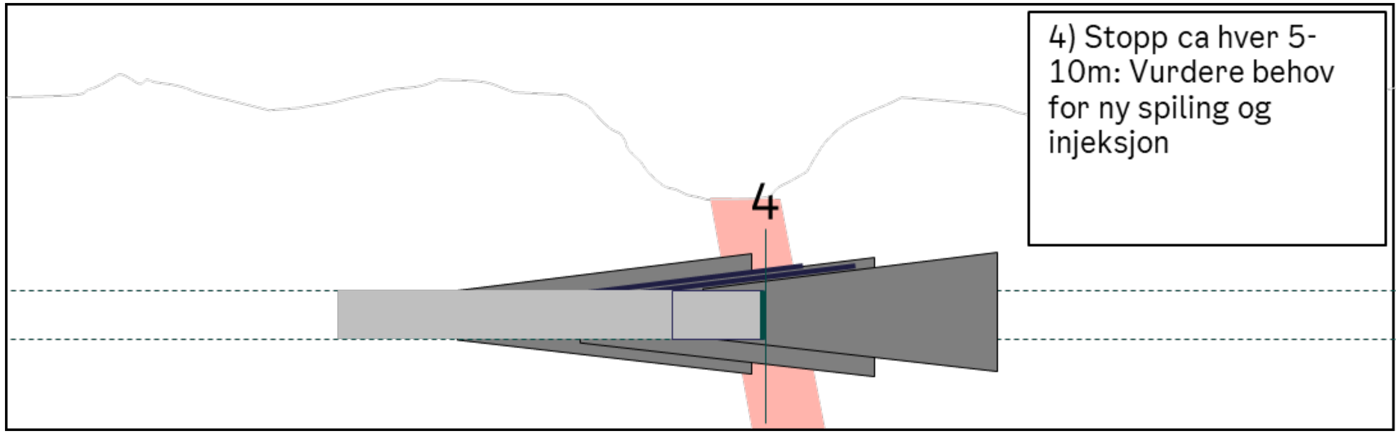
	Prognosis cutter life			Avvik		
	h/c	m/c	m3/c	h/c	m/c	m3/c
Vefsrud→	6,1	25,0	530,9	28 %	-4 %	
Huseby→	4,0	14,4	305,1	-5 %	-9 %	

