DESIGN OF TUNNELS IN VARIOUS ROCK CONDITIONS

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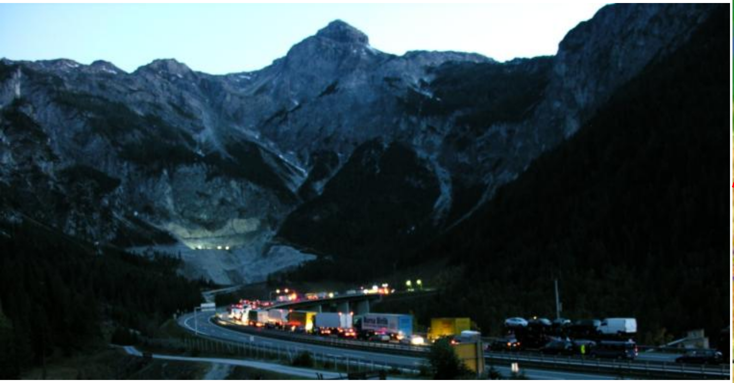
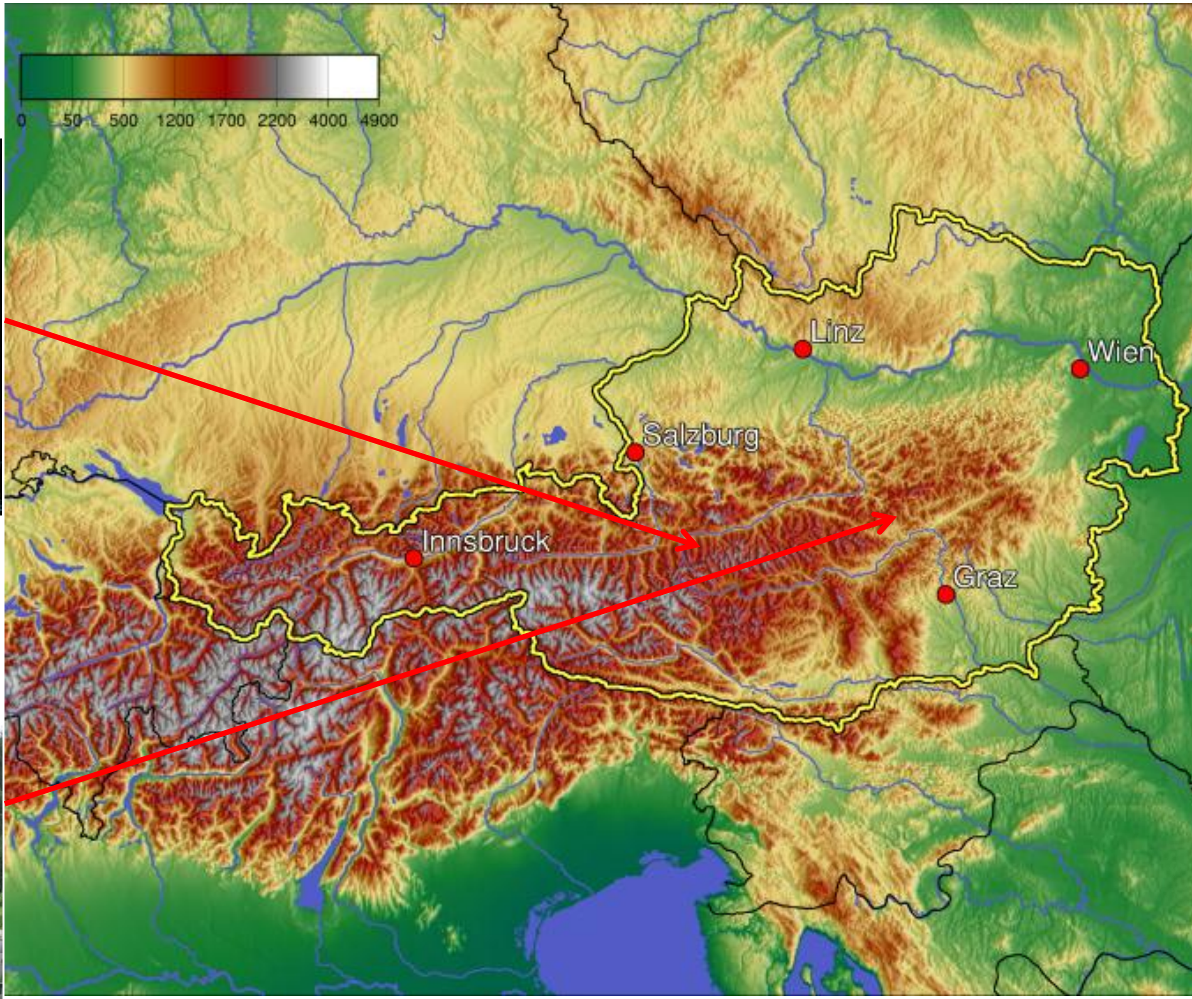
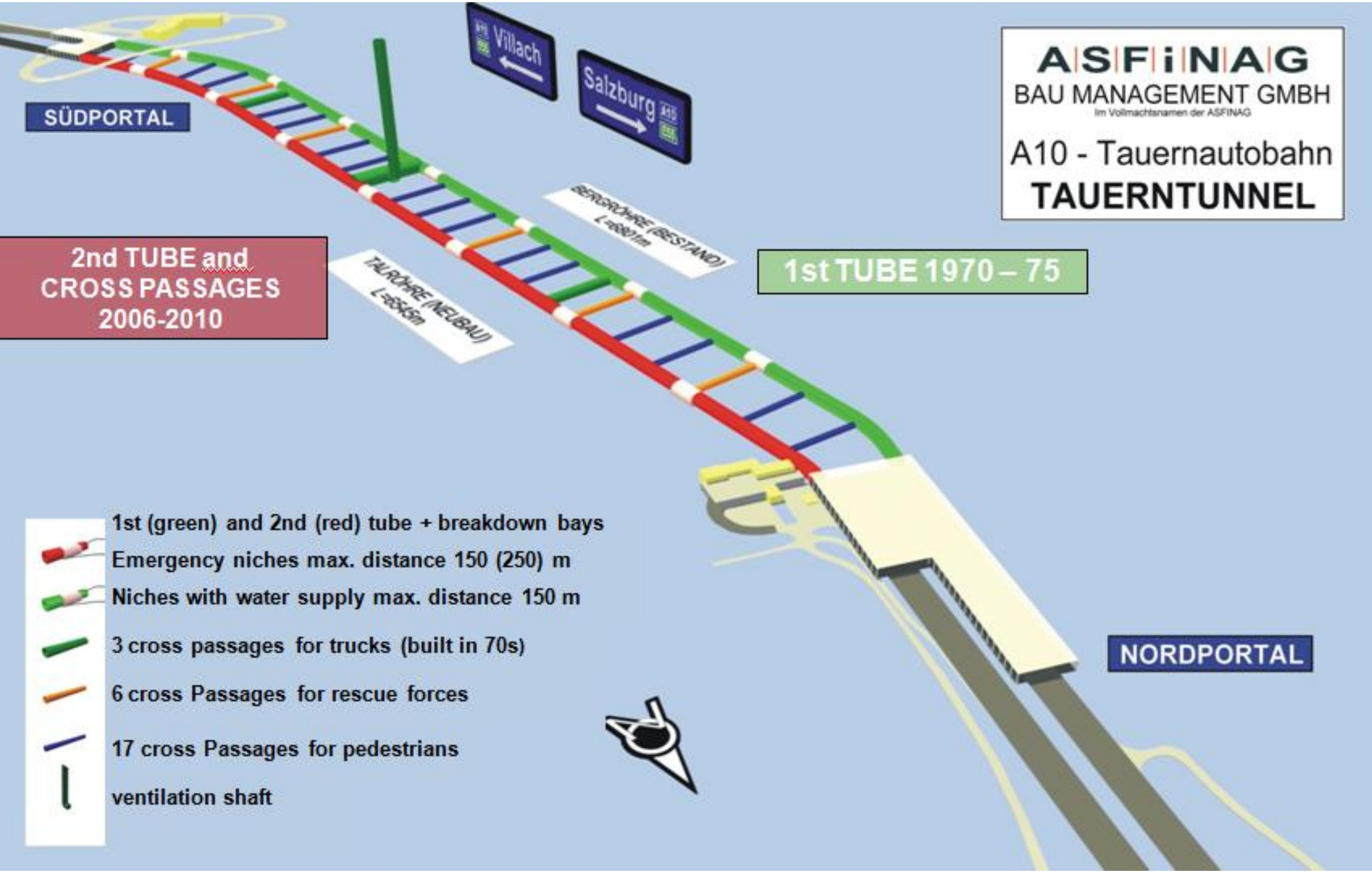
CASE STUDIES

