Erfahrungen beim Tunnelbau im Opalinuston des Tafel- und Faltenjuras

Experience from Tunnelling in Opalinus Clay in tabular and folded Jura

Walter Steiner

B+S AG

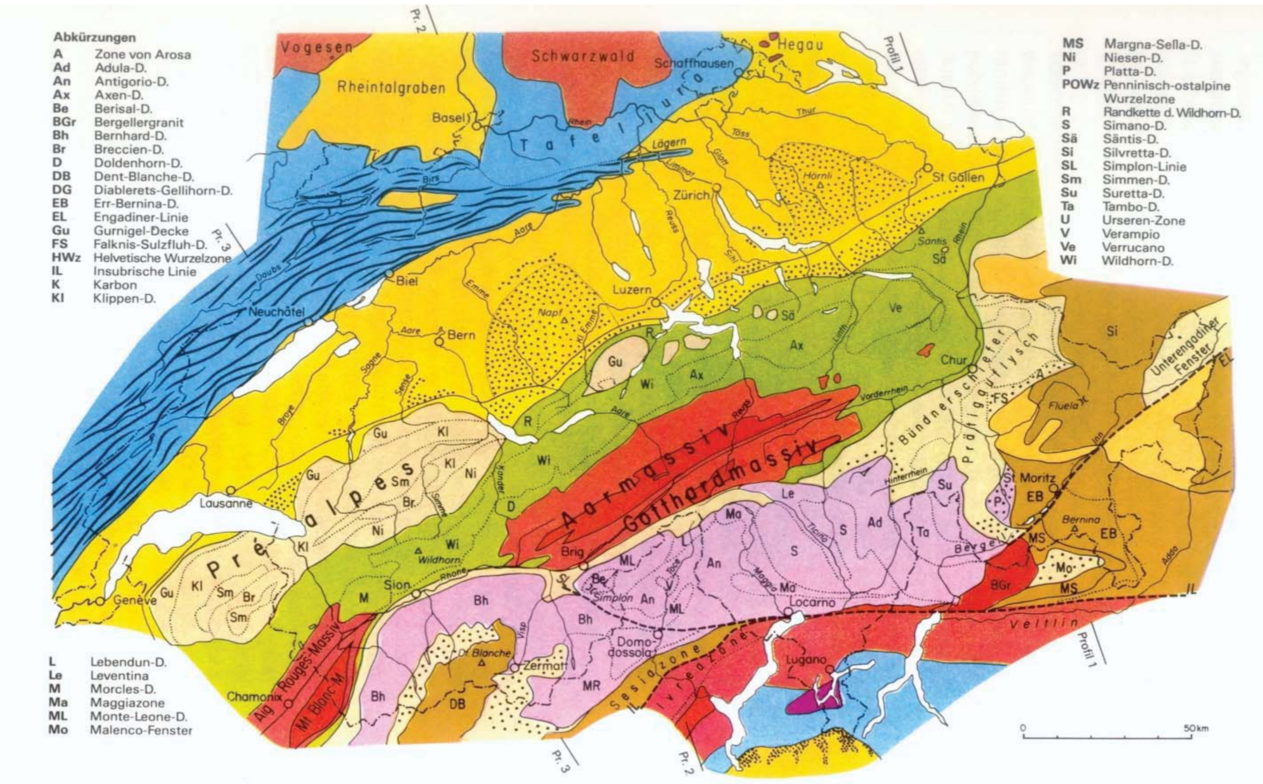
CH-3000 Bern 31

Switzerland

Tunnelling in clay rocks

- Development of tunnelling in soft sedimentary rocks since 1960’s
  - Construction of Motorways and new Railways
  - Experience from Tertiary sedimentary rocks
    - Upper Freshwater Molasse (OSM)
    - Upper Marine Molasse (OMM)
    - Lower Freshwater Molasse (USM)
  - Sedimentary rocks from the Jura
    - Opalinuston
    - Unterer Dogger
- Identification of key factors and changes

Geologische Karte der Schweiz
Geologic Map of Switzerland



Baregg Tunnel N1 near Baden AG

Initially the three-lane motorway N1 in each direction had a double **dual** lane tunnel :

L_{North} = 1142 m

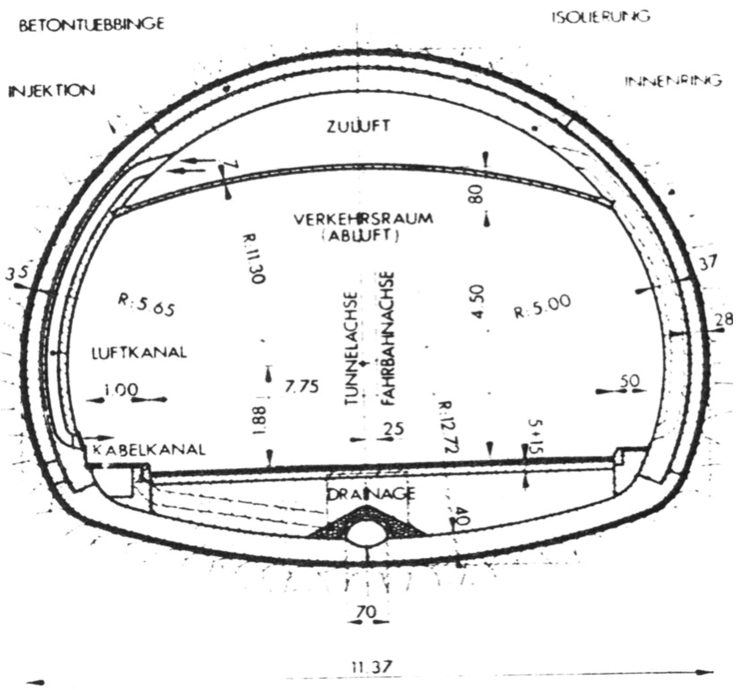
L_{south} = 1120 m

Opened: 7. Okt.1970

Lower Freshwater Molasse (USM)

Horseshoe shield with Drill and Blast Excavation and segmental lining.

It became a notorious bottleneck, until the third tube with three west-bound lanes was opened in 2003.



Probleme mit nicht kreisrunden Schilden
Problems with non-circular shields

Erfahrung Baregg
Experience Baregg

- Difficult, if not impossible to steer:
  - Shield has tendency to roll
  - Width of sidewalk varies several decimeters over ten meters
  - Visible visually
- No non circular shield used by this contractor thereafter

Andere Erfahrung
Other experience

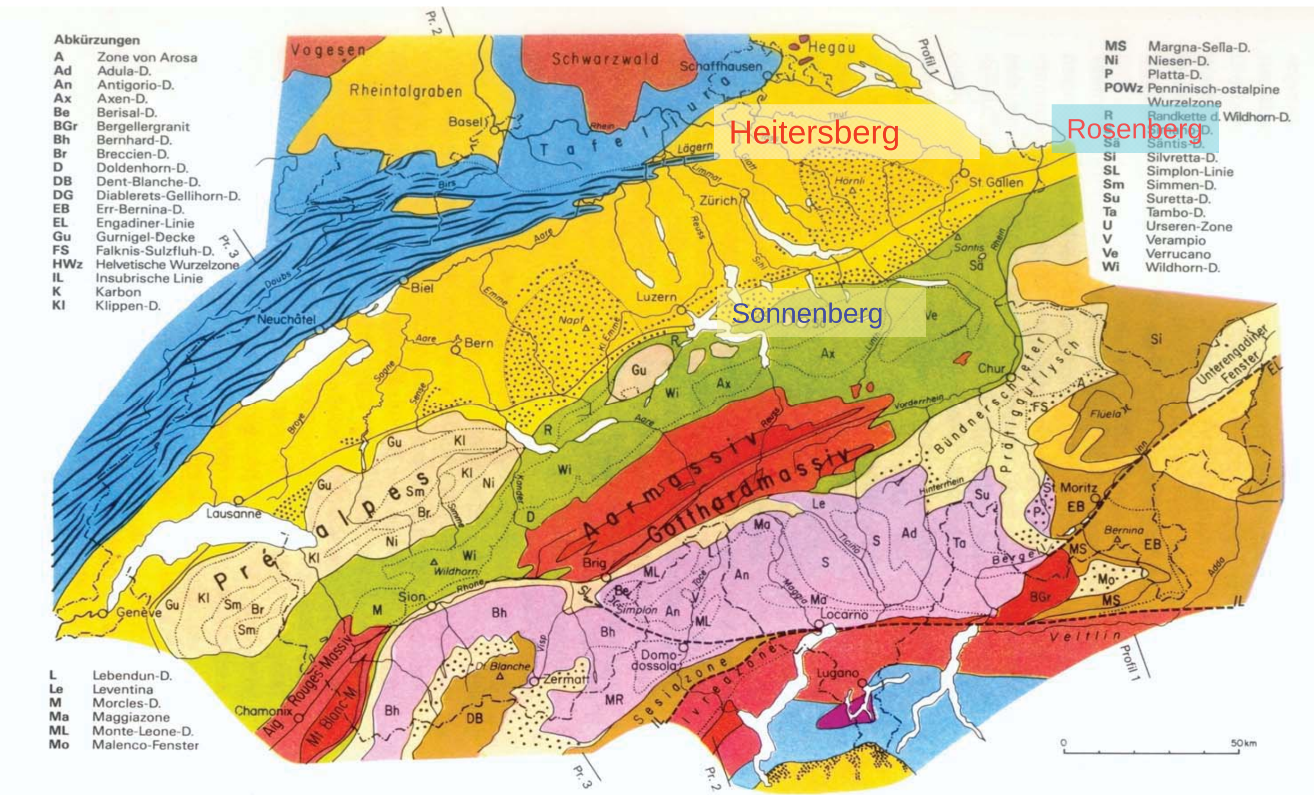
- Castiglione Tunnel on Rome-Florence Direttissima; Consorzio FERROFIR with Robbins Digger Shield (1970 – 1973)
- Elm Tunnel on Frankfurt – Fulda Railway line 1908 – 1911 (Hewitt & Johannesson, 1922)
- now: Distelrasen Tunnel near Schlüchtern

Third tube Baregg Tunnel 2000 – 2003
Three-lane tunnel excavated with top heading:
to illustrate mud on ground: the machinery works the weak rock

Start of tunnelling with large diameter TBM in Switzerland

- Heitersberg Tunnel East: SBB 1968 – 70
  - Horizontally bedded Molasse (Tertiary)
  - Open Robbins TBM Diameter = 10.8 m
- Sonnenberg N2, City of Lucerne, opened 26.10.76
  - Perpendicular to steeply dipping beds of subalpine Molasse
  - Dual stage reaming Wirth TBM
    - Pilot TBM 3.5 m
    - First stage: 7.7 m
    - Second stage: 10.8 m

Application of TBM's (1970's)



Heitersberg Tunnel

Characteristics

Length: 4.9 km

Overburden: Max. 265 m

Section East (Killwangen)

- Cut-and-Cover: 600 m
- TBM 2600 m

- Section West (Mellingen)
  - Glacial Deposits (Gravel)
  - Shield Tunnel. 1700m

Rock Mechanics Properties for Molasse section (East)

- Lower Freshwater Molasse (USM): 43% (= 1118 m)
  - UCS = 8 to 40 MPa
  - Little fine-grained Quartz
- Upper Marine Molasse (OMM): 57 % = 1482 m
  - UCS = 10 to 65 MPa
  - Quartz Content = 30%

Heitersberg East Section: Expectation and Experience

Support foreseen

- Shotcrete with
  - Robot developed by Stabilator AB and Prader AG
- Invert segments
- Steelset Erector:
  - 3.5m from face
  - Wide Flange Beam: HEB 140
  - Spacing= 1.2 m
- Expected behaviour:
  - Less disturbance of rock than from blasting

Experience:

- Without Steelsets: 76% = 2 km
  - Rate of advance = 8 m/day with two shifts
- With steelsets (24% = 630 m)
  - Rate of advance = 3.6m/day with two shifts
- Due to delay, change of contract boundary:
  - Circular Shield Tunnel from West excavated some Tunnel with drill & blast and segmental lining

Problems at Heitersberg Tunnel

Placement of shotcrete with robot developed by *Stabilator* AB, Sweden behind TBM by Robbins.

