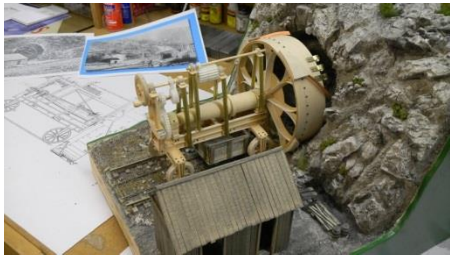
TAC Rock Tunnelling Workshop
Sheraton Wall Centre Hotel, Vancouver, BC
November 15-16, 2013



Mechanical Excavation
Jens Classen

Session 1:	**Principles of Rock Cutting, Rock Support and Logistics**
Session 2:	Risk Management – Dealing with expected and unexpected ground conditions
Session 3:	Industry Innovations

Special Thanks go to:

The Robbins Company

Herrenknecht AG

Aker Wirth

Atlas Copco

Sandvik

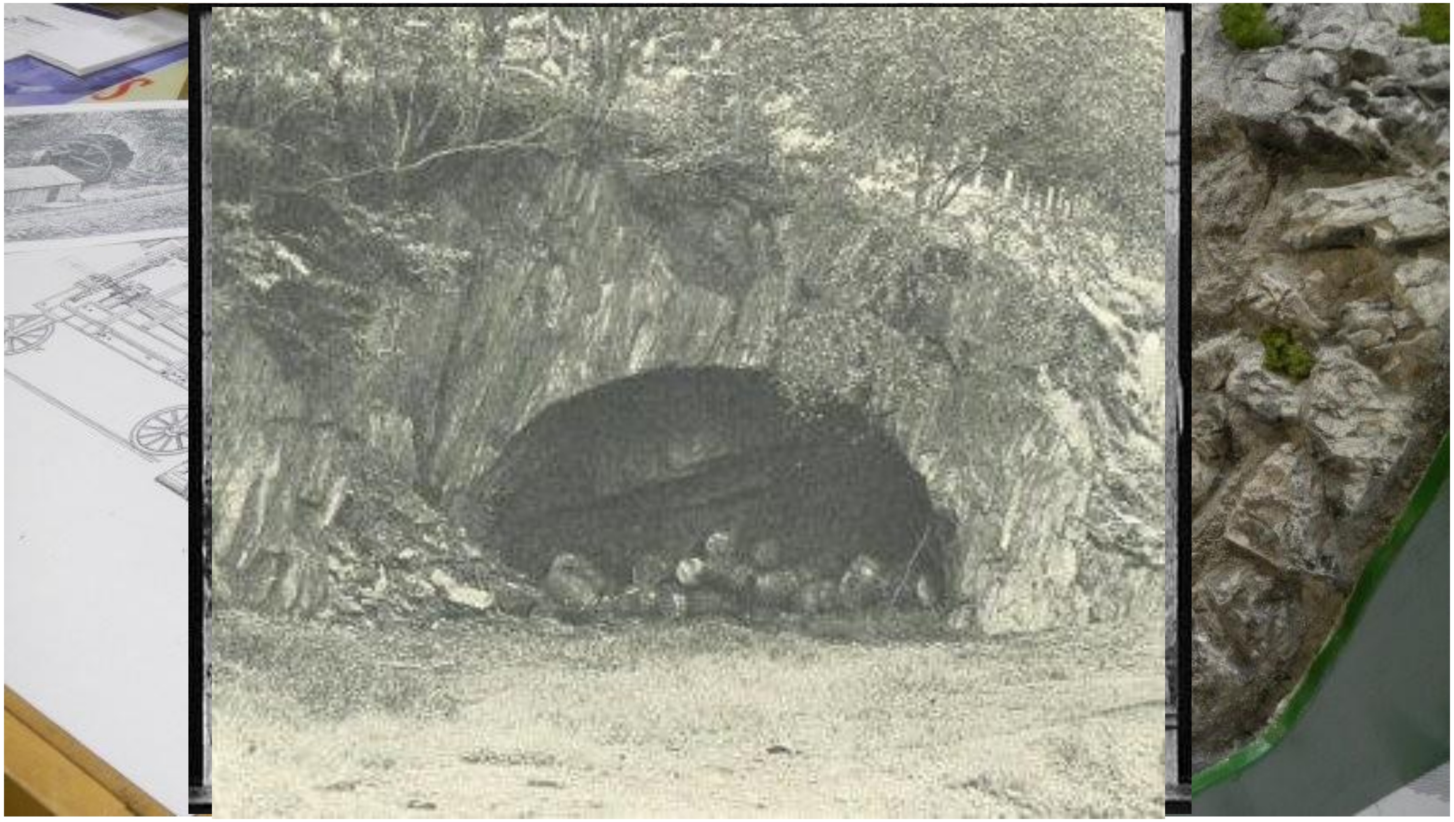
ROWA

Colorado School of Mines

NTNU Trondheim

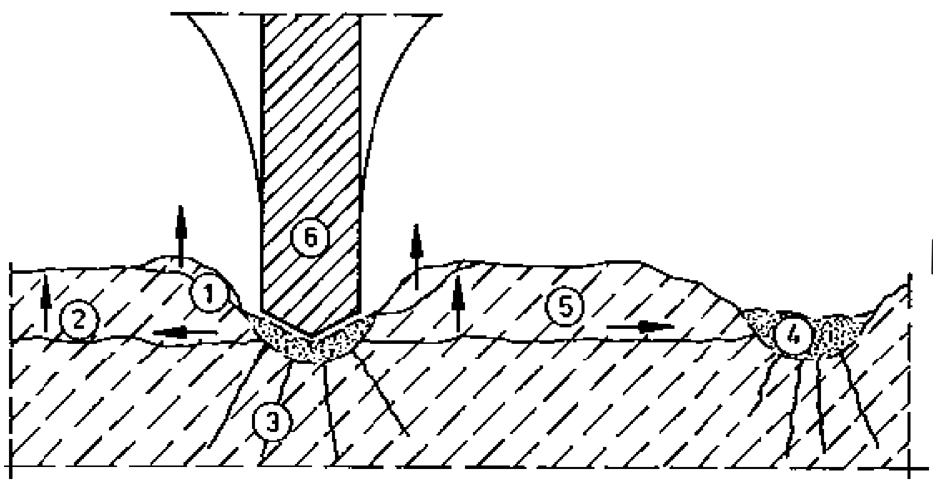
How it all started…

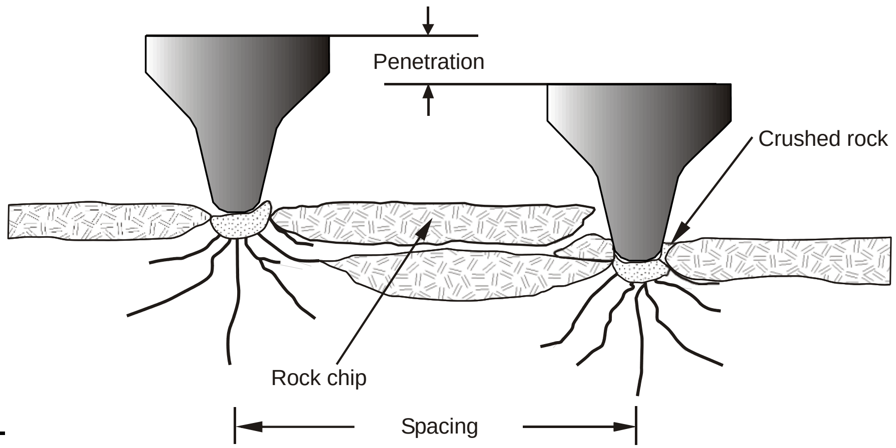
March 16th 1853: Wilson‘s Patented Stone-Cutting Machine started its work!



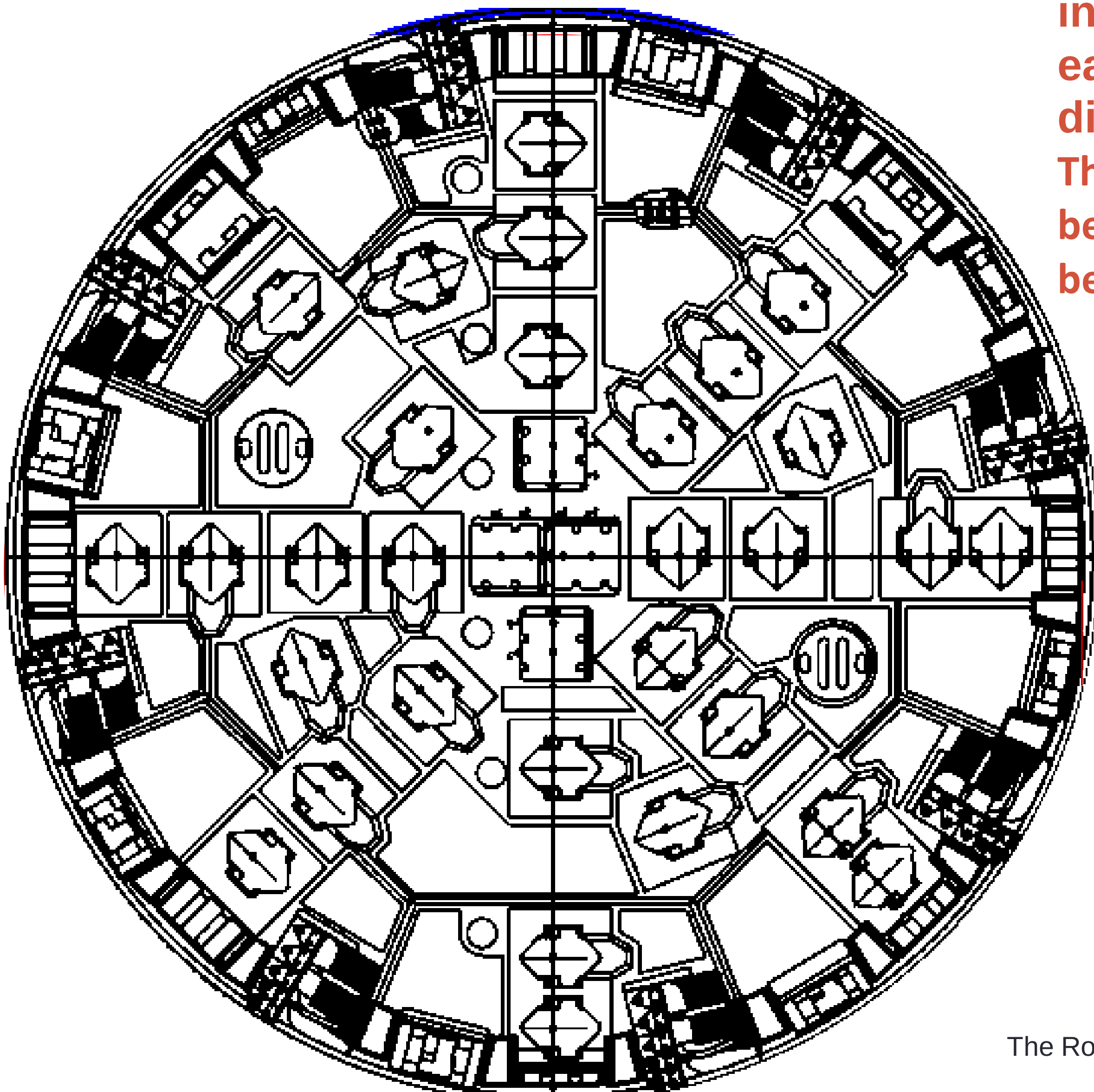
Rock Cutting process.