- Tauerntunnel, Austria



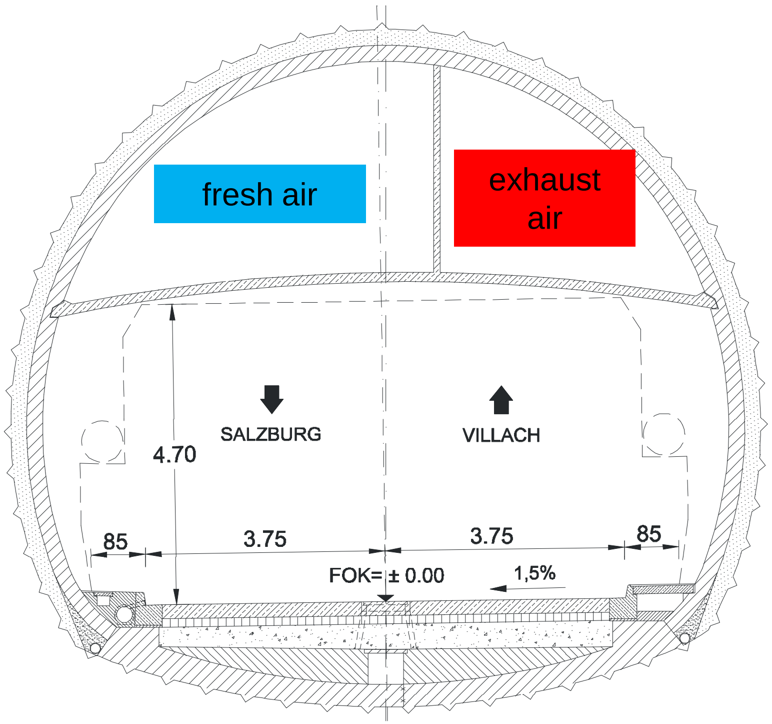
- Gleinalmtunnel, Austria




SÜDPORTAL
Villach
Salzburg
ASFiNAG
BAU MANAGEMENT GMBH
A10 - Tauernautobahn
TAUERNTUNNEL
2nd TUBE and CROSS PASSAGES 2006-2010
1st TUBE 1970 – 75
1st (green) and 2nd (red) tube + breakdown bays
Emergency niches max. distance 150 (250) m
Niches with water supply max. distance 150 m
3 cross passages for trucks (built in 70s)
6 cross Passages for rescue forces
17 cross Passages for pedestrians
ventilation shaft
NORDPORTAL