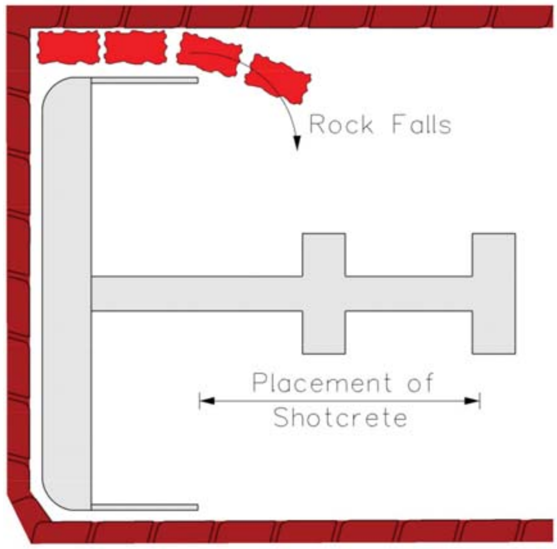
Stand-up time was too short: Pieces of rock separated near the face, dropped on the roof shield and „rained“ into the workspace.

Placement (Threading) of wide flange beams HEB 140 above roof shield of TBM

Rate of advance < 3.6 m/day

Heitersberg TBM:

Full Face TBM: Separation of Rock Blocks along bedding planes in sedimentary rock (Sandstone, Marl)



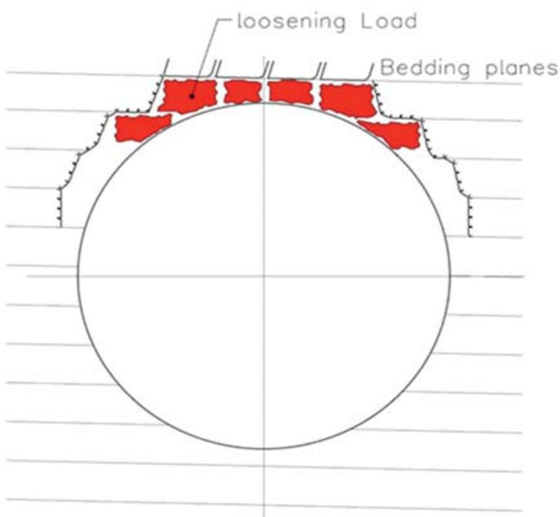
Cause of Instabilities near face at Tunnel circumference *(with the benefits of hindsight and new research)*

Stress driven instabilites in soft rock at low stresses.

Estimates of depth of break-out with formula by Derek Martin

Parameter	Fall 1:	Fall 2:	Fall 3:	Initiation
Überlagerung:	100	200	200	265
Raumgewicht	25	25	25	25
σv (MPa)	2.5	5	5	6.625
K = (σh/σv)	0.8	0.8	0.8	0.8
σ max (MPa)	5.5	11	11	14.575
UCS (Mpa)	**8**	**15**	**20**	**36**
σ_{max}/UCS	0.69	0.73	0.55	0.40
r/a	1.36	1.42	1.19	1.01
d=(r-a) in m	2.16	2.50	1.13	0.04

Schematic of observed behaviour



Entwicklung nach Heitersberg
Development after Heitersberg

Gubrist Tunnel, N20 Zürich North By-Pass

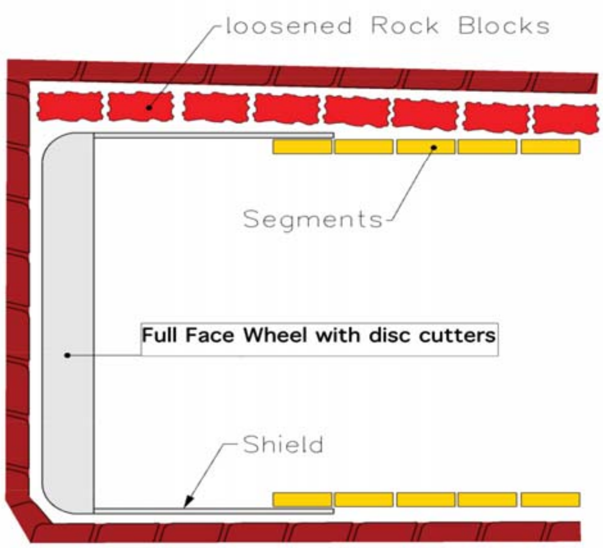
TBM from Heitersberg placed in shield with **segmental** lining, placement of roadway slab below trailing bridge

Rosenberg: L = 1435m, N1 City of St. Gallen

Shield with four Roadheaders and **segmental** lining.

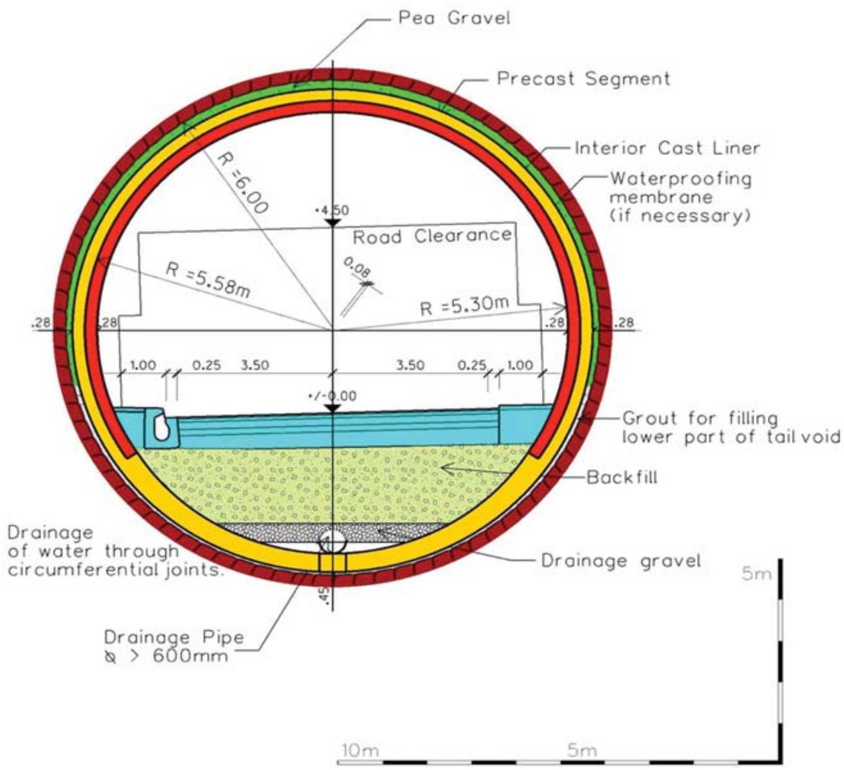
Gubrist Tunnel N20 /A1
North Bypass of Zürich.
Lösung: TBM in Schild mit Tübbing-auskleidung
Selected solution Robbins TBM placed into a shield, designed by contractor's joint venture.

Winning Solution:
Shield TBM with initial support:
- unbolted and not expanded segments
- later final interior cast concrete liner

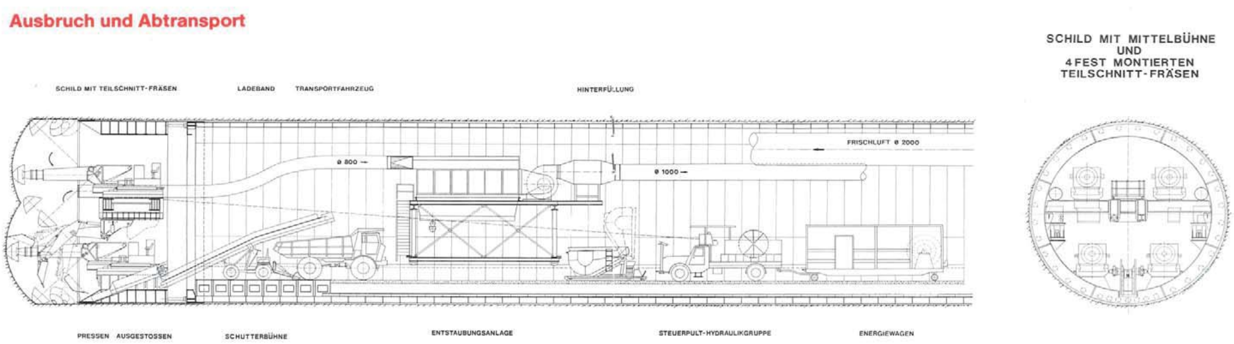


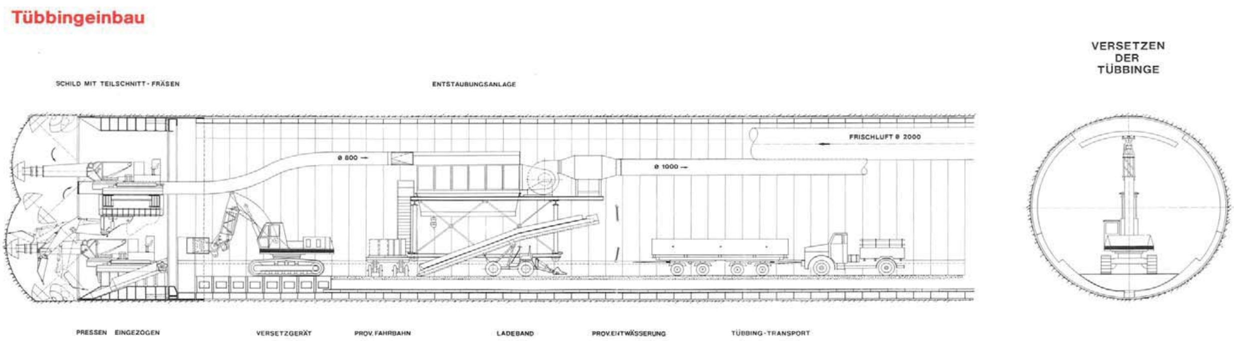
Typical Cross Section of Tunnel with shield TBM:

25 years ago mostly backfilled or ventilation channel
Today for road: mostly cable duct (Werkleitungskanal)