- The cutterhead of Hard Rock TBM´s are equipped with disc cutters.
- The disc cutters are pushed against the rock by the rotating cutterhead.
- The disc cutters form concentric circles on the rock face.
- Causing spalling by tension cracks between their tracks
- Causing shear failure





Rock Cutting process

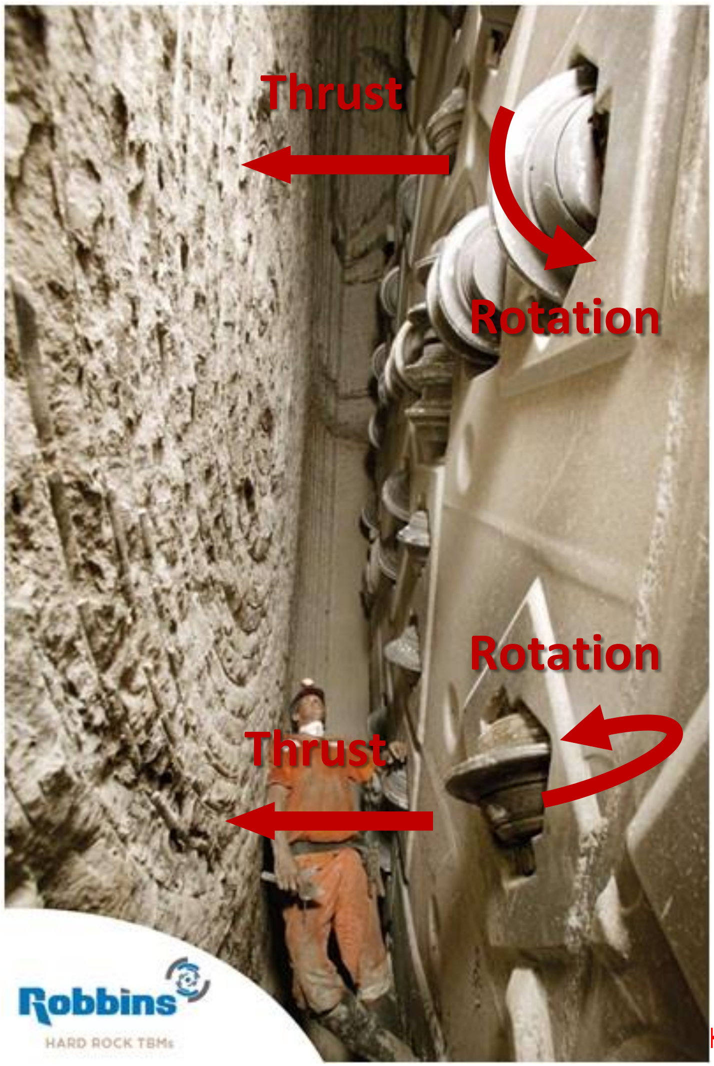


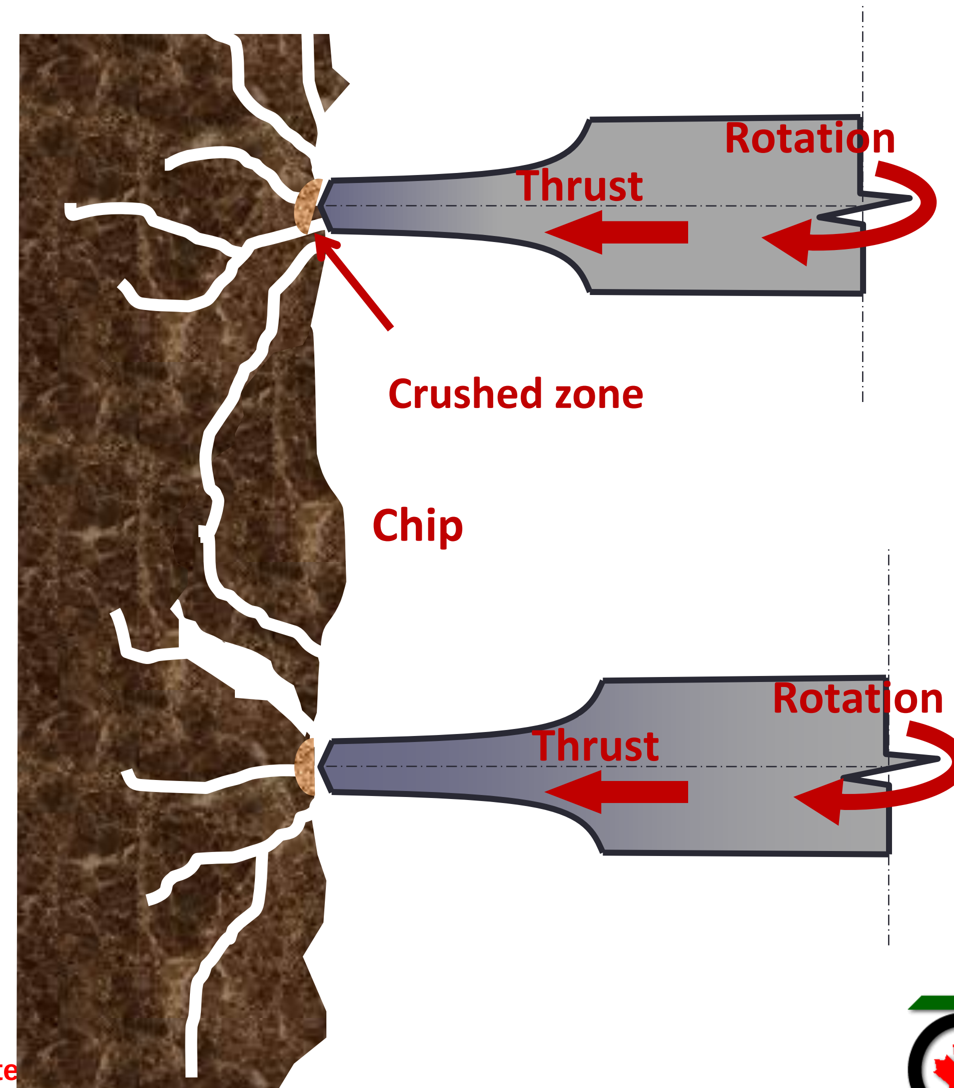
Disc cutters are positioned in such a way that each cutter has different track radius.

The 'spacing' = the distance between the tracks is chosen to be equal for all face disc cutters.

The Robbins Company

Chip formation between two adjacent cutters

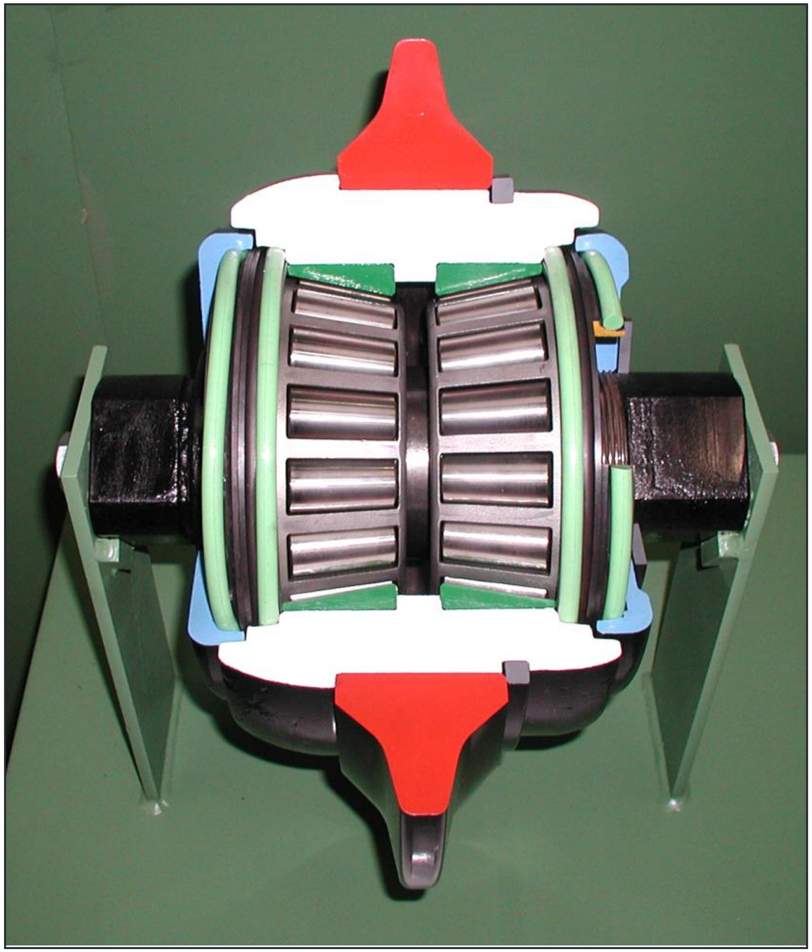




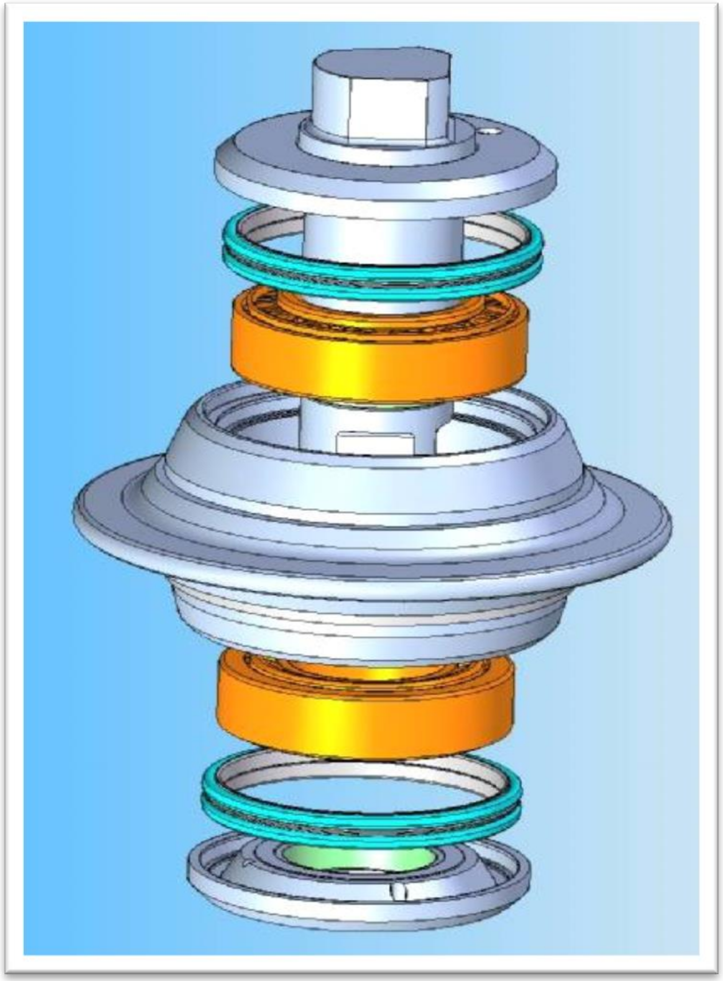
Rock chips

Rock Cutting process

Disc cutters

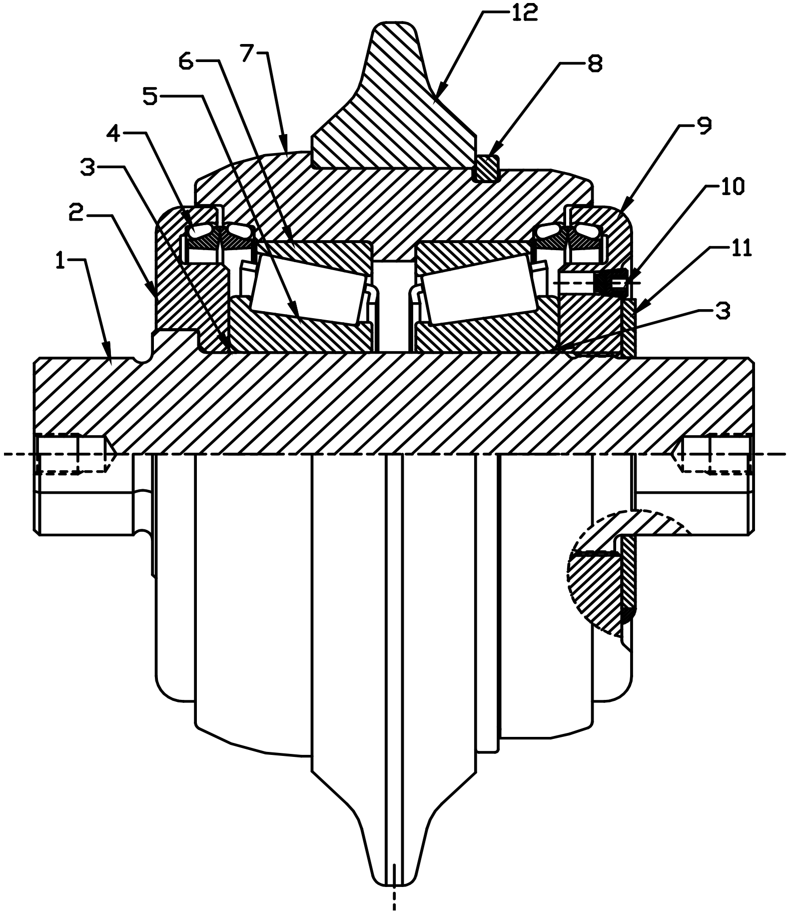


Source: Herrenknecht AG



Source: Robbins

Typical 17" Disc Cutter



1	Shaft
2,9	Seal Retainers
3	O-Ring
4	Seal Set
5,6	Roller Bearings
7	Hub
8	Split Ring
10	Plug
11	Tab Plate
12	Cutter Ring