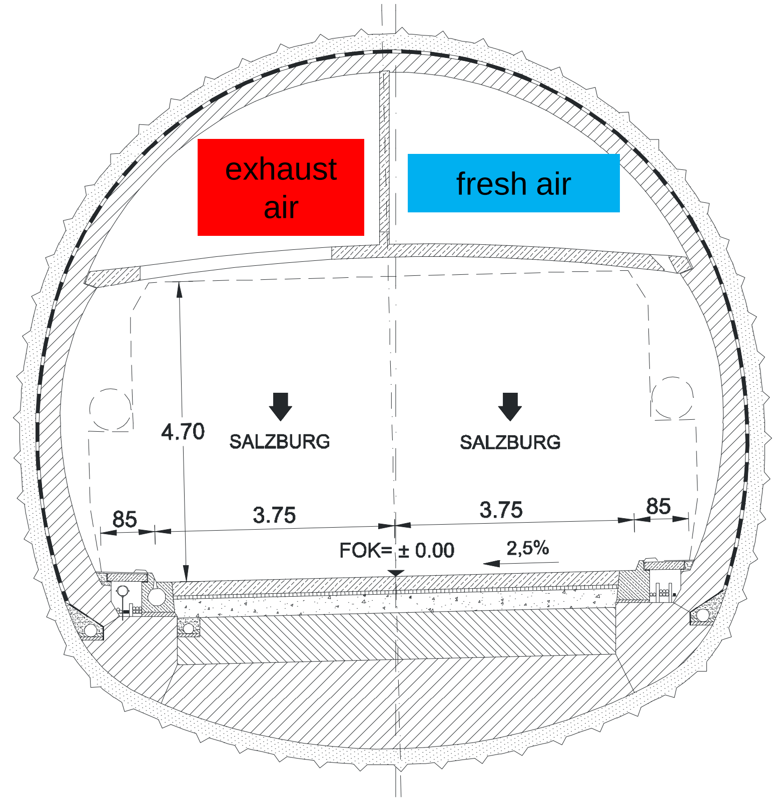
Typical cross sections

- 1st tube

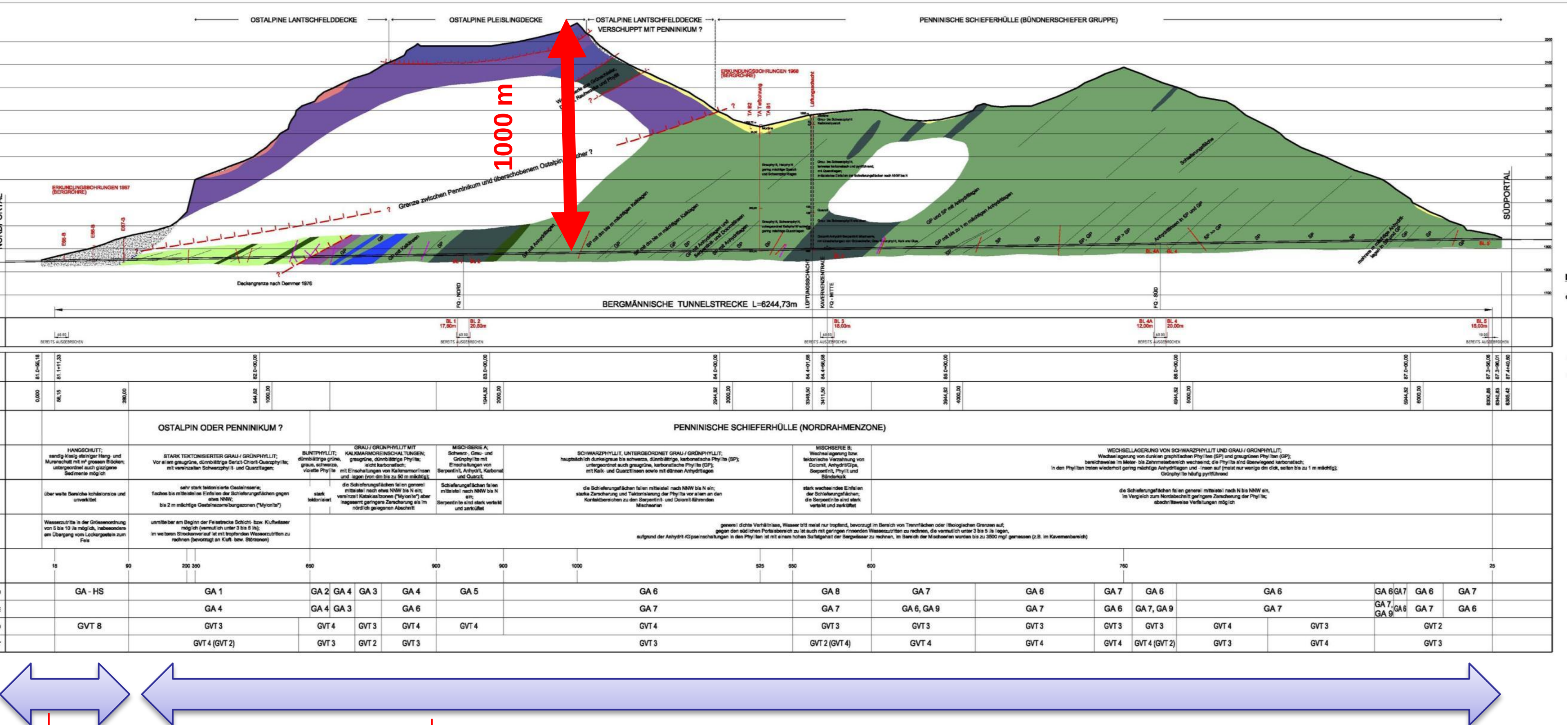


- Excavation area 102 m²

- 2nd tube



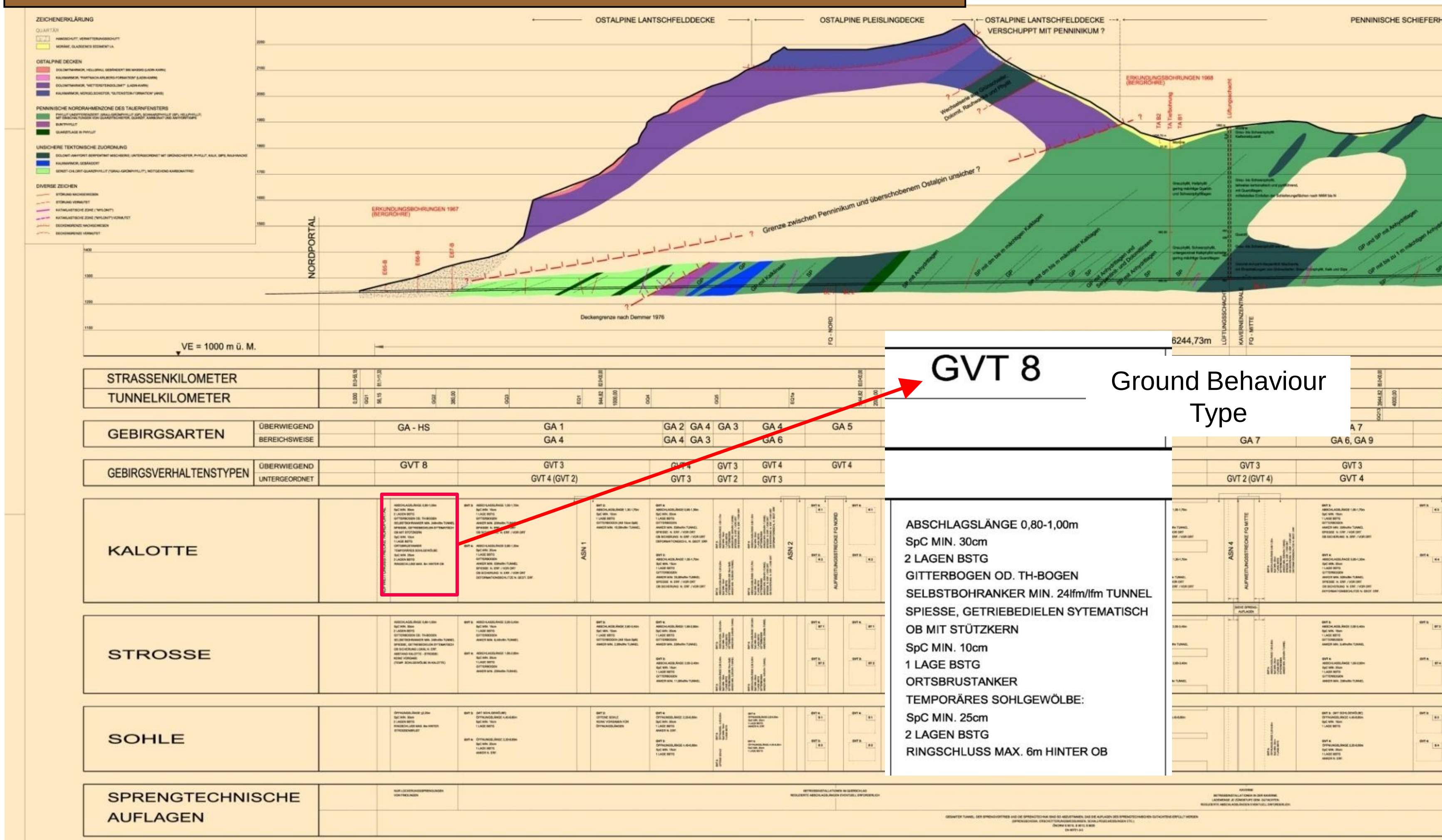
- Excavation area 109 m²



- Slope debris
- Cohesionless gravel

- phyllites
- subsidiary layers of limestone, marble, anhydrite

Technical Tunneling Framework (Extract)



Prognosis → Planning