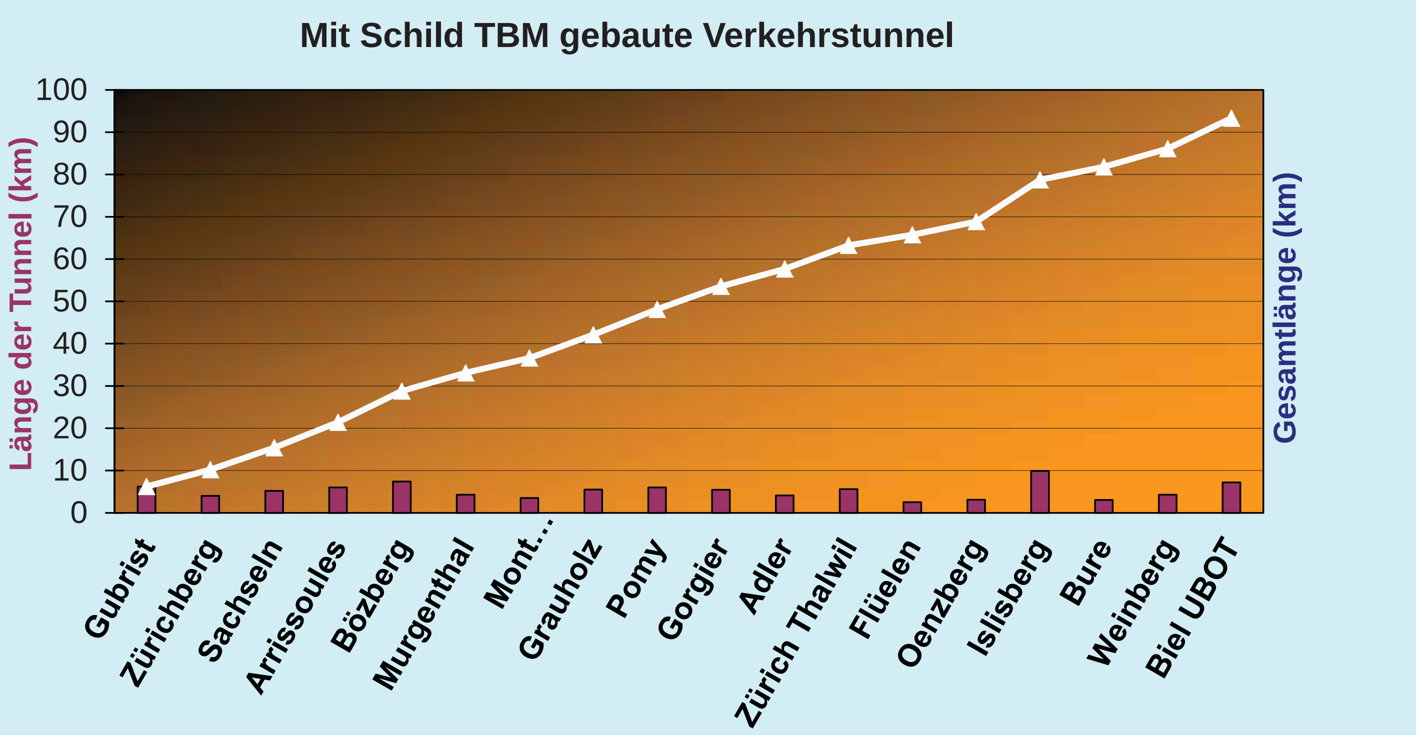


Rosenberg Tunnel: Shield with 4 Roadheaders Placement of segments with modified hydraulic excavator

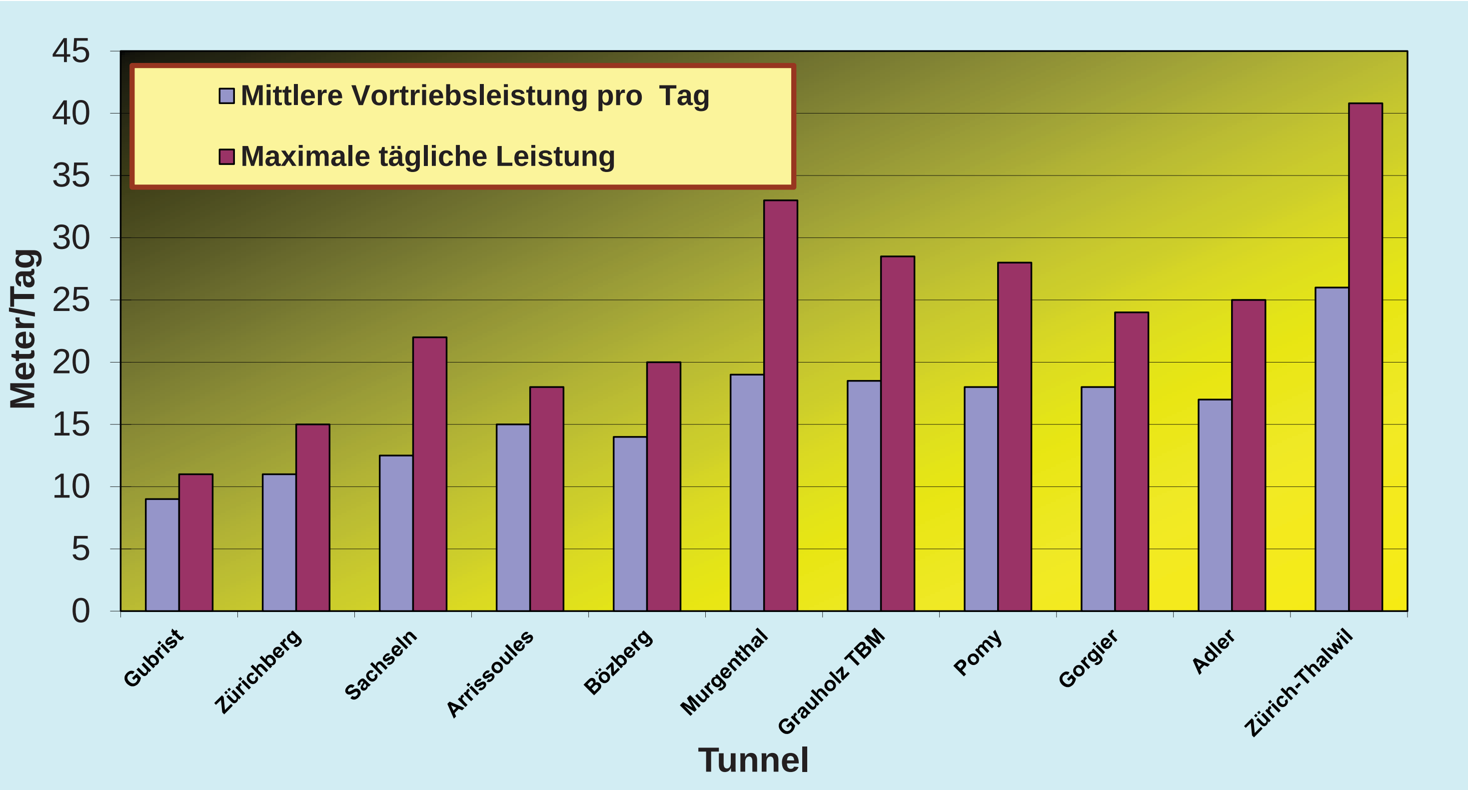




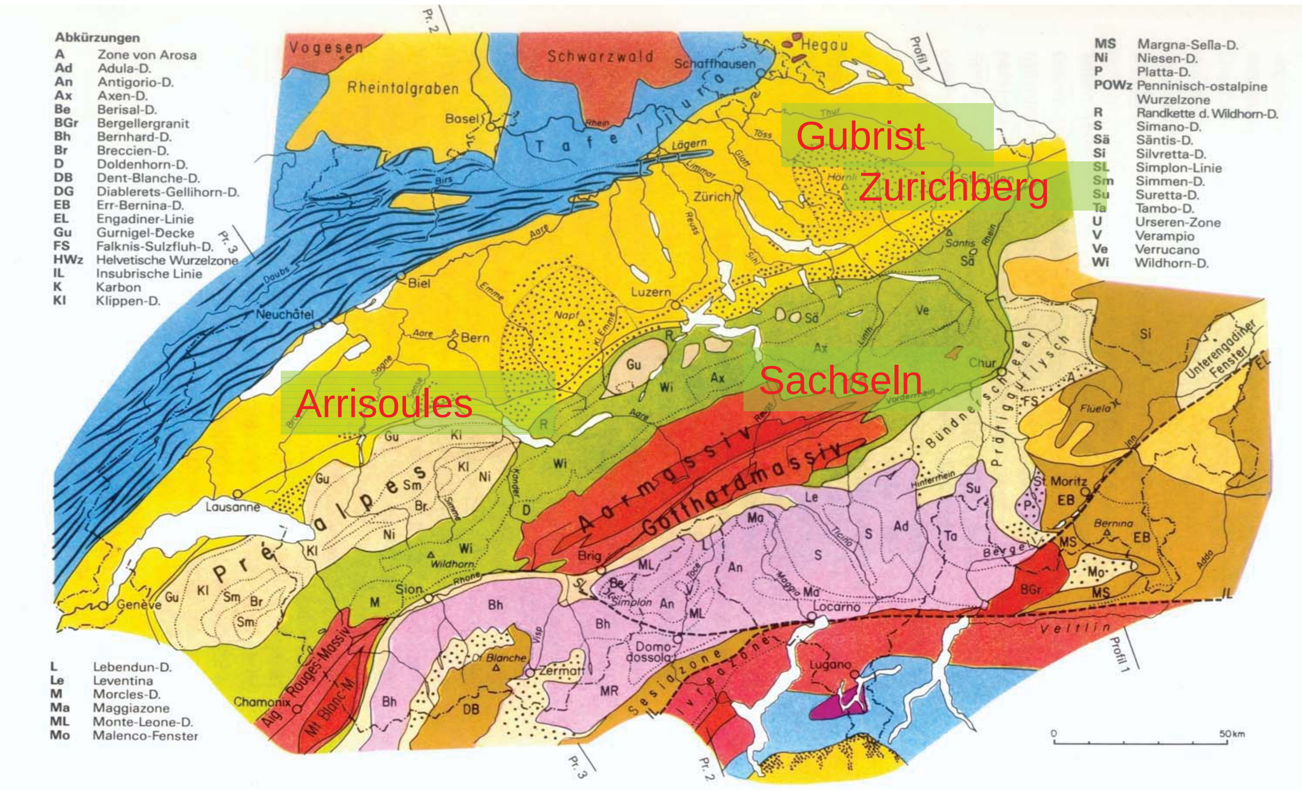
Tunnels with shielded TBM in soft rock 1979 - 2012