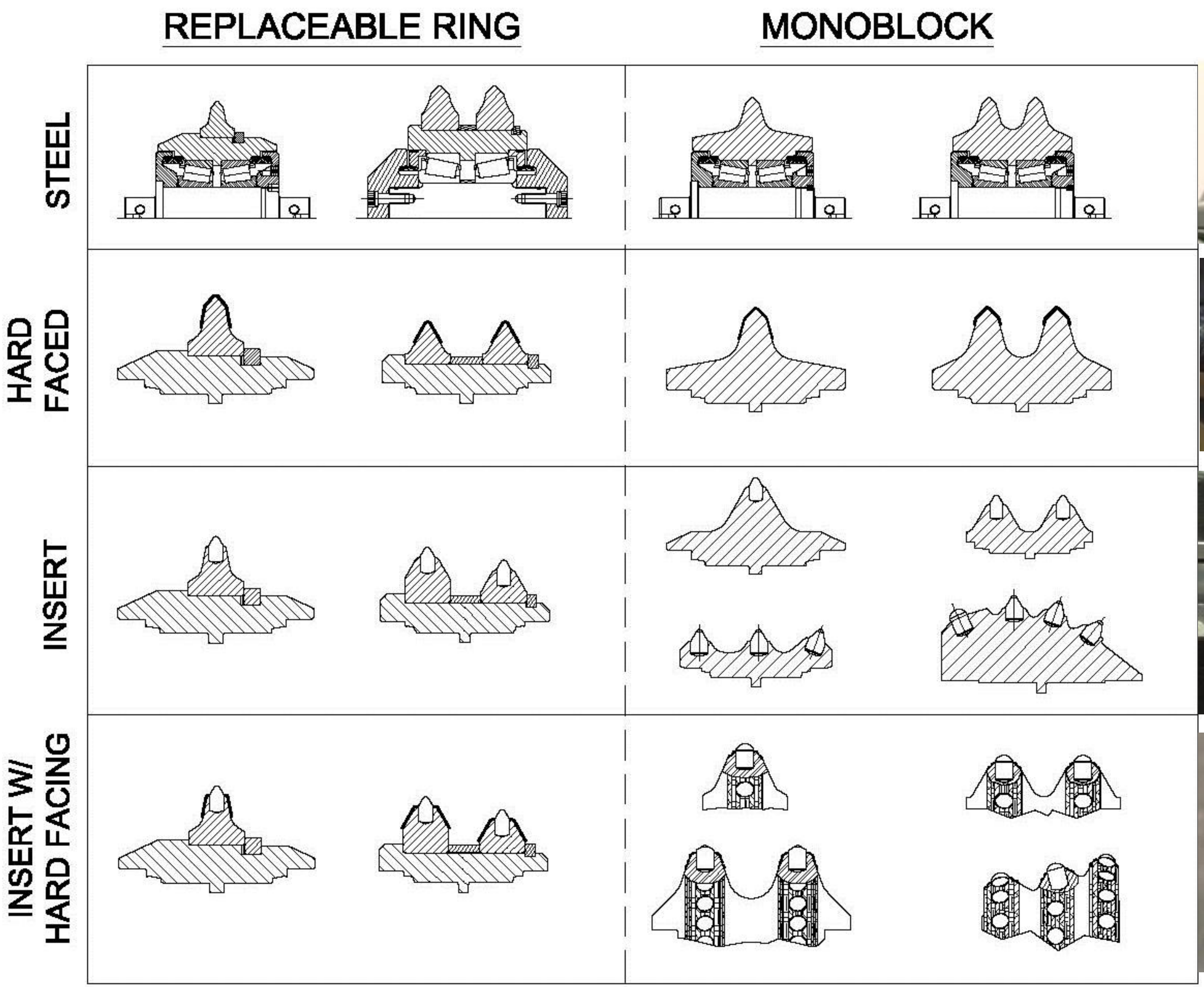
Source: Herrenknecht AG

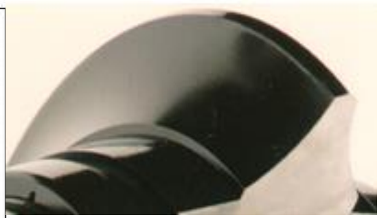
Disc cutter specifications:

- Diameter:	from 6“ to 21“
- Hardness:	from 50-58 HRC (Rockwell Hardness)
- Tip width:	from 12mm to 25mm
- Type:	Single Disc, Twin Disc, Monoblock
- Torque:	from 20Nm to 40Nm
- Bearing type:	straight or conical
- Lubrication:	oil or grease
- Tip type:	hardfacing, tip welding, inserts etc.

What do I choose? → **No golden rule ☹**

Disc cutter specifications:





TBM Performance factors

- Geology → given
- TBM layout → based on geology
- Organisation → self-defined

Geology and TBM layout will define the theoretical performance of the TBM.

The Organisation (Personnel, Logistics etc.) will define the practical performance of the TBM.

All factors will determine the schedule and the overall costs of the project.

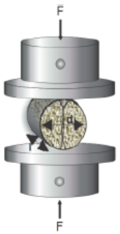
Main factors to be determined in advance are **penetration** and **cutter life.**

Geological background: rock classification.

- Unconfined Compressive strength (UCS)

The UCS is measured in Mega Pascal (MPa) and is a characteristic value for the axial force needed to break a rock specimen.

- Tensile Strength (TS)



The TS is measured in Mega Pascal (MPa) and is a characteristic value for the radial force needed to break a rock specimen.

In combination with the UCS, the rock can be classified as „brittle“ or „ ductile

- Cerchar Abrasivity Index (CAI)

The CAI is an indication for the abrasivity of the rock. A steel needle is scratched over a rock specimen. The wear of the needle is measured to receive the CAI value (ranges from 0 to 6).

- Rock quality Designation(RQD)

The RQD is a modified core recovery percentage that measures the length of sound rock pieces (> 100mm), gained in a core run.

Geological background: rock classification.

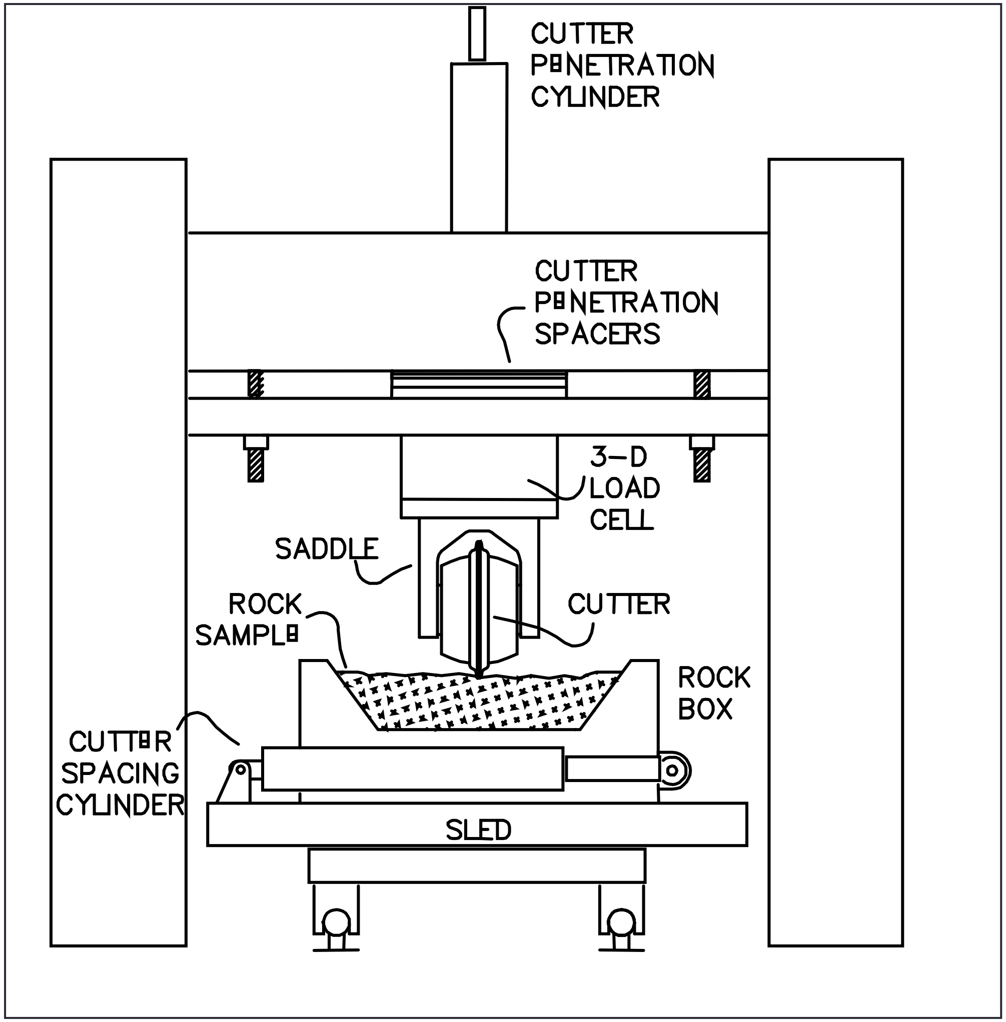
- Rock Mass Rating (RMR)

  The rock mass rating (RMR) system is a geomechanical classification system for rocks, developed by Z. T. Bieniawski between 1972 and 1973. The RMR is a characteristic value for the quality of the rock.
  The RMR is specified by 6 parameters, e.g. UCS, RQD. (ranges from 0 to 100)

	Rock Mass Rating (Rock class after Bieniawski)				
Rating	100 – 81	80 – 61	60 – 41	40 – 21	<20
Classification of rock mass	Very Good	Good	Fair	Poor	Very Poor
Support TBM	No to low support		Medium support		Heavy support