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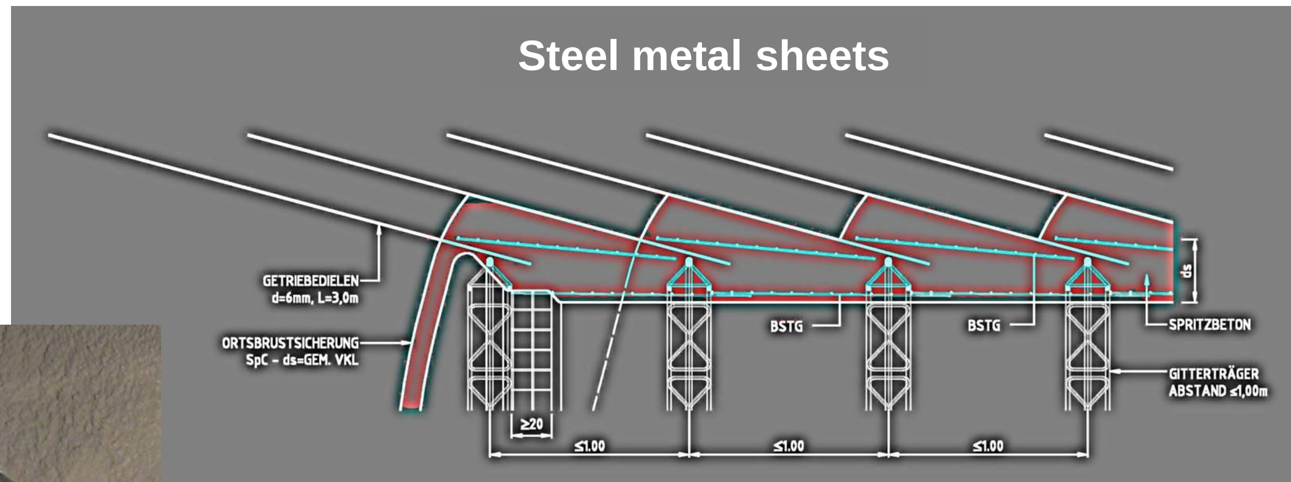
Gravel Section up to TM 380

- Construction in cohesionless gravel area



Top heading in coarse blocky gravel

- Gravel area: boulders obstructing steel metal sheets

Top heading in coarse blocky gravel

- Outflow of gravel – ravelling ground

Top heading in coarse blocky gravel

- Partial face excavation with 12 sections (average)