Rates of advance for TBM's



Tunnels built with shield TBM modified after Heitersberg



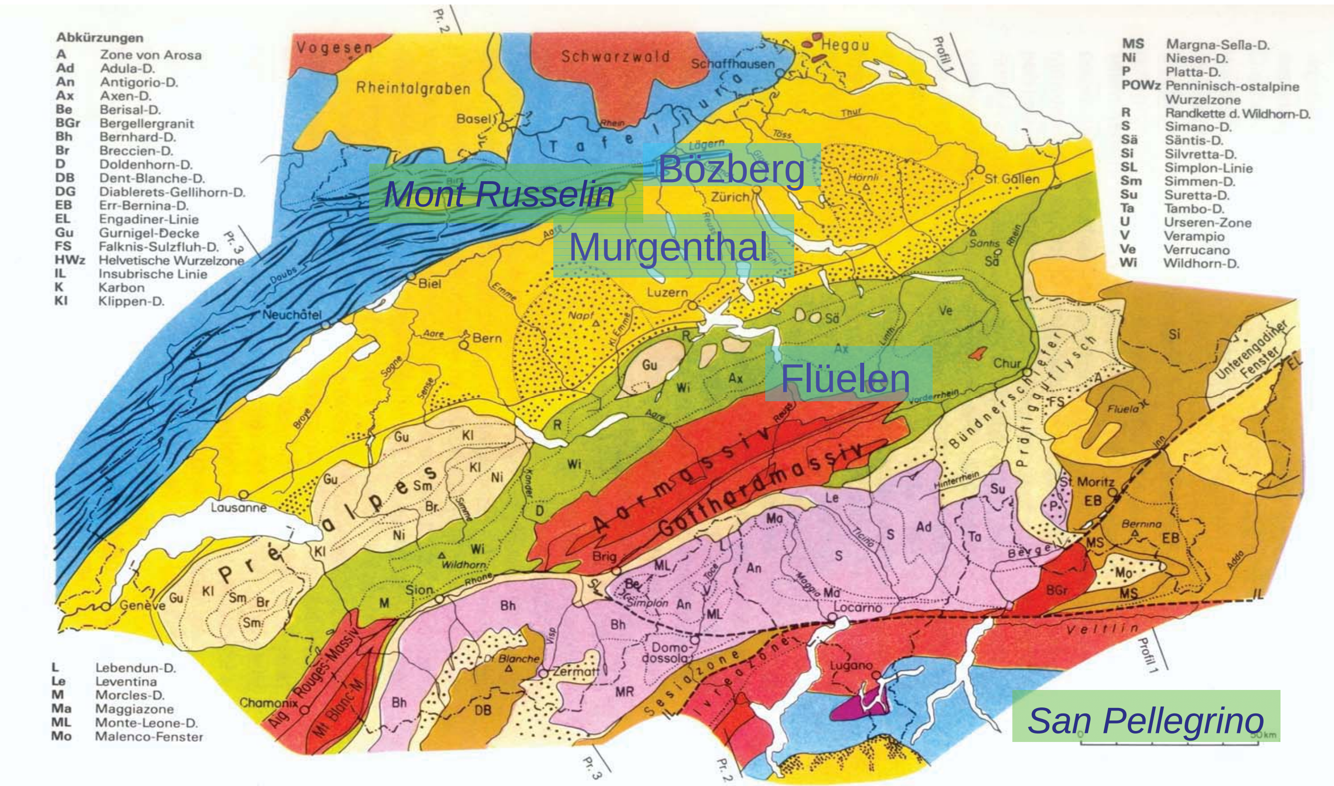
Strength values of Molasse Rock

	Unconfined compressive strength			
	Upper Freshwater Molasse		Lower Freshwater Molasse	
	Range (MPa)	Mean (MPa)	Range (MPa)	Mean (MPa)
Coarse Sandstone	-	-	0.5 - 15	2 - 4
Sandstone (Fine)	50 - 100	60	8 - 50	27
Siltstone	15 - 60	40	10 - 60	30
Marl	0 - 40	20	2 - 18	8
Clay Shale	very variable	20	0.2 - 10	3

Typical properties of rock from Jura

	Unconfined	Compressive strength	Swelling	Pressure
	Range (MPa)	Mean (MPa)	in-situ (MPa)	Lab (MPa)
Limestone	80 –150	100	----	----
Calcareous Marl	50 - 100	80	----	----
Shale	2 - 10	5	0.2 –1.0	2.0
Anhydritic Shale	20 -50	40	2.0 –3.0	8.0

The sons of Heitersberg TBM; Gubrist shielded TBM: Bözberg und *Mont Russelin* Shield TBM’s



Stammbaum der ursprünglichen beiden Herrenknecht-Robbins Schild TBM

Ancestry of the two Herrenknecht Robbins Shield TBM

Bözberg TBM (N 3)

- **Bözberg Tunnel (Road)**
  - 2 x 4.3 km
- **Murgenthal (Rail, SBB)**
  - 4.3 km
- **Flüelen (Road, N4)**
  - 2.51 km
- **Perschlingtal (OeBB)**
  - STRABAG

Mont Russelin TBM (N 16)

- **Mont Russelin (Road)**
  - 3.5 km
- **San Pellegrino (Italy)** Road By-Pass (Subcontractor for SELI)
  - 2.3 km
- **Dublin Port Tunnel (Road)**
  - 2 x 2.25 km
- **Imperia – Ventimiglia (Rail): Italferr (Ferrovial)**

Länge der mit TBM im Jura aufgefahrenen Tunnel und Eigenschaften der Maschinen

Length of Tunnels constructed in Jura with shielded TBM and Characteristics of TBM

Namen	Länge Length	Länge TVM Vortrieb	Gesamt Länge Tunnel	Über-lagerung	Baujahr	Inbetriebnahme Opening
		km	m	M		
Bözberg	2 X 3.7	7.4	3700	260	1989 - 1994	17.10.96
Mont Russelin	3.5	3.5	3550	410	1990 - 1994	13.11.98
Adler	4.3	4.3	5328	200	1994 - 1998	11.12.00
Bure	2.5	2.5	2965	150	2005 - 2008	2014

Name	Maschinenhersteller	Durch-messer Schild	Länge Schild	Antriebs-leistung	Drehmoment (Losbrech-drehmoment)	Vorschub-kraft
		m	M	kW	MNm	MN
Bözberg	Herrenknecht - Robbins	11.81	7.78	3200	18	80
Mont Russelin	Herrenknecht - Robbins	11.81	7.78	3200	18	80
Adler	Herrenknecht	12.535	8.39	3600	11	80
Bure	Herrenknecht	12.535	9.81	2800	13.8 (16.5)	54

Bözberg Tunnel Motorway N3: Autobahn A3

Information from Erwin Beusch, formerly Kanton Aargau
H.P. Stadelmann and J. Bolliger of Implenia AG, before Locher & Cie AG

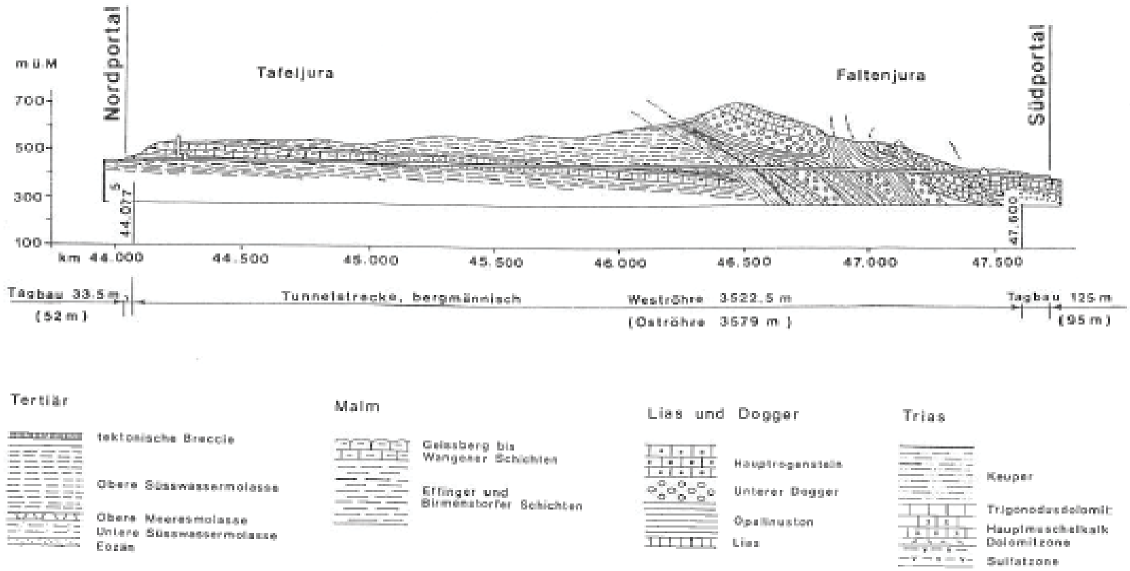


Bild 3
Geologisches Längenprofil (Prognose) nach Dr. L. Hauber / Dr. K.J. Schmidt

Bözberg Tunnel: Querschnitt Cross sections

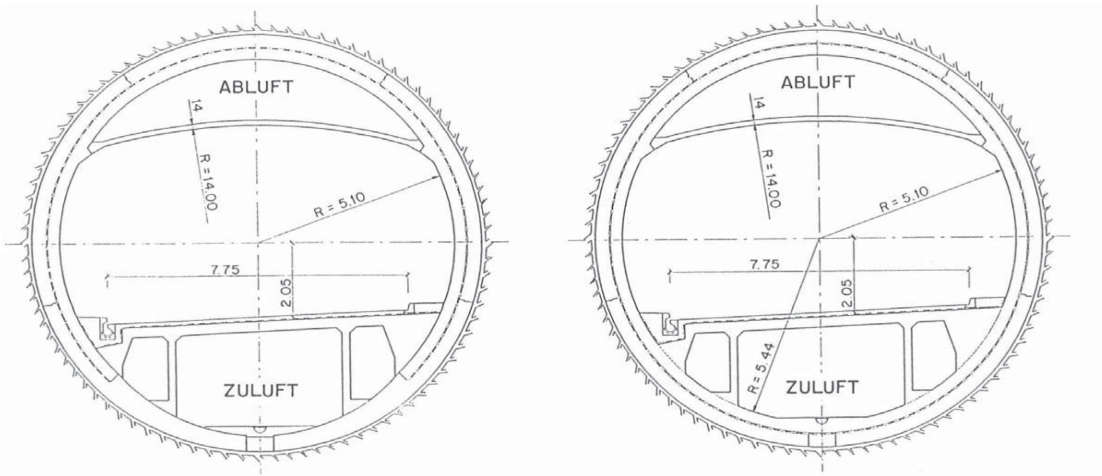


Bild 4
Normalprofil, teilabgedichtet

Bild 5
Normalprofil, vollabgedichtet

- **Experience at Bözberg Tunnel:**
  - Some problems with break-outs in folded Jura
  - No Problems in tabular Jura with Opalinus Clay:
  - no squeezing, no jamming