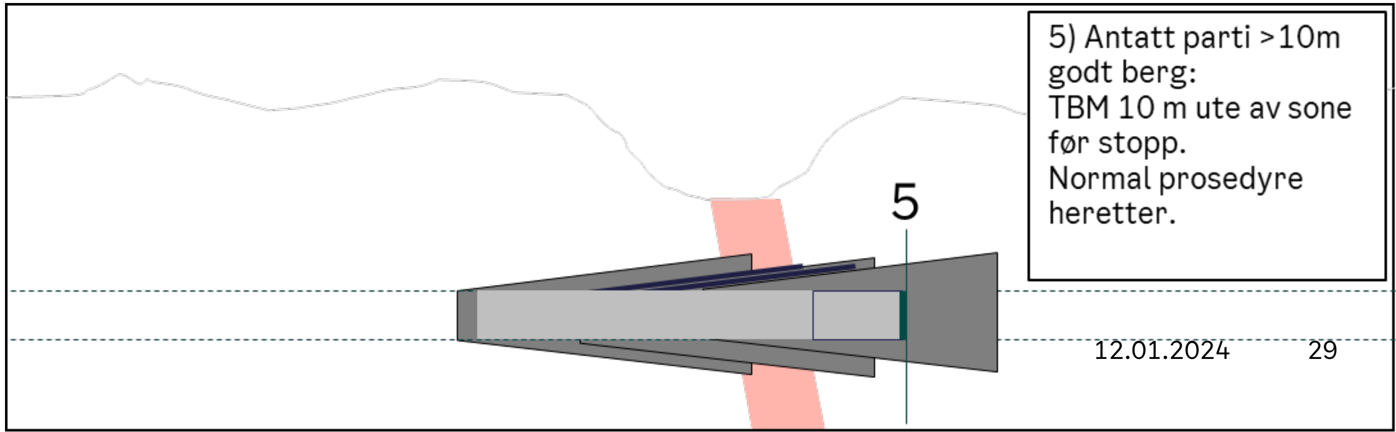
Bergart	Prøve	Lokalitet	DRI	BWI	CLI	CAI
Hornfels	K1, 149 m	Huseby, Oslo	41	19	11,8	3,4
Hornfels	K0518, 127 m	Huseby, Oslo	37	27	15	2,4
Hornfels	K0618, 178 m	Huseby, Oslo	35	22	32	2,8
Hornfels	K0118, 114 m	Grini, Bærum	50	15	56,5	1,8
Gabbro/monzodioritt	K1, 187 m	Huseby, Oslo	47	26	18,1	3,8
Gabbro/monzodioritt	K0418, 199 m	Huseby, Oslo	43	18	-	-
Gabbro/monzodioritt	K0518, 163 m	Huseby, Oslo	41	24	-	-
Syenitt	K3, 57 m	Huseby, Oslo	41	19	40,2	2,7
Syenittporfyr	K1, 107 m	Huseby, Oslo	31	56	6,2	4,6
Syenittporfyr	K0118, 79 m	Grini, Bærum	32	53	5,6	4,6
Basalt	K0718, 95 m	Kleiva, Bærum	46	17	51,7	2,4
Basalt	K0718, 139 m	Kleiva, Bærum	42	27	16,3	4
Basalt	K0818, 122 m	Mellom, Bærum	42	18	56,6	2,5
Basalt	K0818, 133 m	Mellom, Bærum	46	16	78,3	2,4
Rombeporfyr	K1018, 143 m	Bjerkevn., Bærum	54	14	97,3	1,6
Rombeporfyr	K1018, 163 m	Bjerkevn., Bærum	51	15	97,4	1,5
Rombeporfyr	K1018, 175 m	Bjerkevn., Bærum	48	16	85,7	2,6
Rombeporfyr	K0318, 31 m	Vefsrud, Lier	52	14	60,1	1,9
Rombeporfyr	K0318, 59 m	Vefsrud, Lier	58	12	60,3	2,5
Rombeporfyr	K0318, 86 m	Vefsrud, Lier	49	15	52,5	2,8

Svakhetssoner

- Prosjektet har utarbeidet en generell angrepsplan
- Spesifikke forberedelser og planer i forkant av hver sone



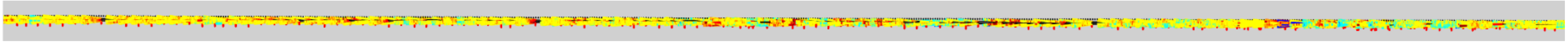




Sonderboringer avgjørende for vurderinger i dårlige soner

- Borerapporter, MWD og OTV gir informasjon om kommende bergforhold
- Vurderinger av bergmassekvalitet gjennom svakhetssoner
- Planlegging av neste stans for sonderboring.
- Viktig for å vurdere spesielle tiltak (ikke behov enda)
  - Enkeltskjoldmodus
  - Forsterket lining
  - Spiling

RP8 RP4 RP4 RP3 RP2 RP1



Mærradalen Lysakerelva Griniveien Ringgangen

Oppsummering

- Råvannstunnelen ca 30 % ferdig boret, godt an i forhold til fremdriftsplanen
- Forinjeksjon fra TBM i krevende hydrogeologiske forhold er fullt mulig
- Tidlige forberedelser og fokus på utstyr, injeksjonsstrategi og kompetanse er viktig
- Utvikling og tilpasning – innkjøring av ny maskin, utveksling av kompetanse
- Jevnlige gjennomganger av injeksjonsopplegg og geologiske forhold, i dialog med entreprenør

Takk for oss!