CSM Model: Concept

- Analytical model
- Linear Cutting Test
- detailed consideration of cutter disc



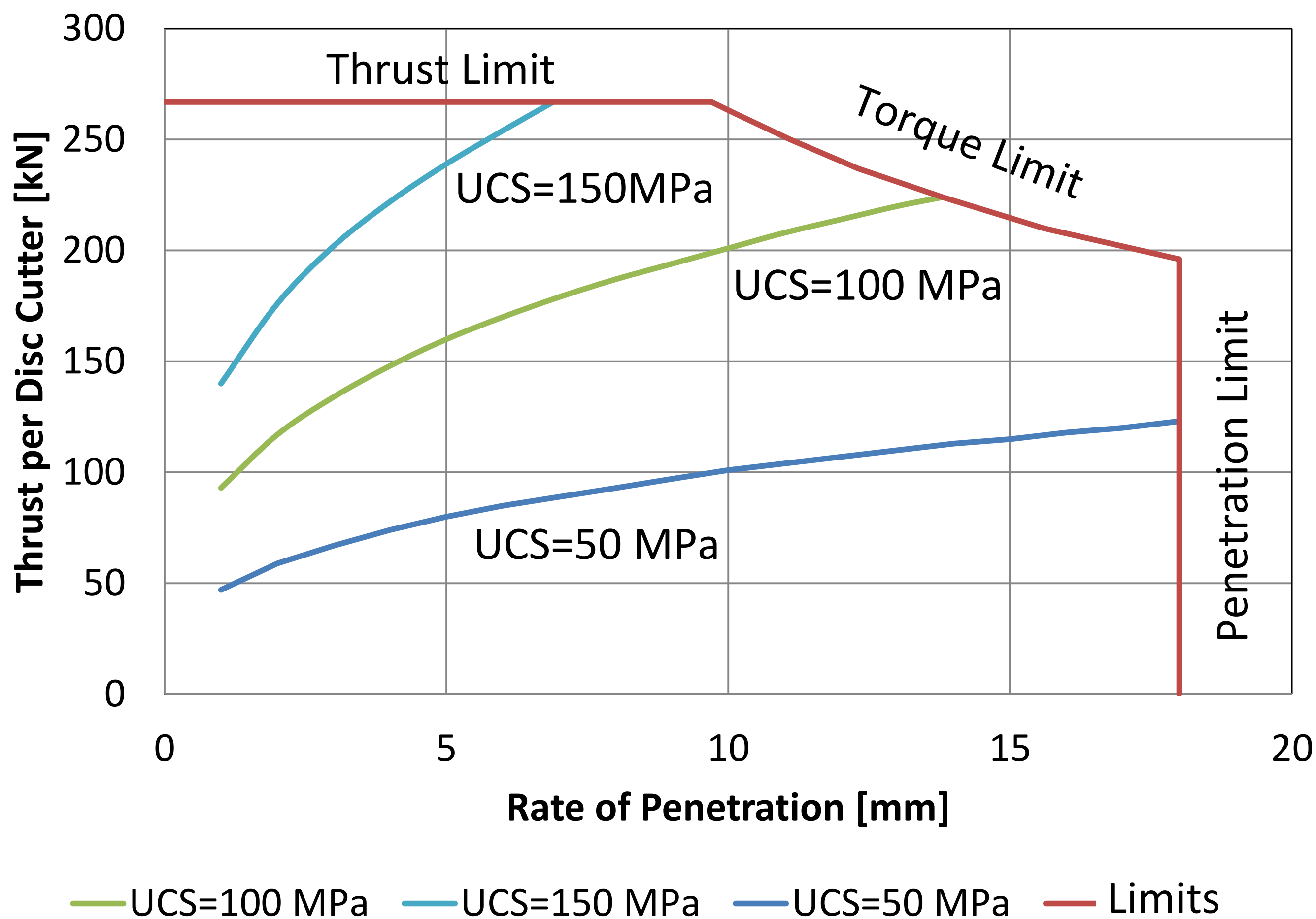
CSM Linear Cutter Tests

CSM Linear Cutter Tests

Input parameters

- Geotechnical
  - Uniaxial compressive strength (UCS)
  - Brasilian tensile strength (BTS)
  - Cerchar Abrasivity Index (CAI)
- TBM features
  - diameter and width cutter ring
  - spacing
  - maximum thrust force per cutter
  - installed power
  - rotation speed

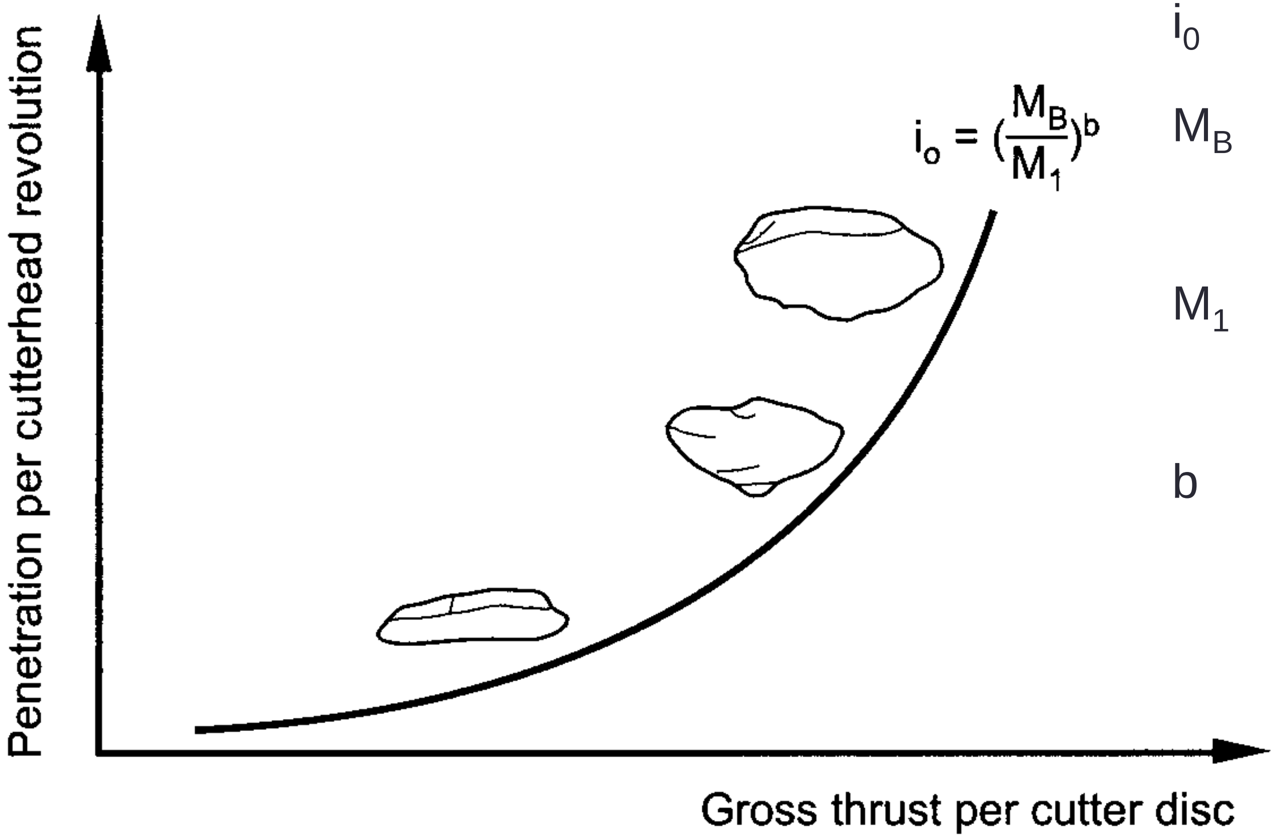
Penetration limits



NTNU model: concept

- Norwegian Technical University in Trondheim, Norway
- Empirical model based on:
  - Analysis of TBM tunnels in Norway
  - 35 headings
  - Total length: approx 250 km
  - Diameters: 2,3 m to 8,5 m (majority small diameter, hydro power projects)
- Prediction of:
  - Penetration
  - Cutter Consumption

Penetration model



i_0 Penetration [mm/rev]

M_B Maximum thrust per disc cutter [kN]

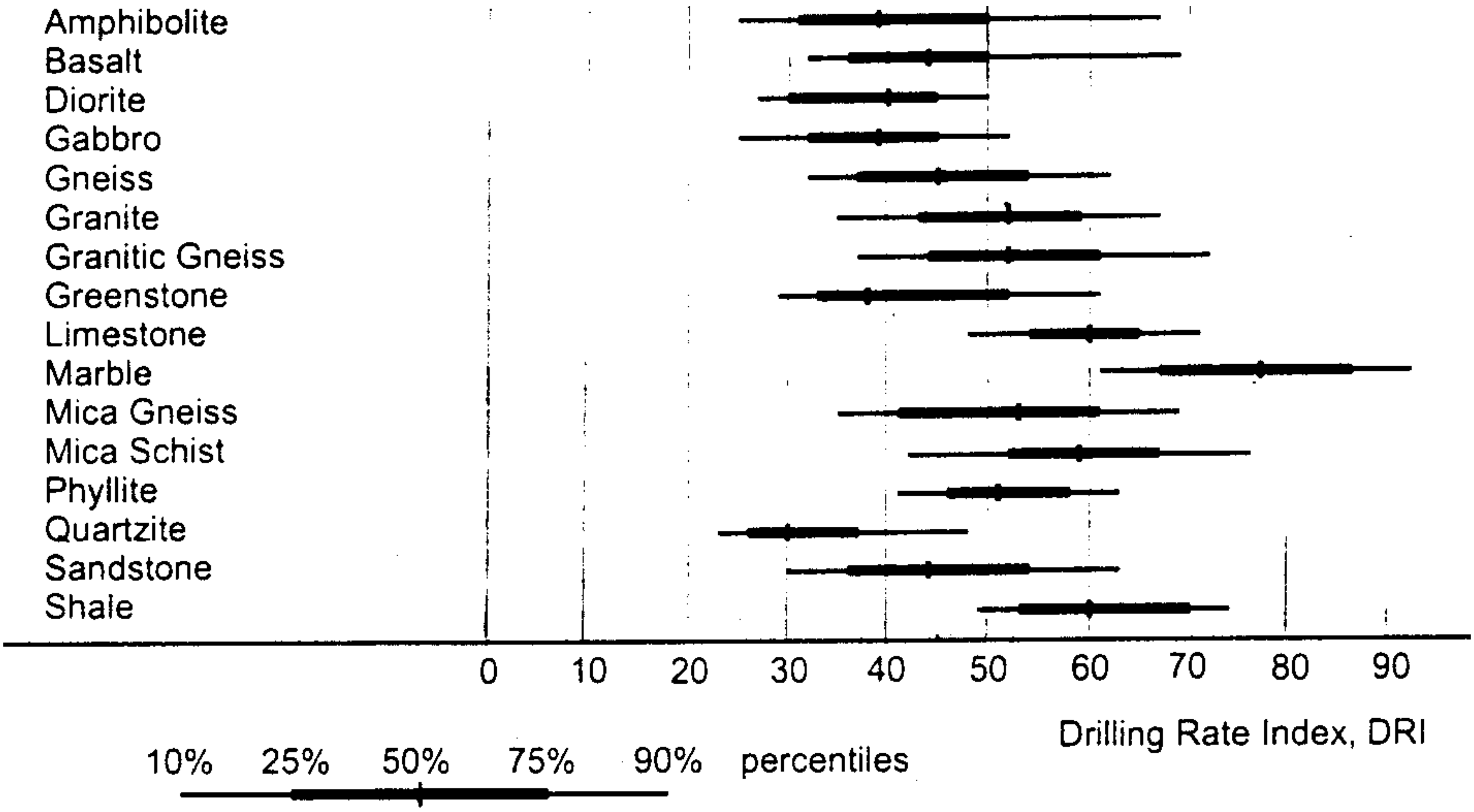
M_1 critical thrust per disc cutter [kN]

b penetration coefficient

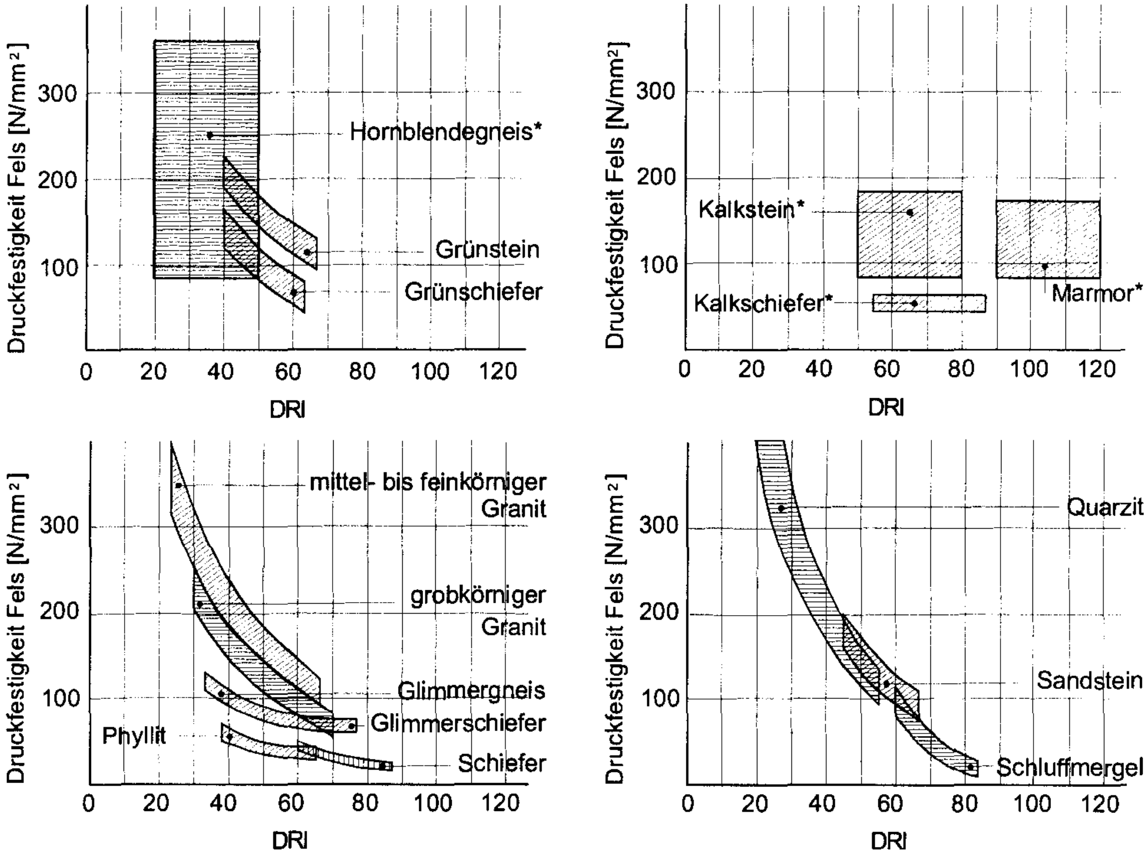
Input parameters for penetration prediction