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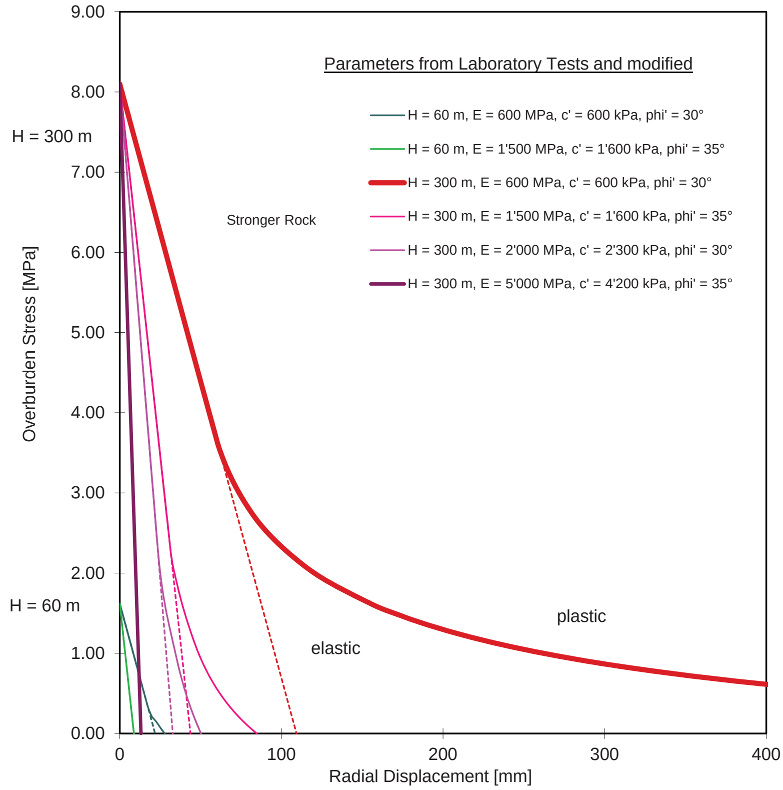
Predicition of convergence from drill core samples uiaxial tests and comparison with dilatometer tests and observed behaviour

For the design of the Wisenberg Tunnel in 1990 we faced the same problem as our colleagues and predicted large radial convergence of several decimeters. By comparison to the observed behaviour in Hauenstein Tunnel we concluded that the mechanical properties were to low, due to sample disturbance (micro fissures).

At that time dilatometer tests were not yet carried out below 150 m. By comparison with another project near-by project we came to the conclusion that the moduli were to low ba a factor of five.

Today we carry out dilatometer tests in parallel.



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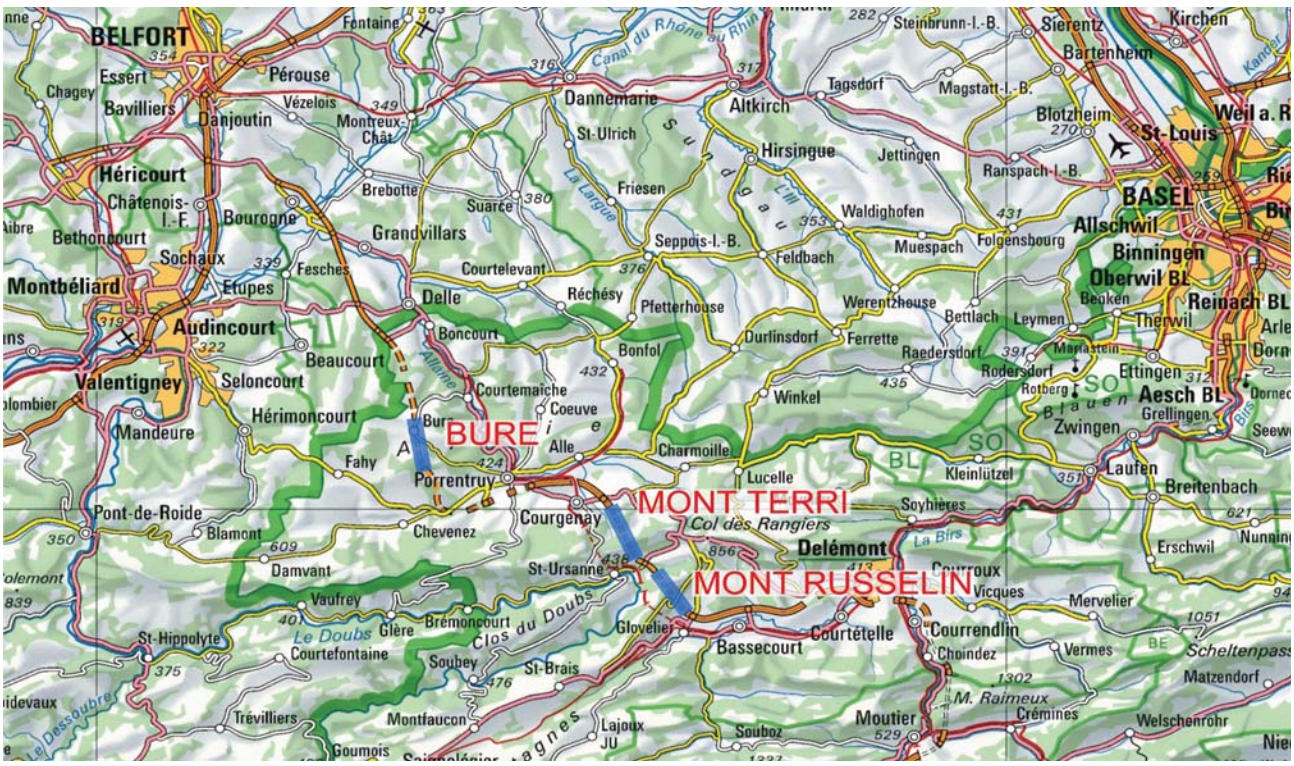
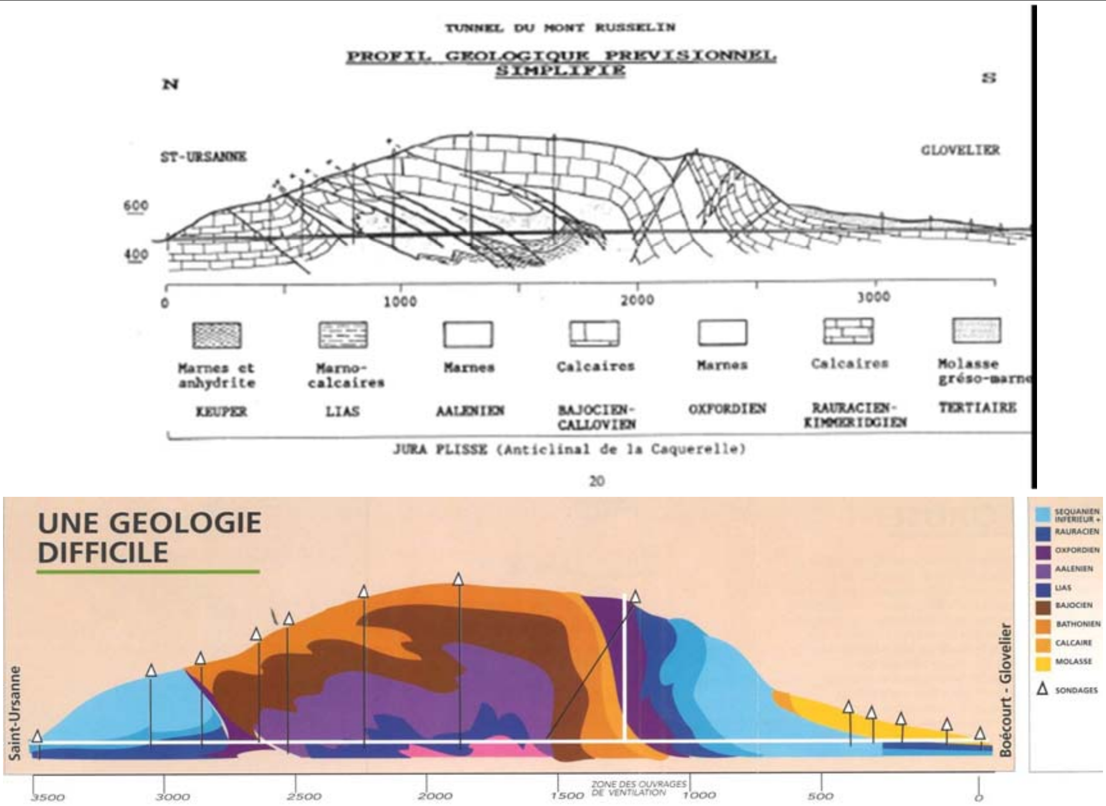
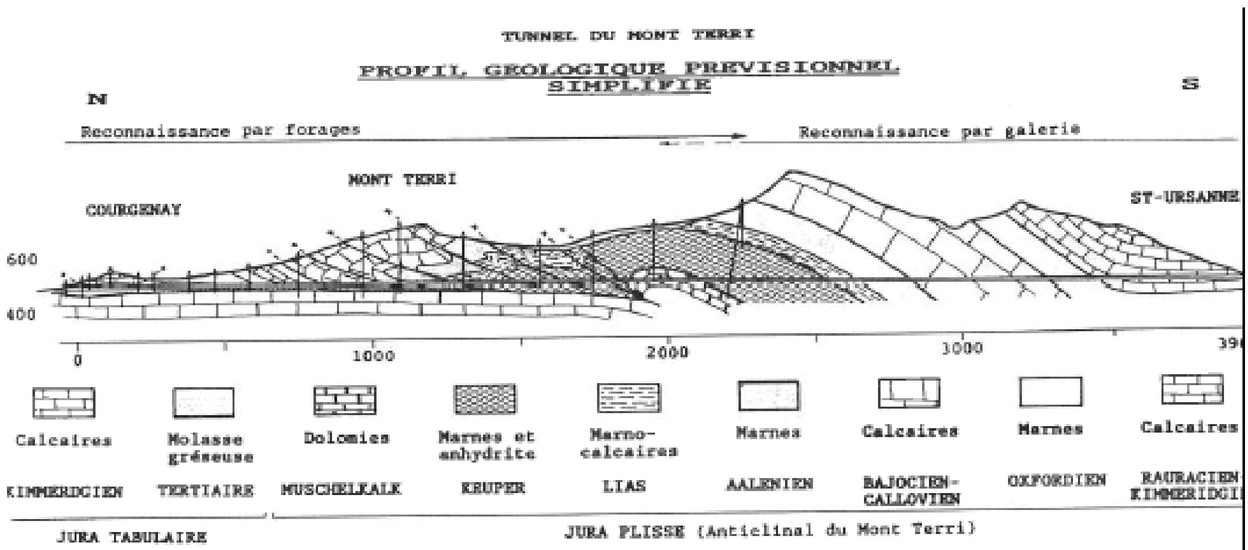
New Tunnels in the Jura mountains
Neue Strassentunnels im Jura