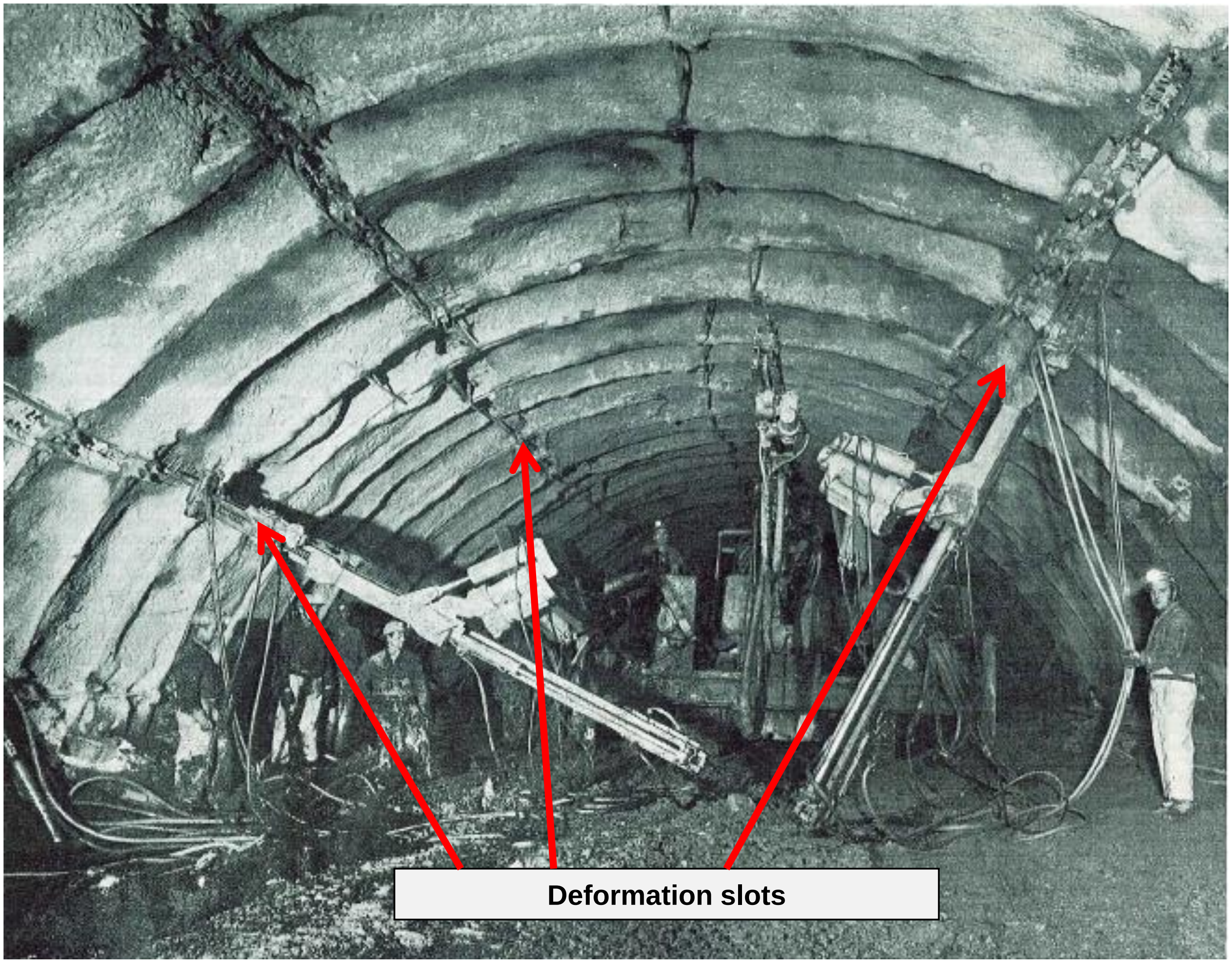
Rock section - experience gained from constr. 1st tube

- Squeezing rock conditions
- Extreme top heading settlements up to 1.3 m

Rock section - experience gained from constr. 1st tube

- Squeezing rock, buckled steel arches

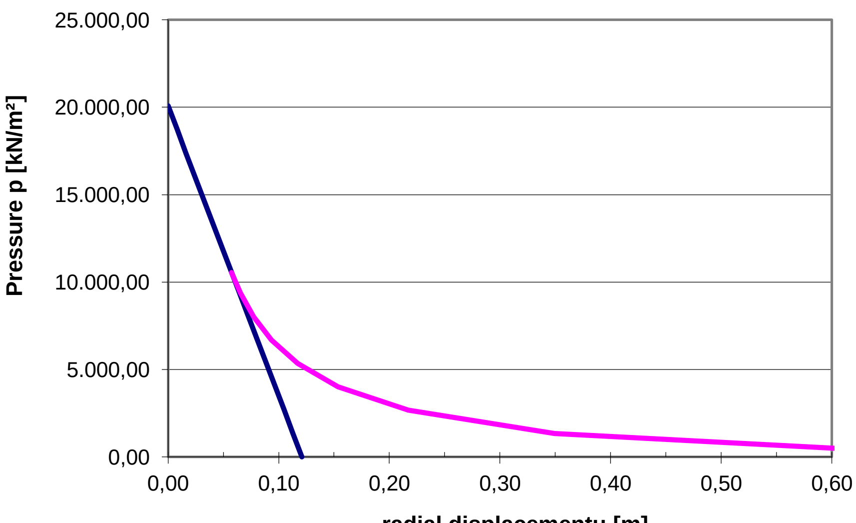
Rock section - experience gained from constr. 1st tube



Design of 2nd Tube - Geotechnics

- Basis for the design
  - Geological documentation of 1st tube and prognosis of 2nd tube
  - Deformation and convergence measurements of 1st tube
  - Testing programme: uni- & triaxial compression tests, shear tests, dilatometer tests