- Rock properties
  - Drilling Rate Index (DRI)
  - Porosity
- Rock mass properties
  - Discontinuity spacing
  - Orientation of discontinuities
- TBM input parameters
  - Maximum thrust per disc cutter
  - Diameter of cutter ring
  - Exavation diameter of TBM
  - Spacing of disc cutters

Drilling Rate Index



Drilling Rate Index



*) Diese Felsarten weisen über den gesamten Druckfestigkeitsbereich eine grosse Streuung der DRI-Werte auf. Hier wird eine genauere Untersuchung der Bohrbarkeit angeraten.

Determination of DRI (Step 0)

- The Drilling Rate Index is determined by use of the brittleness (S_{20}) and the surface hardness (SJ).
- The brittleness value is evaluated as the percentage of a pre-sieved fraction that passes through the finer sieve after 20 impacts.
- The Sievers' J-value is defined as the penetration of the drill bit in 1/10mm after 200 revolutions.

Determination of DRI (Step 0)

Calculation (Step 9)

- Equivalent fracturing factor

$$k_{ekv} = k_s \cdot k_{DRI} \cdot k_{por}$$

- Equivalent thrust per cutter

$$M_{ekv} = M_B \cdot k_d \cdot k_a$$

M_B	maximum thrust per cutter [kN]
M_{ekv}	equiv. thrust [kN]
k_{ekv}	equiv. fracturing factor [-]

Calculation (Step 12)

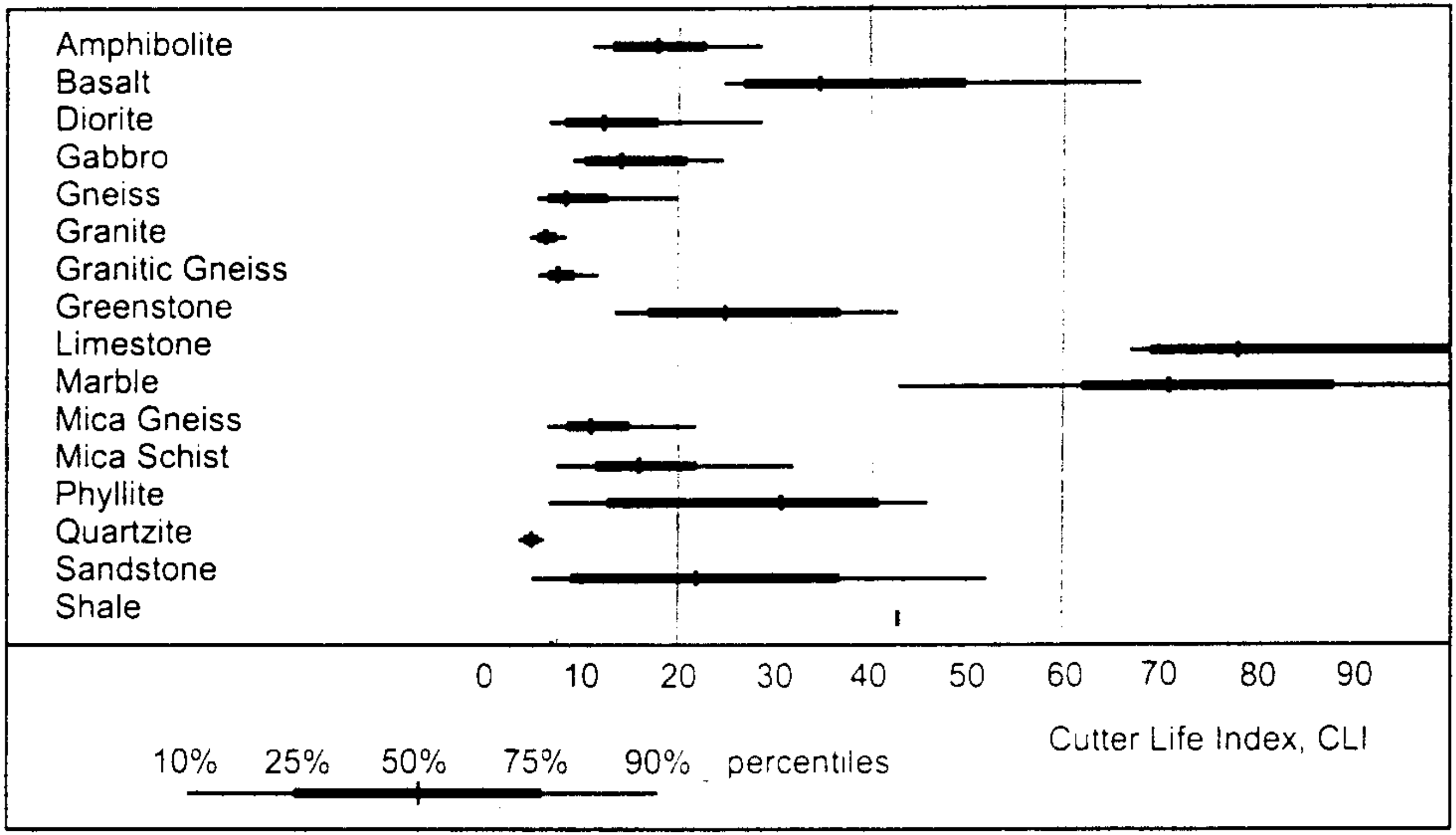
- Calculate base penetration

$$i_0 = \left(\frac{M_{ekv}}{M_1} \right)^b$$

Input parameters for wear prognosis

- Geotechnical
  - Cutter Life Index (CLI)
  - Quartz content
  - Penetration
- TBM
  - Excavation diameter
  - Cutterhead RPM (rotational speed)
  - Number of disc cutters
  - Diameter of disc cutters

Cutter Life Index



Determination of CLI (Step 0)

- The Cutter Life Index is determined by use of the surface hardness (SJ) and the wear capacity on cutter ring steel (AVS).
- The Abrasion Value Cutter Steel (AVS) is defined as the weight loss of the tungsten carbide and the cutter ring steel test pieces in mg after 5 min and 1 min respectively.

Calculation (Step 6)

- Cutter life (hours/cutter)

$$H_h = H_0 \cdot k_D \cdot k_Q \cdot k_{RPM} \cdot k_N / N_{TBM}$$

i_0	Penetration [mm/rev]
RPM	Rotation speed [rev/min]
N_{TBM}	Number of disc cutters

- Cutter life (m^3/cutter)

$$CutterRingLife = \frac{D^2_{cutterhead} \cdot \pi}{4} \cdot i_0 \cdot RPM \cdot \frac{60}{1000} \cdot H_h$$

Cutter Management

Cutter Management in hard rock includes:

- Right choice of cutters
- Constant monitoring of cutter wear
- Constant monitoring of cutter damages
- Constant monitoring of cutter housings and protection plates
- Cutter change optimisation
- Cutter shop including experienced personnel on site
- Spare parts storage management
- etc.