Tunnel du Mont Russelin, A 16:
TBM Geologic section Geologischer Schnitt



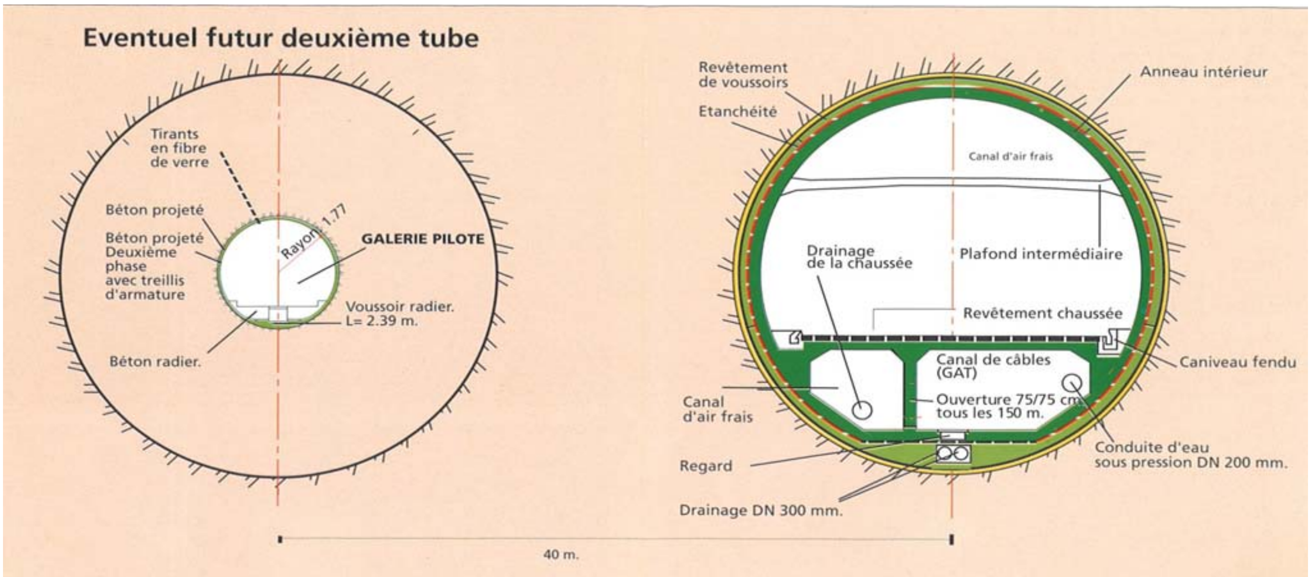
Tunnel du Mont Terri, A 16 Transjurane
Erkundungsstollen von Osten mit Versuchsabschnitten
Die Resultate waren auch für Mont Russelin wichtig.
Conventional Tunnelling and Trial adit from east
Results from test sections assisted also Mont Russelin



Mont Russelin Tunnels

Links: Erkundungs- und Sicherheitsstollen
Rechts: Haupttunnel

Left side: Cross Section of Exploratory and safety Tunnel, Right side: Main Road Tunnel



Mont Russelin Pilote Tunnel with open TBM in folded Aaleanian (Opalinus Clay) Photos from R.T. Haarpainter, Site Geologist, 1991

Break-outs on tail

Breakouts on Trailer

Mont Russelin Pilote: Overbreak Chainage: 1677 m Loosened blocks to 1.1 m height above crown

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Mont Russelin Pilote Tunnel: Blocky rock (Meter size) in tectonized Opalinus shale (Aalénian)

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Mont Russelin Tunnel: Ring 1477, 1931 m
Vorbruch vor die Ortsbrust der TBM im zerscherten Opalinuston
Overbreak in front of face of TBM in sheared Opalinus clay :

Ausweitung des tunnel für Ausstellbuchten mit Kunstharzinjektion in der Kalotte (Zugrisse)
Enlargement of TBM Tunnel for Emergency Bays with grouting of rock in crown with resins (tension cracks)

Querschläge im Mont Russelin Tunnel mit Tübbingen des Haupttunnels und Hinterfüllung, links teilweise mit nachgebrochenem Fels, links Perlkies

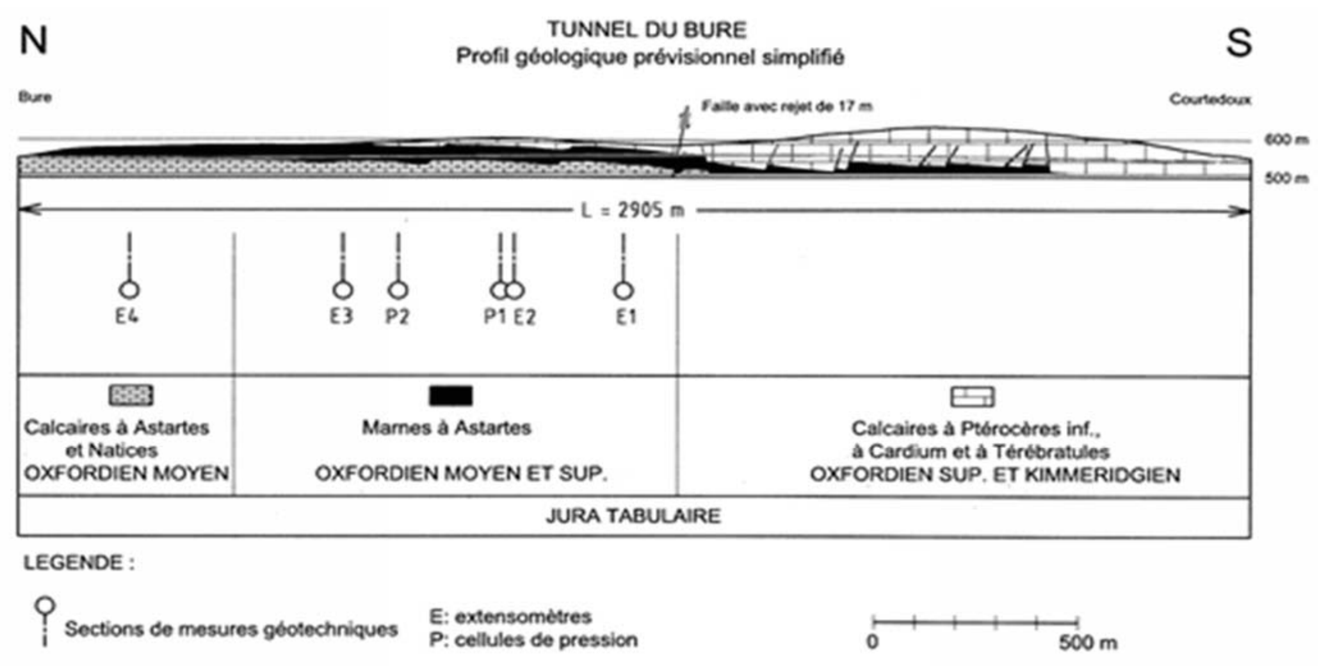
Mont Russelin Cross Cuts with Segments of Main tunnel and backfill partly with broken rock (left side) and pea gravel on right side

Tunnel de Bure:

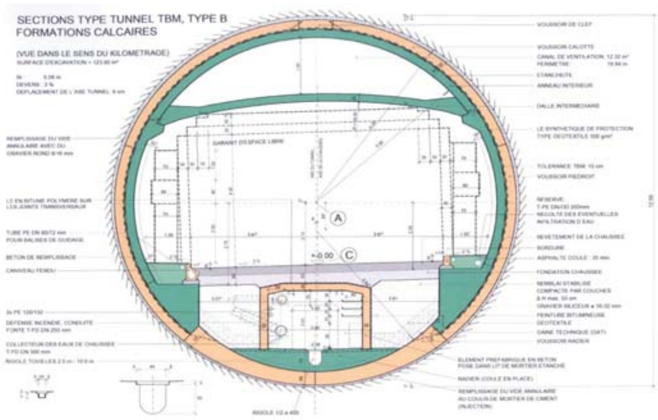
Geologisches Längenprofil, Überdeckung = 50 bis 70 m

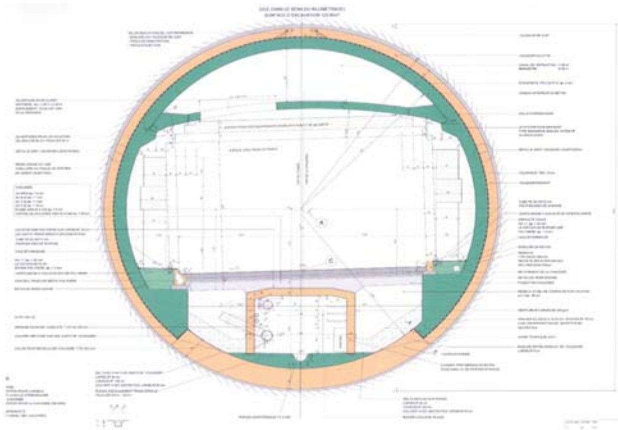
Geologic Section: Overburden = 50 to 70 m

L= 400 m Calcareous Marls;
1200 m of Clay Stone Oxford middle and upper,
1500 m limestone Upper Oxford and Kimmeridge



Tunnel de Bure:
Querschnitte im Kalk und Mergel (Website A16)
Cross Sections in Limestone and Marls





Tunnel de Bure A16: Montage und Start der TBM
Assembly and Start of TBM

Photos from Marti Tunnelbau AG (Adrian Müller; Sergio Massigniani)

Tunnel de Bure A16: Durchschlag und Nachläufer
Holing through and Trailer inside Tunnel

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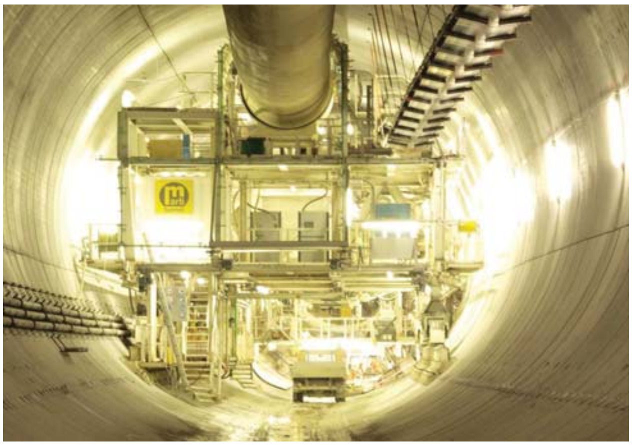
Auskunft vom Unternehmer: keine Probleme beim Vortrieb
Information from contractor: No problems



Tunnel de Bure N16

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Besuch mit FGU im 2008
Photos from Site visit with FGU in 2008 (by W. Steiner)
Advance rates in limestones = 18.4 m/d; Marls = 22.5 m/d)

Hinterblasen mit Perlkies und Segment versetzen
Backfilling the tail void with pea gravel and segment erector (Site visit 2008)

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Tunnel de Bure:
Zwischendepot der Tübbing, geliefert aus Balsthal, mit Band geförderter Ausbruch