→ back analysis using ground reaction curve



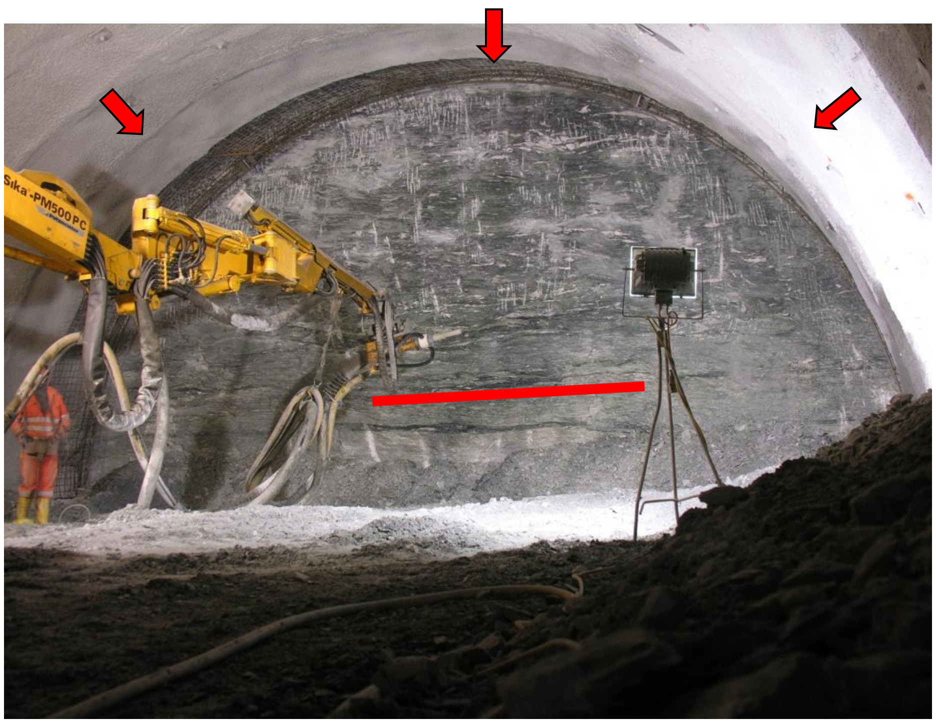
Ground reaction curve

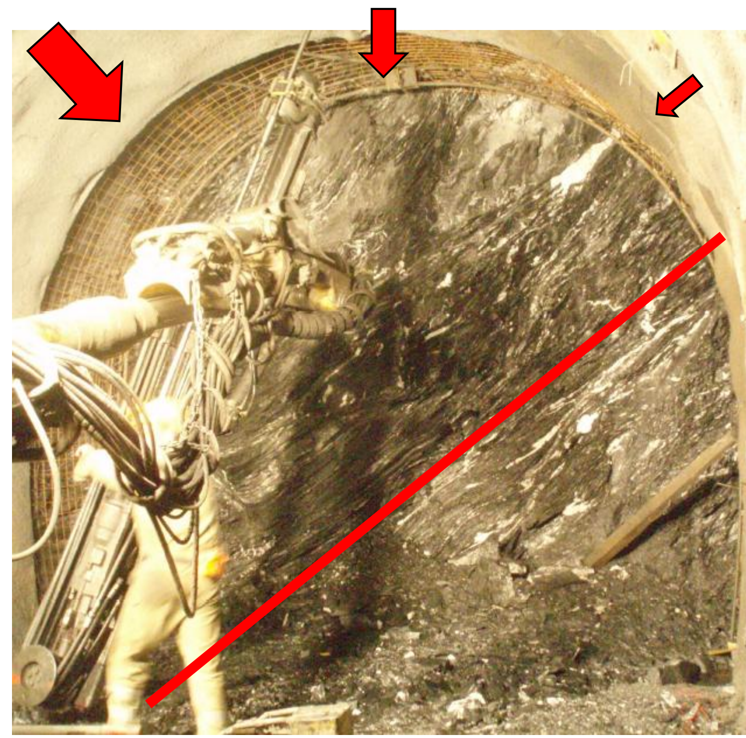
Uncertainties

- Determination of „real" rock mass parameters is usually very difficult.
- Methods like Hoek-Brown rely on simplifications and estimations.
  → Back analysis of displacements of 1st tube permits a check of the range of rock parameters
- Interpretation of monitored displacements in 1970ies:
  no standard 3D monitoring
  monitoring sections were installed later than nowadays
  → documented displacements were set as lower limits

Uncertainties

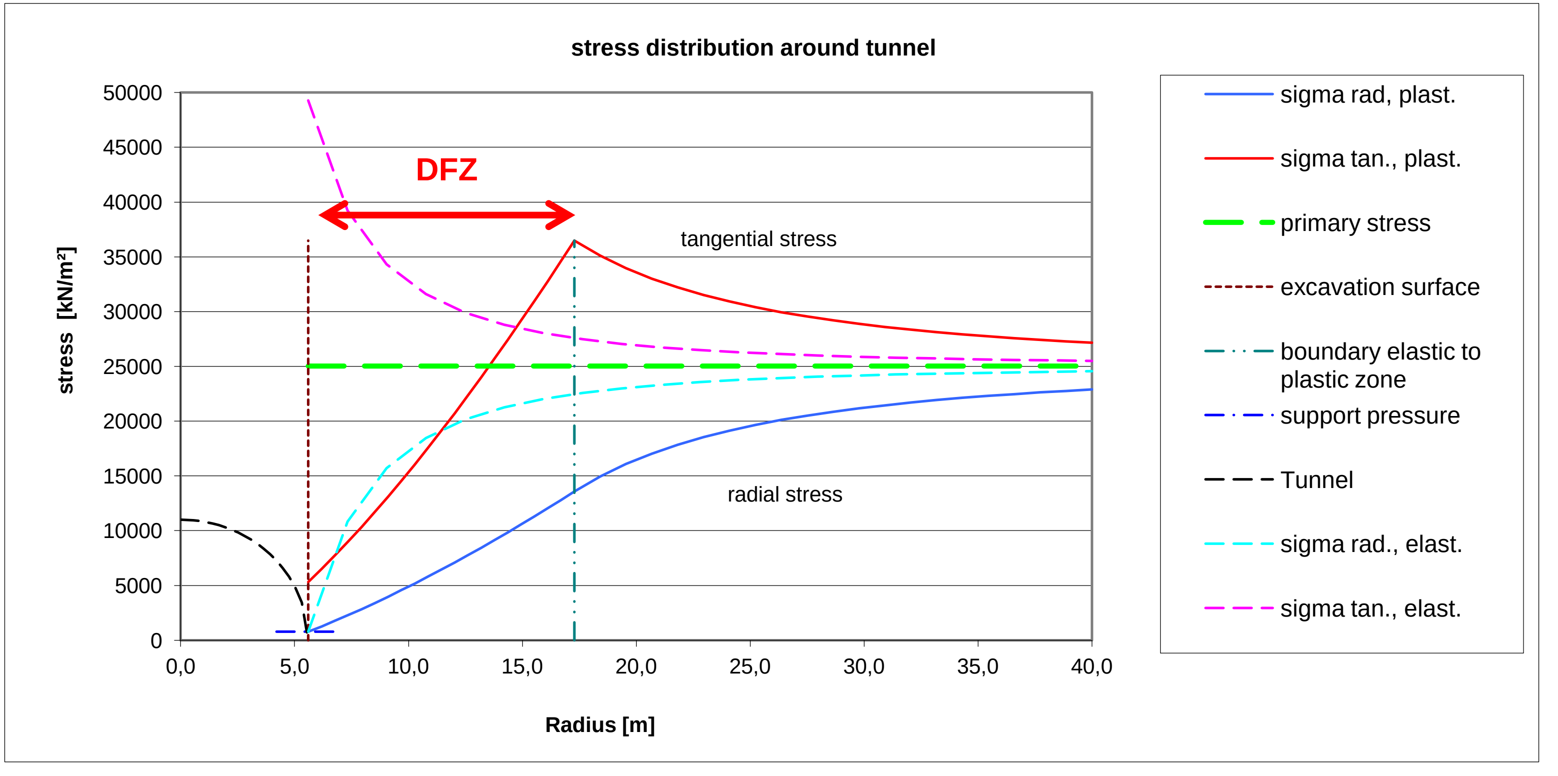
- Convergence confinement method:
  Ground reaction curve does not take into account the orientation of schistosity relative to tunnel → different set of rock mass parameters for different orientations