Wear Patterns

normal wear

blocked disc

crack, brittle fracture

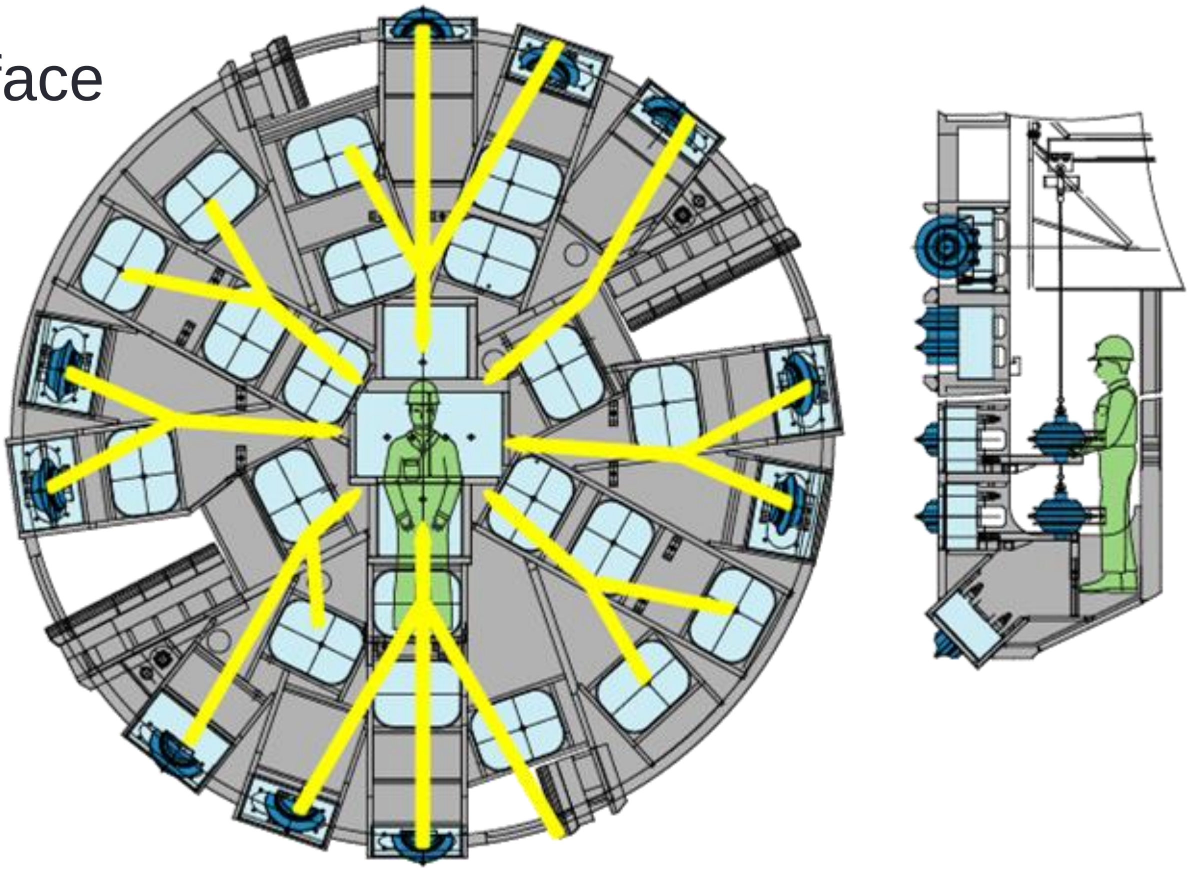
chipping

mushrooming

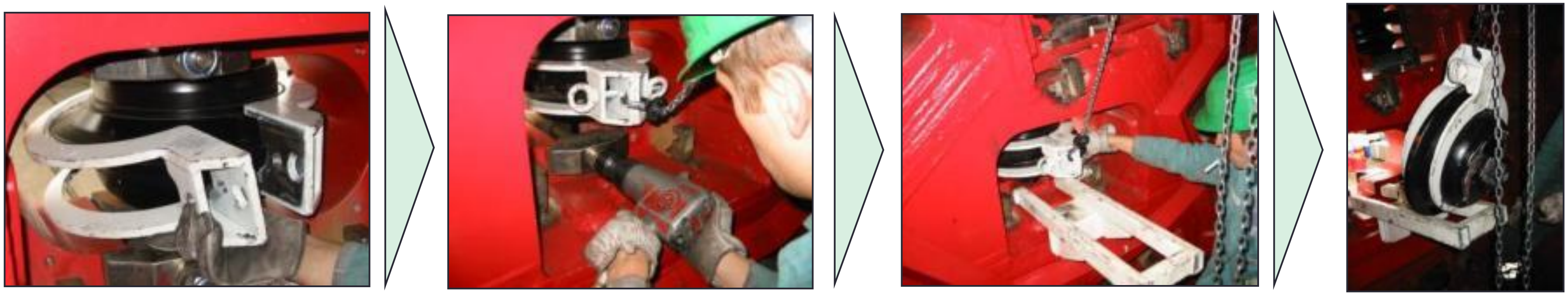
wear at housing

Cutter change

- Backloading cutters
- No access to tunnel face required



Cutter change



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TBM Layout: Cutterhead

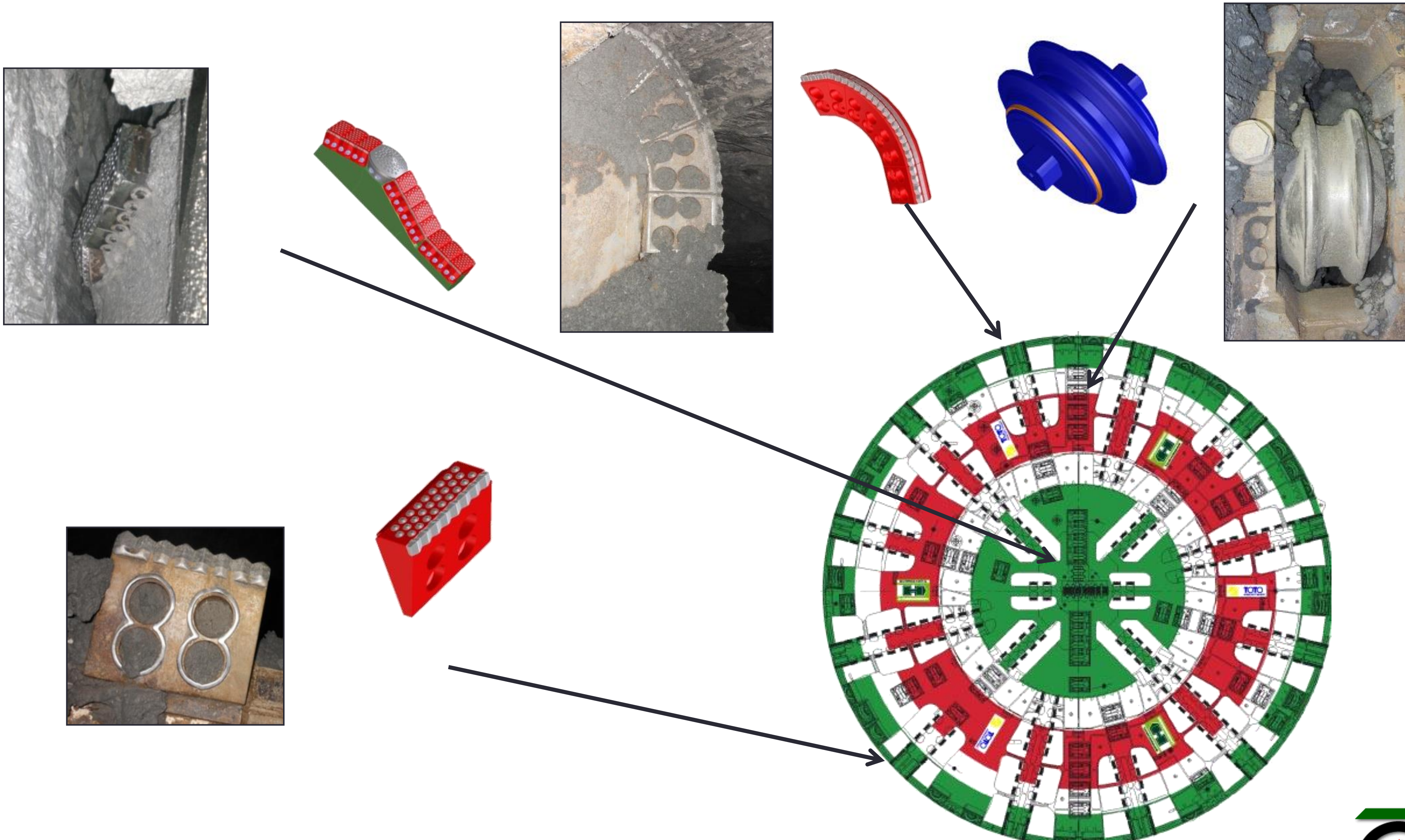
Design requirements:

- Robust steelwork
- Number and distribution of cutters
- Number, width and distribution of buckets
- Type of bucket lip fixation
- Opening rate
- Type of wear protection
- Curve radius in gauge area
- Number and distribution of sprinklers
- Number and height of grill bars
- Number of manholes

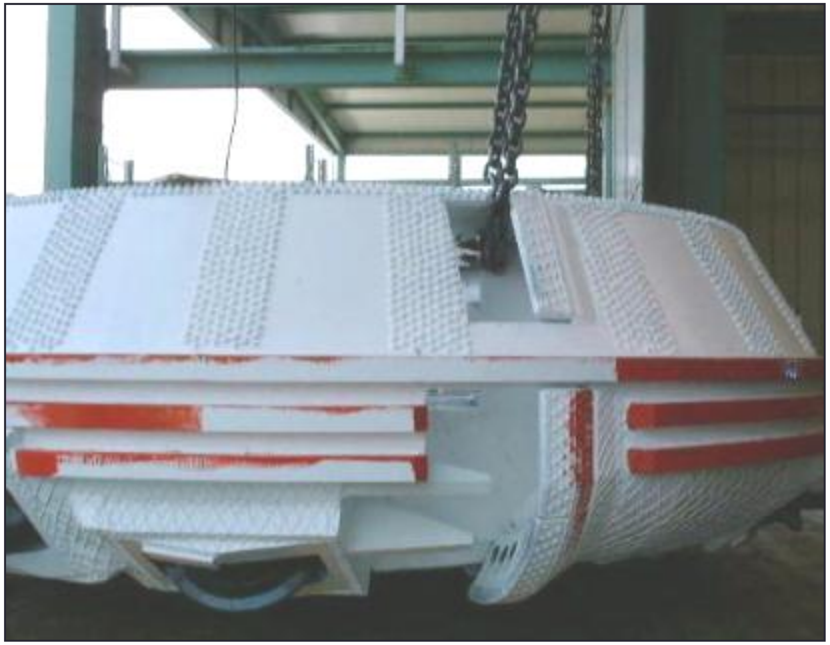
- → influencing factors to be discussed in Session 2

TBM Layout: Cutterhead (hard rock)

TBM Layout: Cutterhead (mixed face)

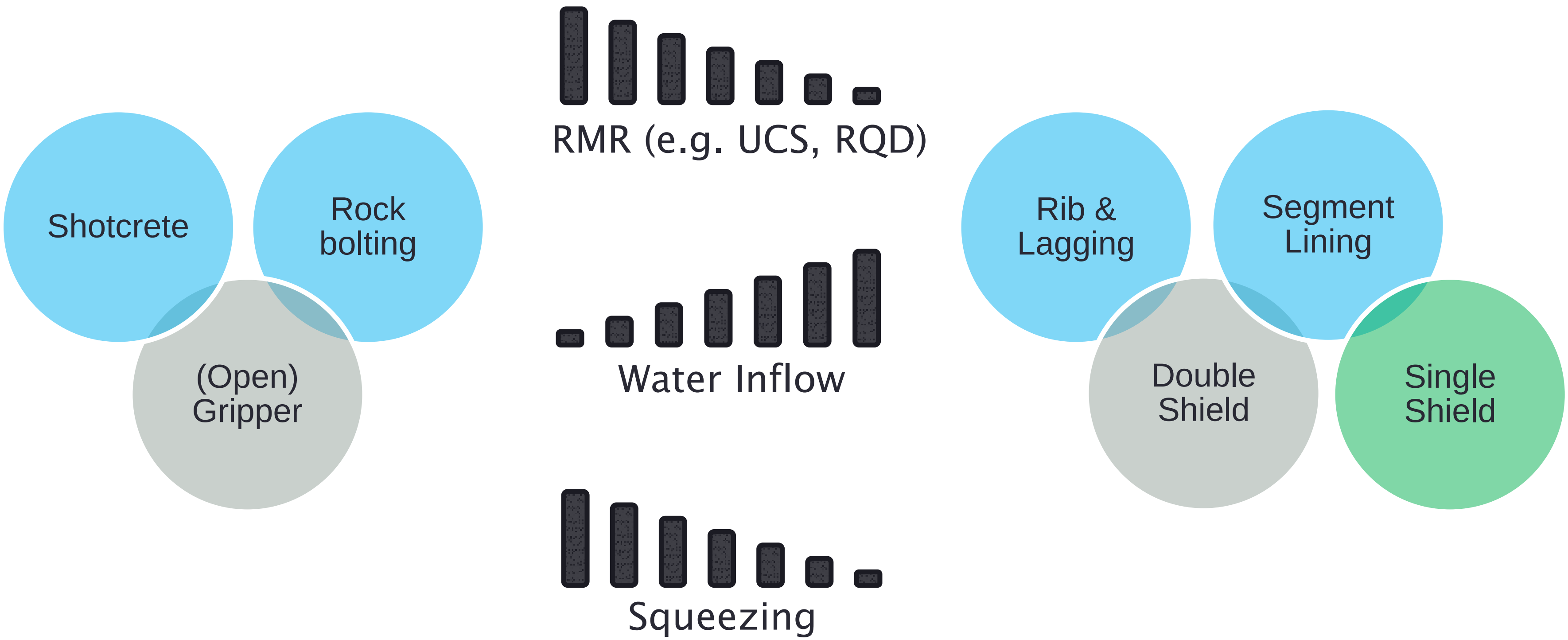


Wear protection



Choice of machine concept

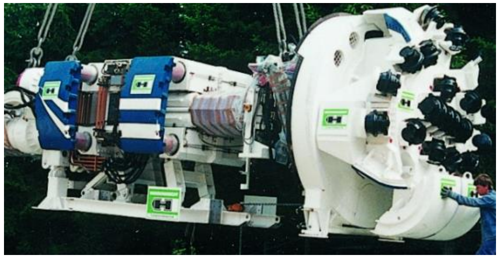
ACCORDING TO ROCK CLASSIFICATION AND TUNNEL LINING.