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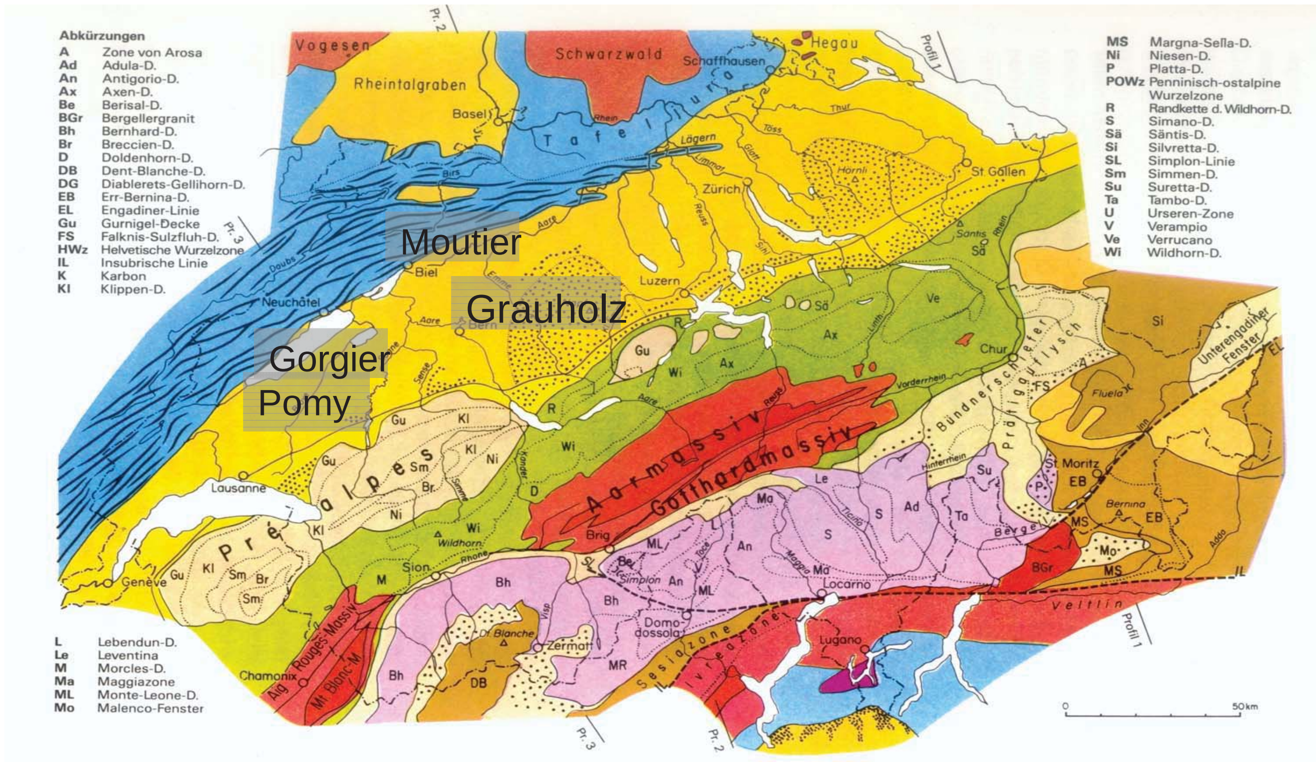
Segments delivered from plant at Balsthal, Tunnel Muck transported by conveyor belt

Tunnel erstellt mit Grauholz Mix-Schild, als TBM verwendet
Tunnels excavated with Grauholz Mix-shield applied as TBM



Herausgeschobener Grauholz Mix Schild
Holing through of Grauholz Tunnel (Mix Shield)

Tunnel mit Schild TBM und Mix-Schild : 1995 -2003
Other Shield TBM and Mix-Shield Tunnels: 1995 - 2003

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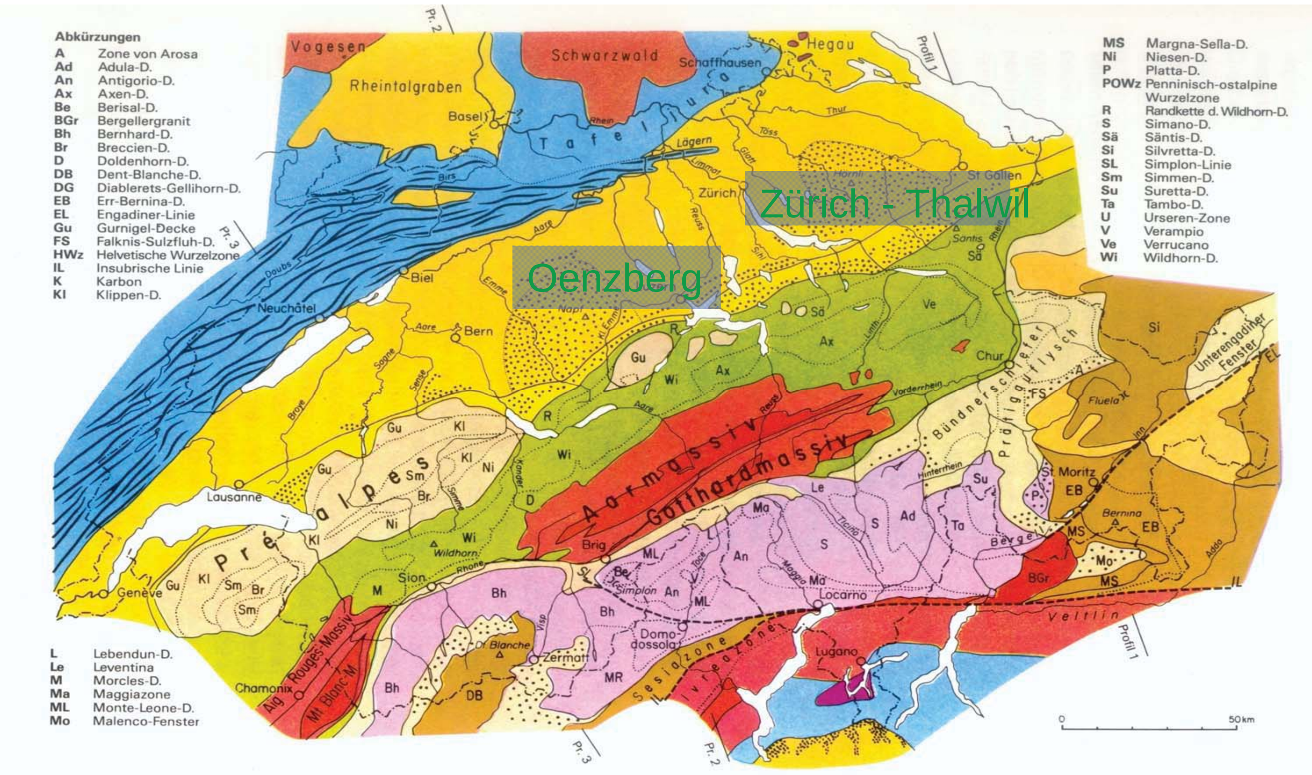

Tunnel mit weiteren Schild TBM erstellt: seit 2006
Other Tunnels built with TBM since 2006

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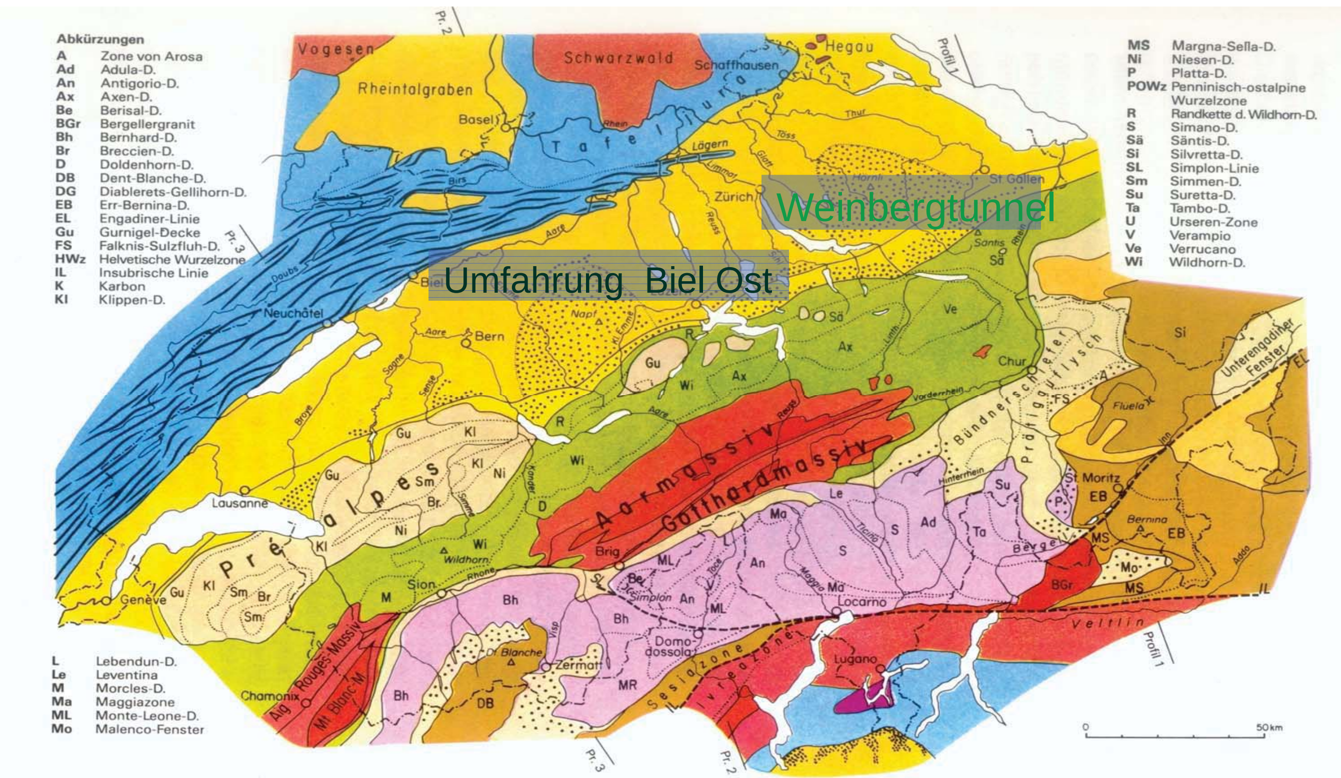