Design of 2nd Tube - Geotechnics

- Determination criteria for rock mass behaviour types
  - Radial displacements r
  - Depth of failure zone DFZ (plastic radius around tunnel) in relation to tunnel radius R (=5.6 m)



Design of 2nd Tube - Geotechnics

- Determination criteria for rock mass behaviour types
  - Radial displacements r
  - Depth of failure zone DFZ (plastic radius around tunnel) in relation to tunnel radius R (=5.6 m)

Rock Mass behaviour type	Criterion	
	Primary	Secondary
Discontinuity controlled block failure	r < 50 (-100) mm	(DFZ < 2.5 m)
Shallow stress induced failure	r < 100-150 mm	DFZ < R
Squeezing rock (deep seated rock induced failure)	DFZ > R	r > 150 mm

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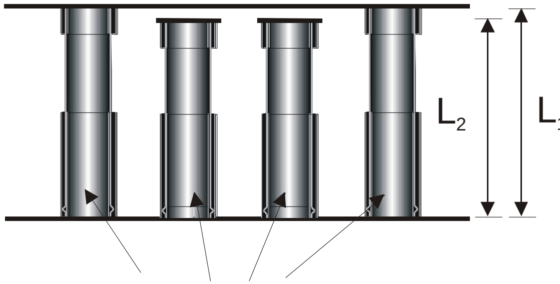
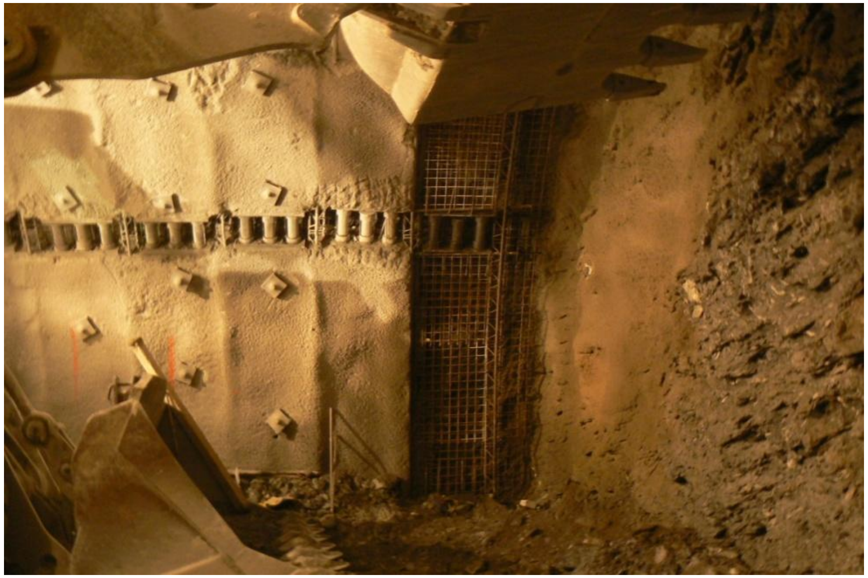
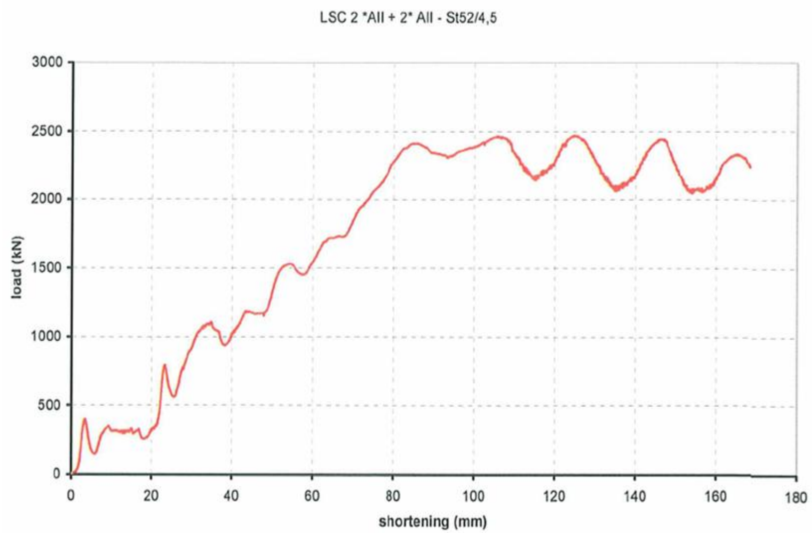
Design of 2nd Tube - Geotechnics

- Support Design
  - max. displacement ~12 cm absorbable by shotcrete at 1.5-2% strain
  - Radial displacements > 12 cm attributed to yielding elements
  - Max. expected displacement 600 mm