Choice of machine concept

MACHINE TYPES FOR ROCK CONDITIONS

Non-Shielded TBMs



- Mainbeam Gripper TBM
- Cutting Ø > 3600mm

Partly-Shielded TBMs

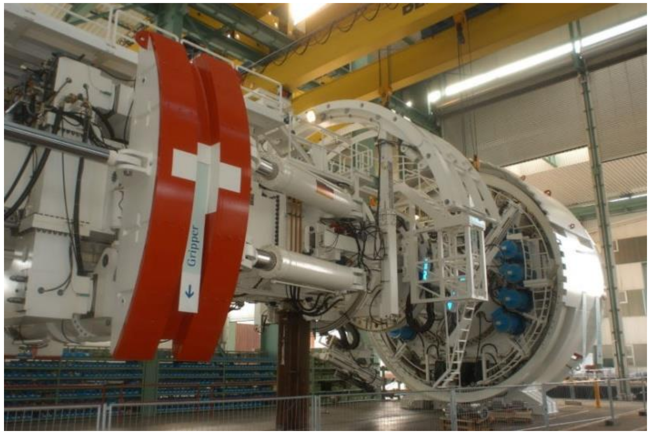
- Micro Gripper TBM
- Cutting Ø > 2580mm

Shielded TBMs

- Single Shield TBM
- Cutting Ø > 2800mm

- Double Shield TBM
- Cutting Ø > 2800mm

Open Hard Rock Gripper TBM‘s



- Length: 180 – 450m
- Weight: 2‘000 -3’000tons
- Diameter: 2m -14m
- Cutters: standard today 19"
- Load per cutter: 32 tons
- Load distribution by Gripper
- Active rock support by bolts, wire mesh, shotcrete, steel ribs
- Mucking out by belt or train

Open Hard Rock Gripper TBM‘s

TBM Operations: Primary Rock Support

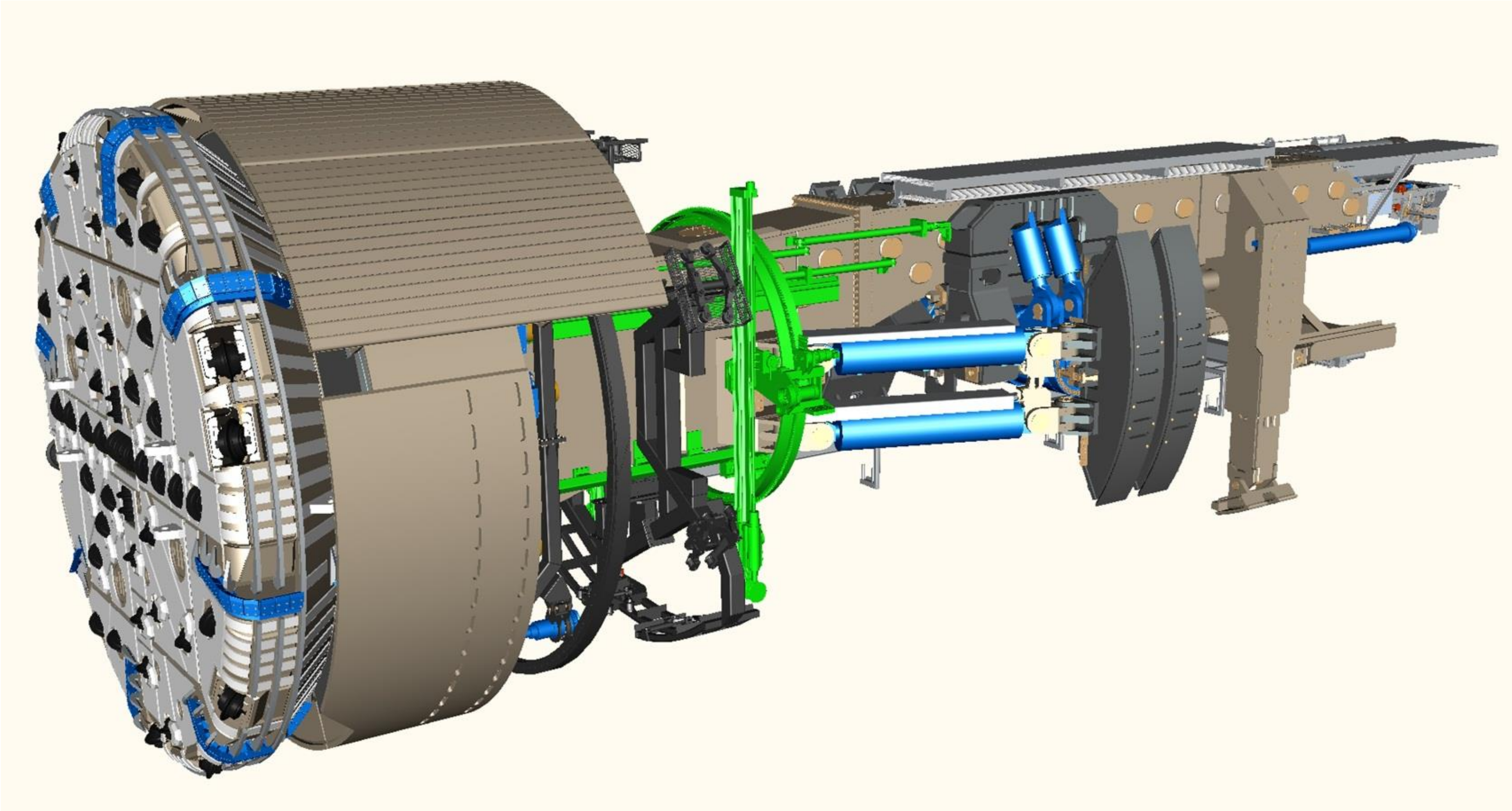
1. Installations in the L1 Zone (directly behind Cutterhead)

- Wire Mesh Erector
- Two Drill Rigs for Installation of Rock Bolts
- Robot for Application of Shotcrete in bad rock
- Ring Beam Erector

2. Installations in the L2 Zone (60m behind Cutterhead)

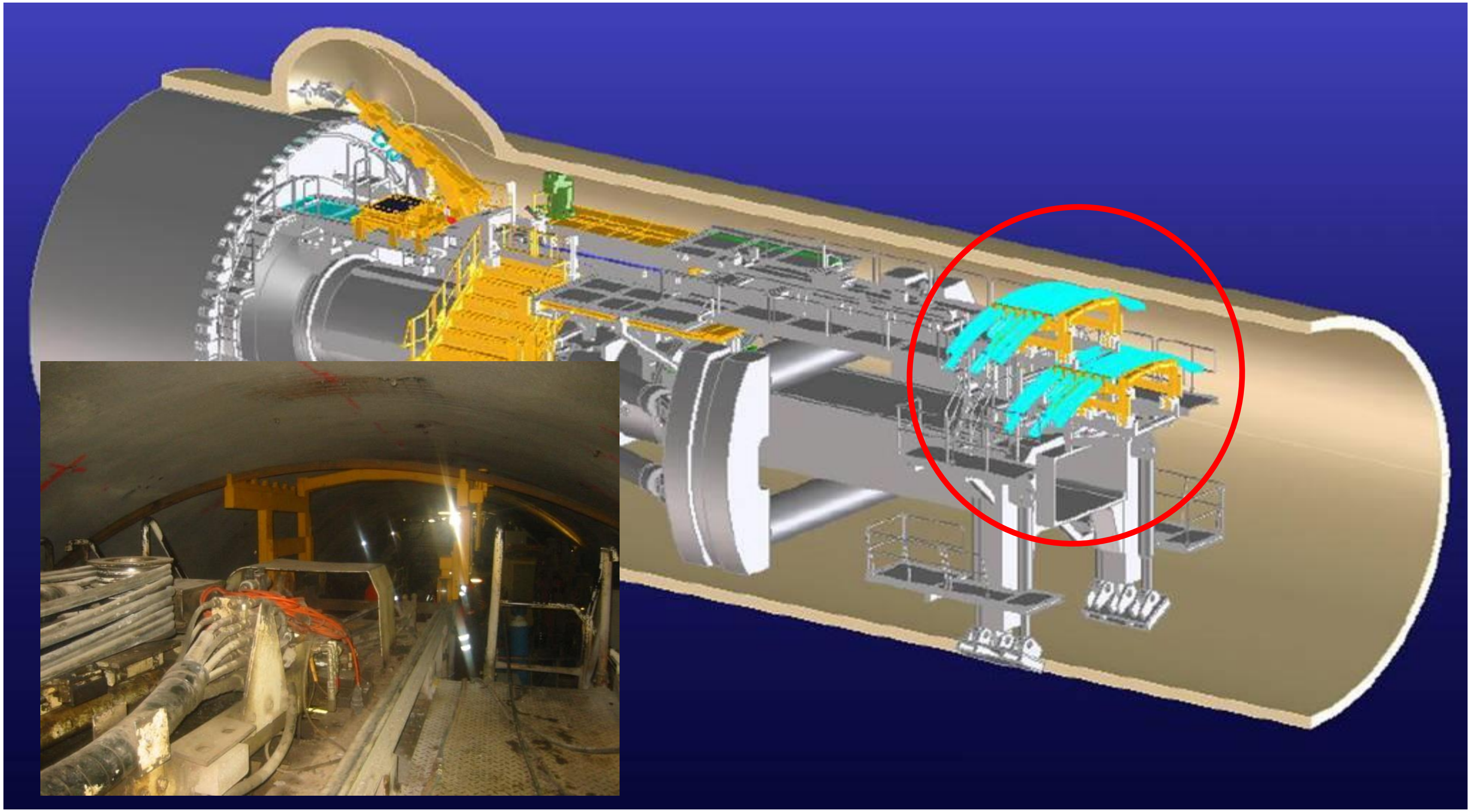
- Two Drill Rigs for Installation of additional Rock Bolts
- Two Robots for systematic Application of Shotcrete

Drill rigs



Shotcrete robot

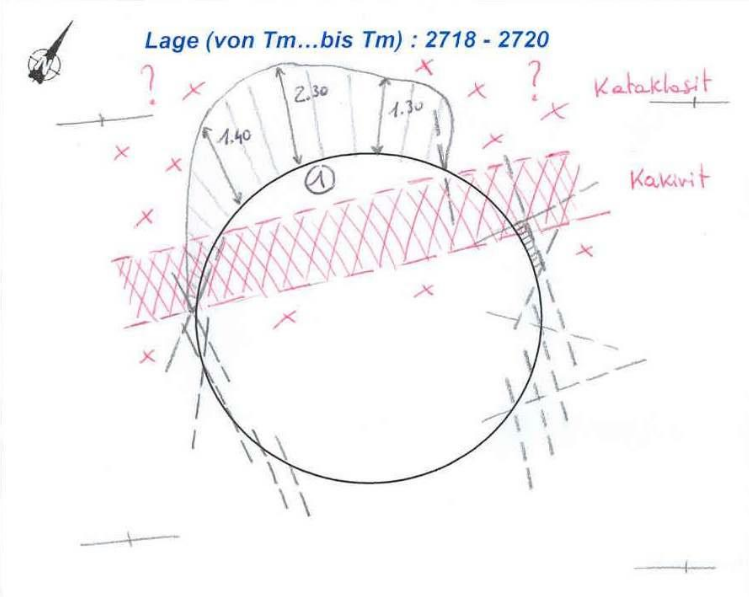
Ring beam transport system



Working Platforms

‘Light’ Rock Support

‘Heavy’ Rock Support



‘Heavy’ Rock Support

‘Heavy’ Rock Support

Rock Support?

Rock Support?

Shielded TBM‘s

2 possible types of TBM

1) Single Shield
- TBM pushes off segments during advance
- no advance possible during ring building
- shield sealed against rockfall and inflowing backfill

2) Double shield
- TBM pushes off grippers in good rock conditions
→ allows continuous advance also during ring building
- TBM pushes off segments in loose rock conditions
→ no advance possible during ring building
- Shield partly sealed against rockfall; gap between front and back shield

Lining: Precast Concrete Segments

Design Requirements:

- Number of segments per ring
- Ring shape and positions
- Outer diameter
- Thickness
- Length
- Type and amount of reinforcement
- Type and number of radial and longitudinal segment connections
- Type of sealing
- Type of backfilling