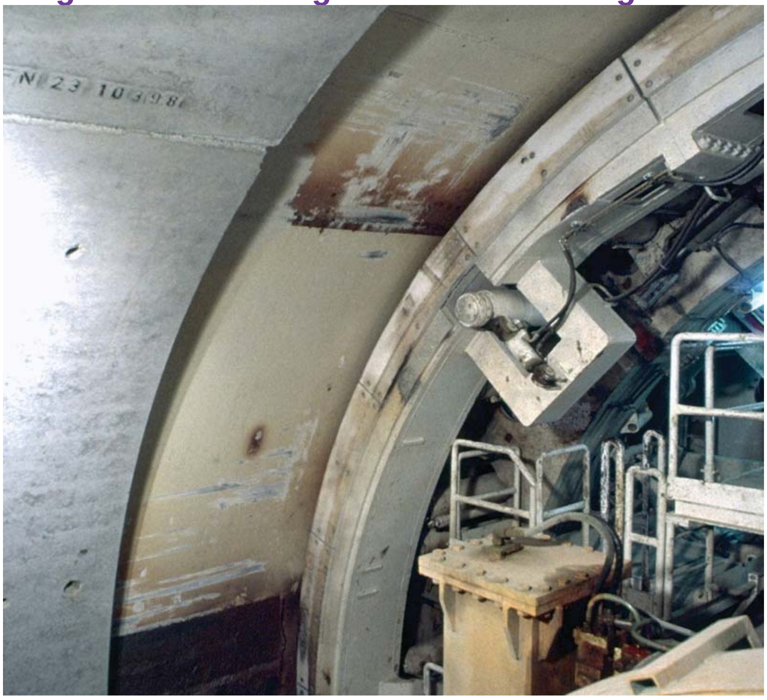
Tunnel Murgenthal SBB: 1998

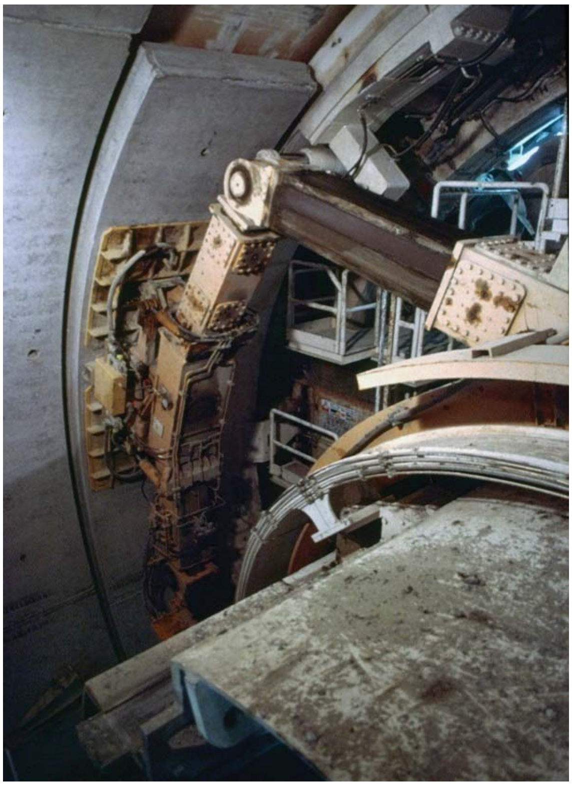
Hinterblasöffnungen

Opening for injecting peagravel

Tübbing Einbau: Halterungsrolle und Druckring

Ring of unbolted segments: Thrust Ring and Roll





Tunnel Murgenthal 1997 -1998:
Versetzen des linken Ulmentübbings
Versetzen Firsttübbing mit Versetzen des Schlusssteins stabiler Ring im Schildschwanz

Tunnel Murgenthal: 1997-98
Sohleinbau: *Backfilling the invert*

Tunnel Murgenthal:
Voreinschnitt Ost: Verschlammung
East Portal Cut: Formation of Mud

Bemessung: Erkennen der wesentliche Faktoren
Design: Recognize important factors

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Gebirgsbelastung/Rock loads

Einbauzustände/ Assembly

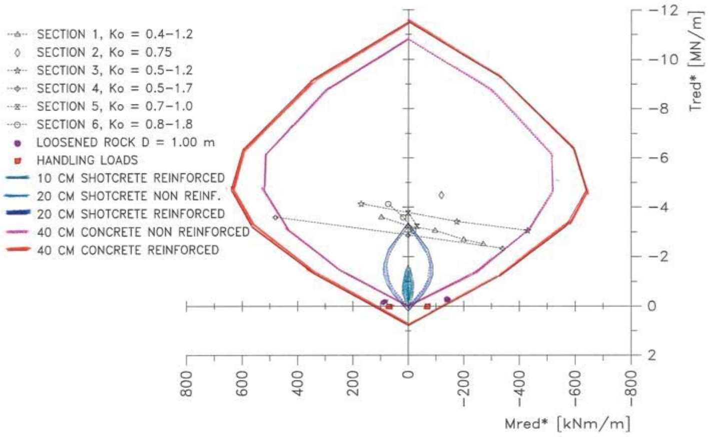
Transportation Loads

- Important Factors:
  - Radial Ground Displacements in the order of **Centimeters**
  - Tail Void Width one to two **Decimeters**
- Consequence:
  - Tail Void filling is the key issue
  - Loading of segments
  - Impervious single shell lining?

Vergleich unterschiedliche Auskleidung:

Comparison of different lining thickness

- **Tübbing 400mm (*Segments*)**
- **Spritzbeton (*Shotcrete*) 200 mm**
- **Spritzbeton (Shotcrete) 100 mm**



Example of Design of Grauholz Tunnel: Circular Shield

Differences in computed load do not matter, as long as they inside M-T Diagram

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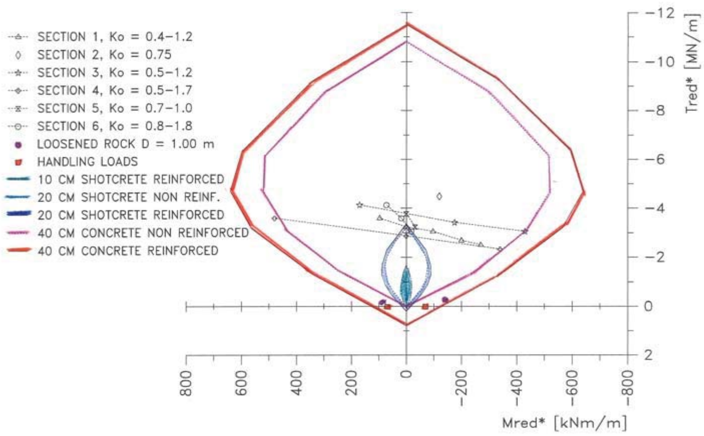
Bemessung der Auskleidung für (Grauholz): Schildtunnel mit kreisförmigem Querschnitt

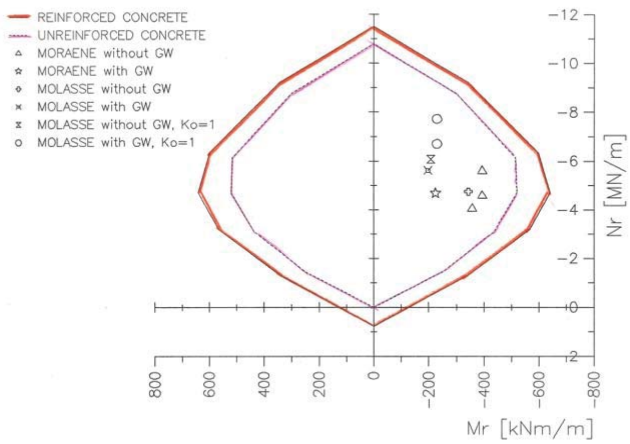
Design with analytical solution by Einstein-Schwartz with correction for face effects

Anwendung der analytischen Lösung von Einstein-Schwartz mit Korrektur für Ortbrust

Design with German Recommendations by DGEG (Duddeck – Windels)

Berechnung mit Empfehlungen der DGEG (Duddeck- Windels)





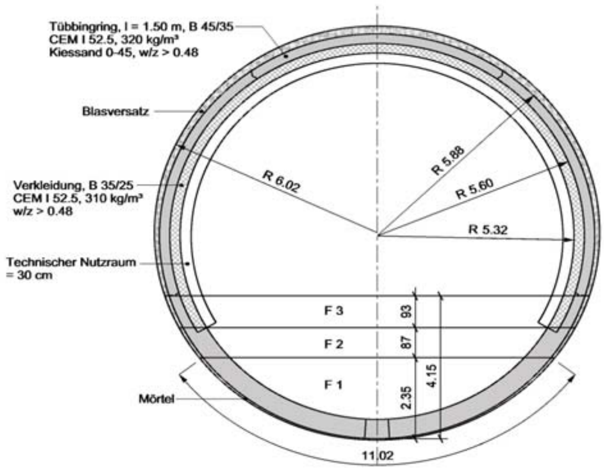
Key Elements for TBM advance in rock

Backfilling of Tail void with grout in invert and pea gravel in crown

Schlüsselelemente bei Fels TBM

Hinterfüllung mit Mörtel in der Sohle und Perlkies im Scheitel

Handwerkliche Elemente im Nachläufer am Schildschwanz



Bauteil	Fläche in m2	Gewicht (kN)	Teile	Gewicht (kN) **Weight (kN)**
Mörtel **Grout**	0.63			
Blasversatz **Pea Gravel**	4.42			
Schlussstein **Keystone**	0.35	8.75	1	8.75
Sohltübbing **Invert segments**	3.47	86.75	2	173.5
Tübbing seitlich Segments lateral	2.00	50.00	2	100
Scheitel-tübbing **Crown segment**	2.00	50.00	1	50
Gewicht Tübbingring				**332.25**
	Teilflächen	Totalfläche	Auftrieb Wasser: γ = 10 kN/m3	Auftrieb Mörtel: γ = 20 kN/m3 Uplift from mortar
Fläche 1; H = 2.35 m	16.12	16.12	161.2	**322.4**
Fläche 2: H = 3.22 m	8.91	25.03	250.3	500.6
Fläche 3; H = 4.15 m	10.29	35.32	353.2	706.4

Qualitätskontrolle der Hinterfüllung I

Quality control of back filling I

Tübbingring exzentrisch

- Vermeiden Aufschwimmen des Tübbingrings
  - Begrenzte Mörtelinjektion in der Sohle
- Hinterblasen mit Perlkies in Ulmen und im Scheitel
  - Umsetzen der Ansatzpunkte zum Hinterblasen
  - Nachrutschen des Perlkies beim Vorschieben der TBM

Ring of Segments: Eccentric

- Avoid Uplift of Ring of Segments
  - Limit Volume of grout in invert
- Backfill Springlines and crown
  - Alternate between openings where pea gravel is filled-in with advance of TBM
  - Pea gravel will slide down the walls

Qualitätskontrolle der Hinterfüllung II
Quality control of back filling II

Absetzen von Schichtpaketen im Scheitel: Massnahmen

- Kontrolle des eingeblasenen Volumens an Perlkies
  - Vergleich eingebrachtes mit theoretisch einzubringendem Volumen
  - Wenn zu gering: Folgerung: abgesetztes Schichtpaket.
- Kontrollbohrungen
  - Injektionen über Schichtpaket
  - Kontrolle Injektion mit Volumen und Druck

Large loosening loads: Identify and take measures

- Verify Volume of injected Pea Gravel
  - Compare placed volume with theoretical volume
  - If volume insufficient: large loosening load is likely (Block)
- Borings through lining
  - Grout voids
  - Verification of volume and pressure

Schild TBM (Kreisprofil) im Fels haben viele Probleme gelöst
Shield TBM (Circular Section) have let disappear problems

- Quellendes Gebirge
  - Automatisch ein Sohlgewölbe vorhanden
  - Kleinere potentielle Quellzone
- Auflockerungsdruck
  - Instabilitäten als Folge von spannungsbedingten Ablösungen (stress-driven instabilities)
  - Stabilität der Ortbrust kann entscheidend sein
- Verformungen
  - Kreisförmiger Ausbau (Tübbing) hoher Ausbauwiderstand mit hochfestem Beton
- Saubere, gesicherte Sohle
  - Keine Aufweichungen
  - Keine “Schlammschlacht”

- Swelling Rock
  - A strong invert is part of the system
  - Smaller potential zone of swelling
  - Smaller damaged zone (Crack formation)
- Loosening Loads
  - Stress-driven instabilities can be managed
  - Stability of tunnel face in fault and broken zones can be critical
- Verformungen
  - Circular liner with substantial structural capacity
- Secured invert:
  - No softening
  - No «Mud slinging»

Durchbruch Murgenthal Tunnel
Holing through

Staub verzieht sich; *The dust settles*

Fertiger Durchbruch *Complete*