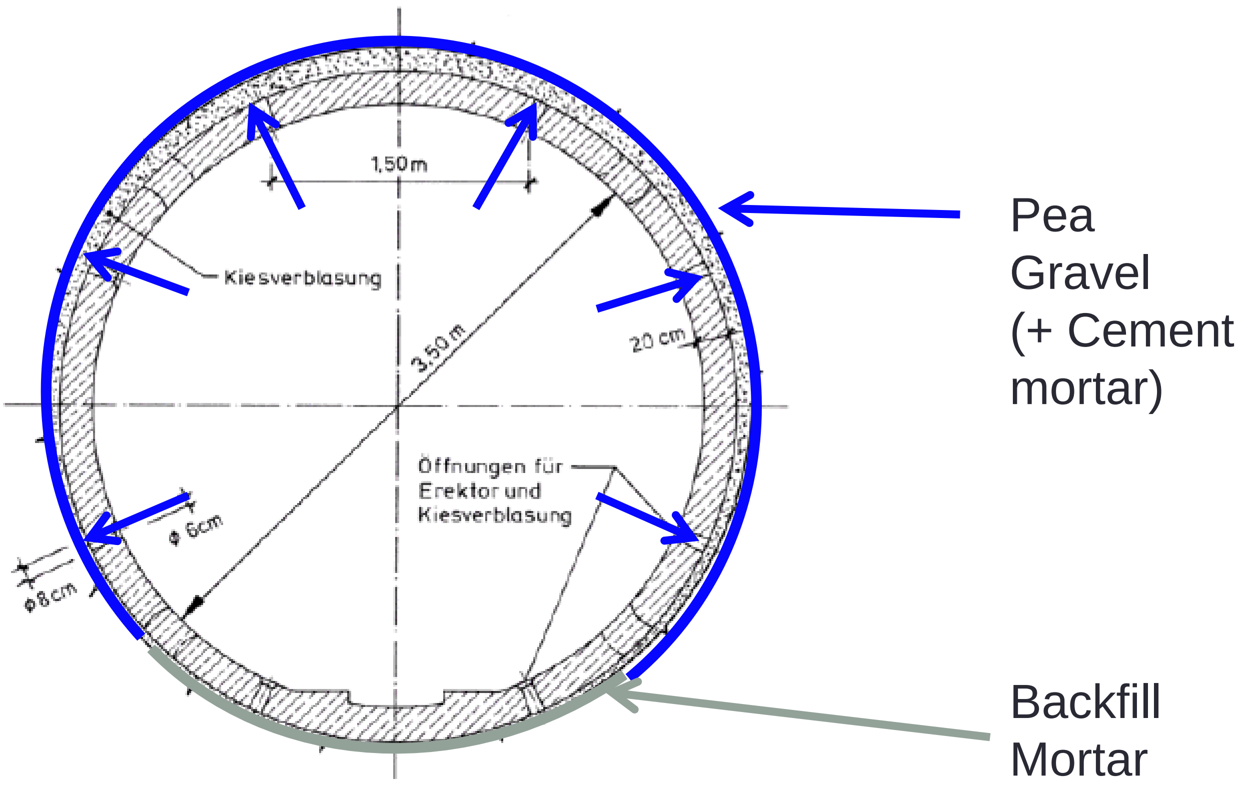
Generally segment lining is more expensive than rock support, but is usually accepted as final lining.

Lining: Backfill Technology

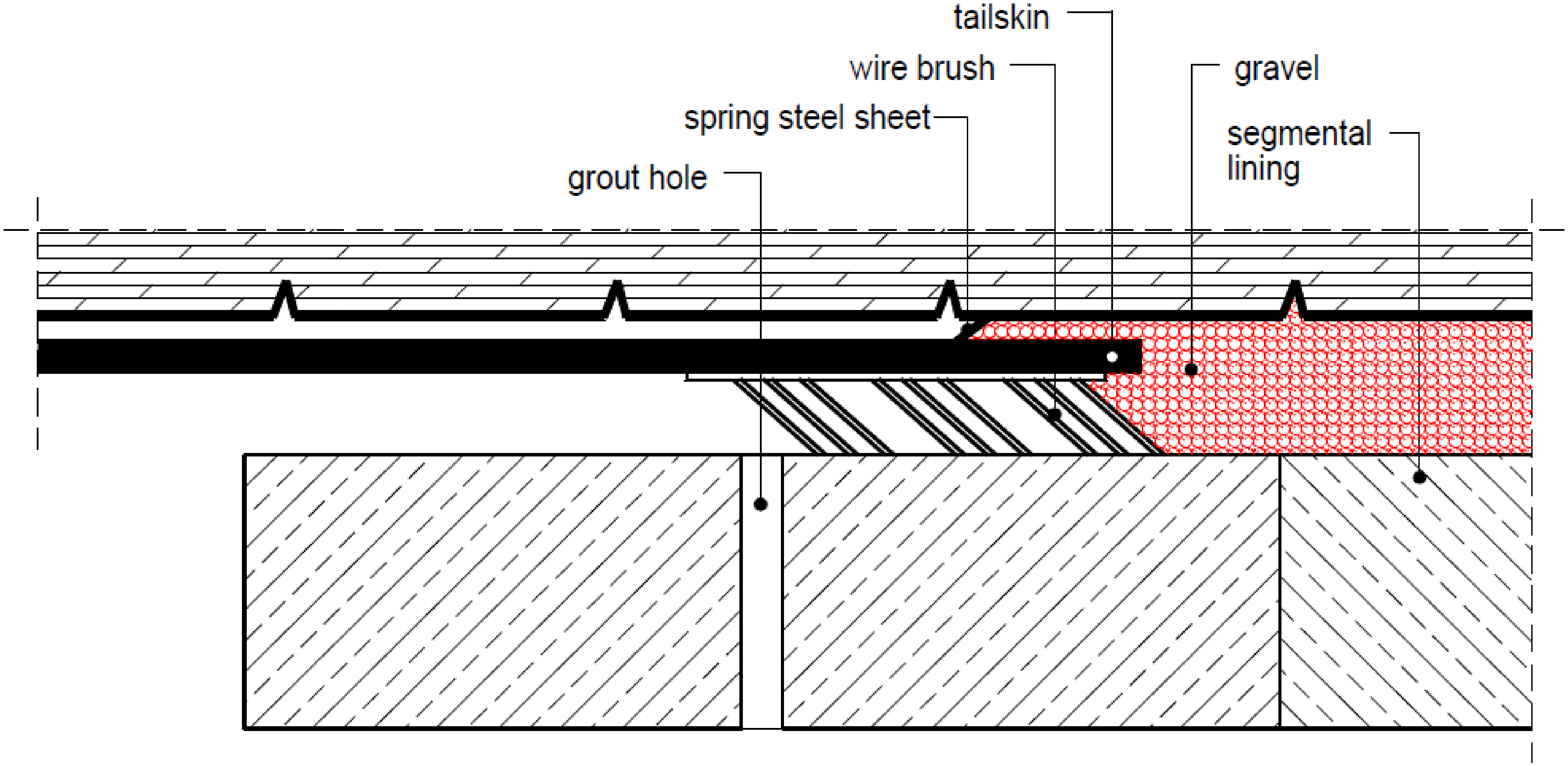
Backfill of segment rings in hard rock:

1) Initial Backfill in invert
   - backfill with stiff mortar mix in invert (70 – 90°)
   - injection through tailskin or segments during repositioning of grippers and pushing ring out of tail shield
   - in order to stabilize ring position
2) Backfill with pea gravel
   - upper 270°
   - injection with compressed air through segments
   - as soon as possible behind tail shield
3) Secondary grouting with cement mortar (mandatory)
   - filling the voids in the pea gravel
   - in order to stop longitudinal water flow along outside of segments
   - also possible in intervals to create bulk heads

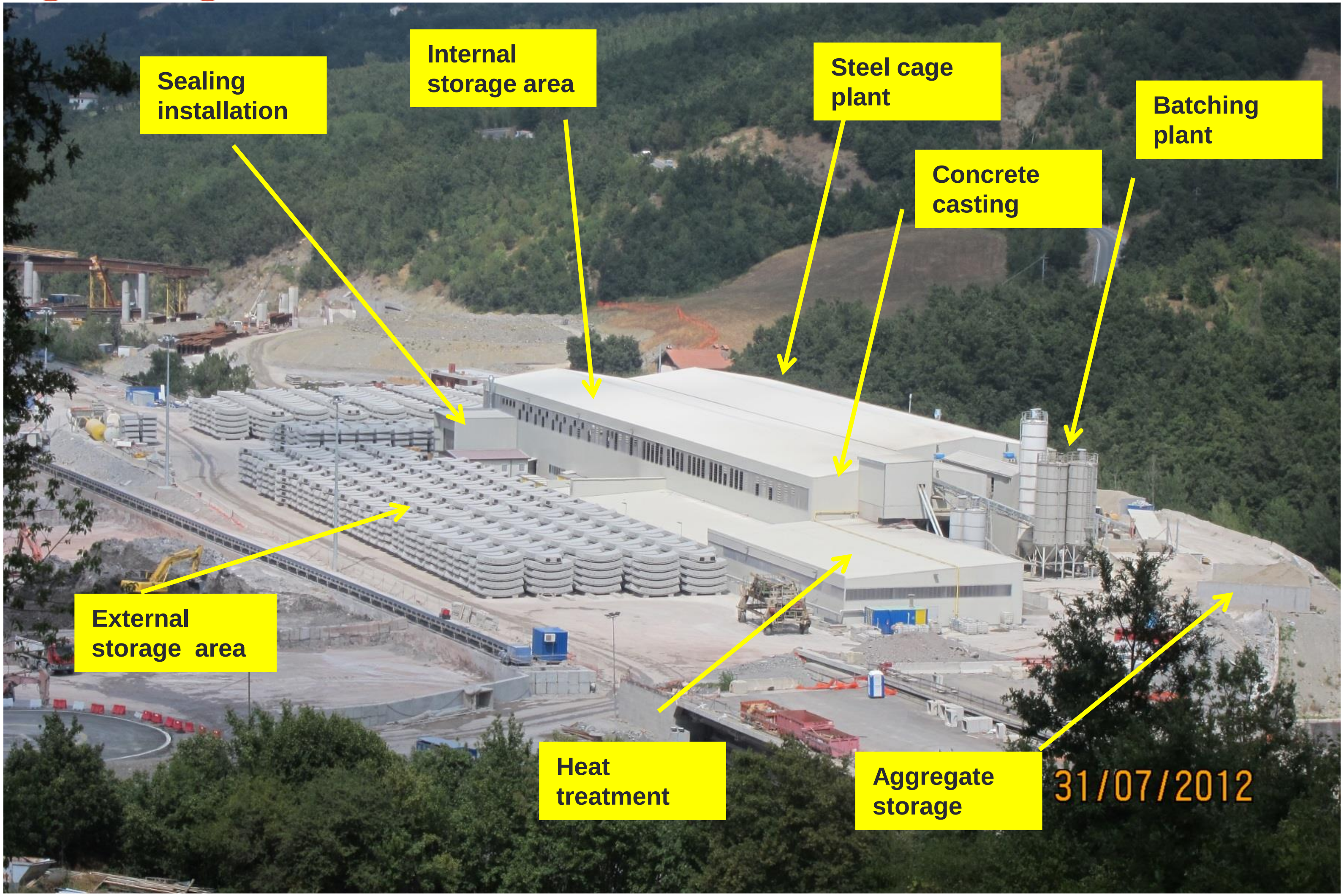
Lining: Backfill Technology



Lining: Backfill Technology



Lining: Segment Plant



Segment Handling and Transport

Logistic Factors

- Personnel
- TBM Consumables
- TBM Utilities
- TBM Spare Parts
- Mucking Out
- Rock Support
- Assembly/Disassembly/Translocation

TBM Consumables, Utilities and Rock Support

- Spare Parts
- Grease (in barrels)
- Oil (barrels)
- Disk Cutters (boxes)
- Bucket Lips (boxes)
- Drill steel (bundles)

- Power (cable drums)
- Water (pipes/hoses)
- Communication lines
- Rails
- Conveyor belt
- Ventilation ducts (storage boxes)

- Rock bolts
- Wire mesh
- Ring beams
- Shotcrete
- Segments
- Grout/Pea gravel

Transport Options

Getting rid of the muck – conveyor belts

Transport Options

Getting rid of the muck – trains

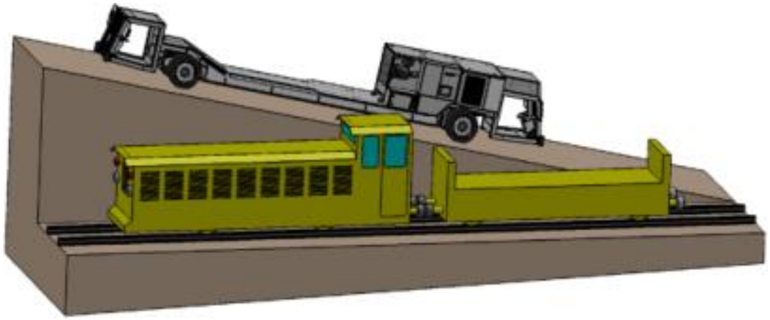
Transport Options

Getting the stuff in - trains

Transport Options

Getting the stuff in – MultiServiceVehicles (MSV)

- Depending on slope and length of tunnel drive
- Standard configuration: 3 - 4 % slope
- On demand and according to jobsite profile: 10 % slope
- Slope up to 25 %; modifications necessary for:
  - Power Pack
  - Transmission
  - Braking



Transport Options

Getting the stuff in – MultiServiceVehicles (MSV)