Yielding steel elements
Type, number and length adjusted to lining capacity and displacements (min. 2)





igure 3. Load displacement diagram for a group of 4 LSCII

Design of 2nd Tube - Geotechnics

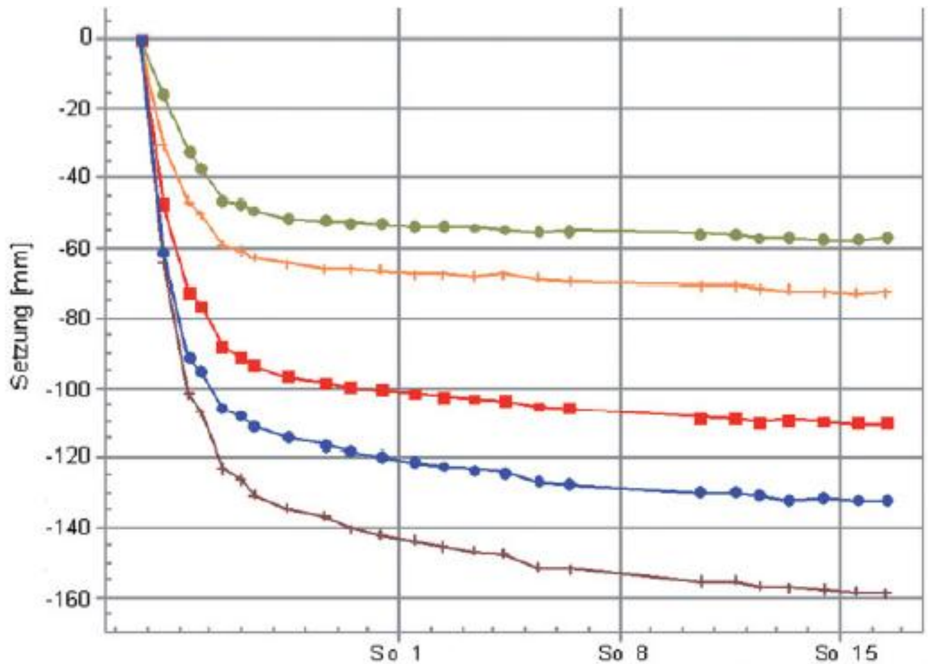
- Systematic installation of rock bolts with increasing number and length of bolts in increasingly squeezing rock conditions
  - Max. rock bolt density: 380 running meters of rock bolts per m tunnel
  - rock bolt plates with deformation pipes

Spraying of the shotcrete shell

- Construction execution – rock area

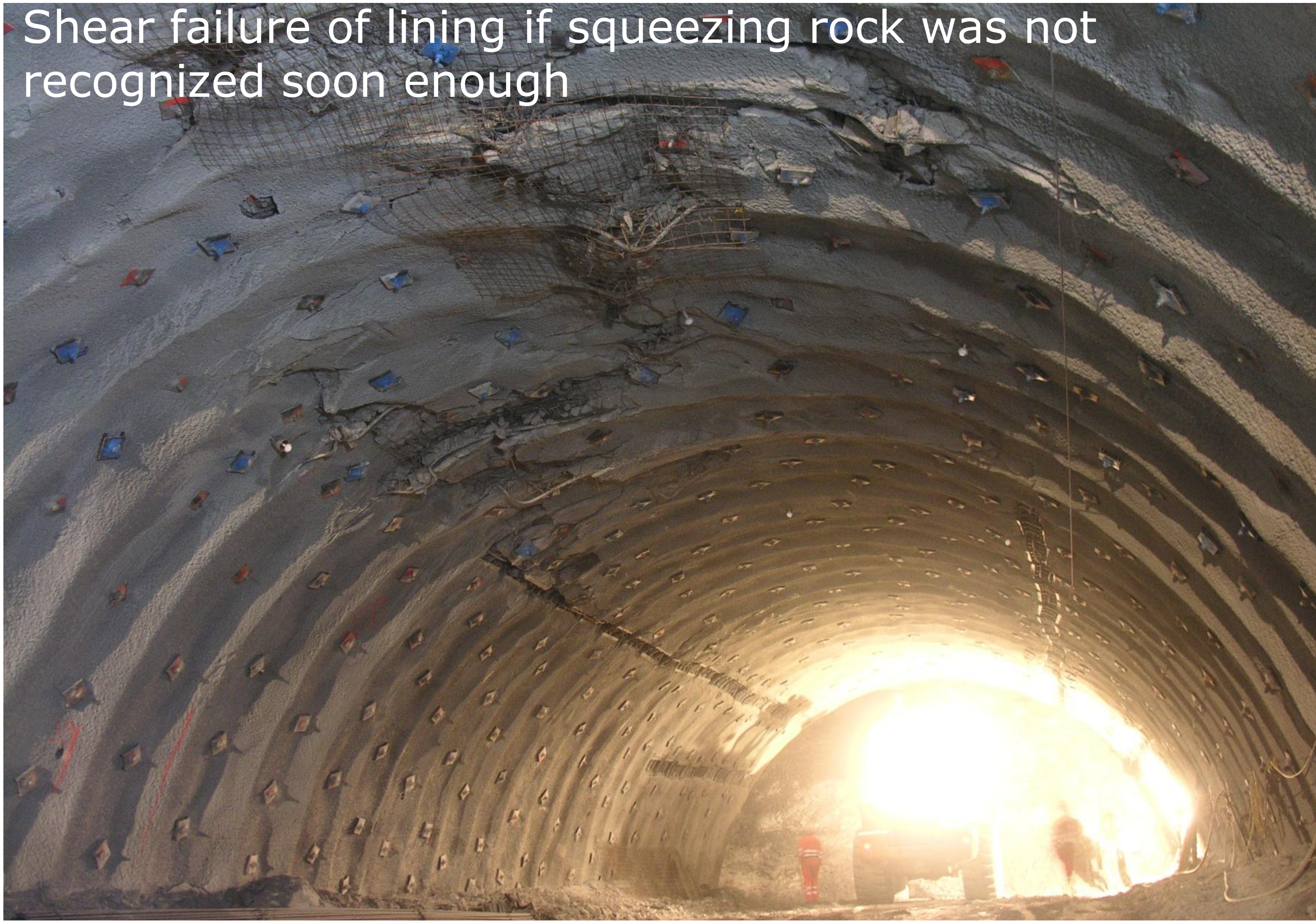
Recognizability of squeezing rock conditions

- Documentation of tunnel face does not reliably allow a priori determination of squeezing rock conditions
- Especially predicting slight squeezing areas was difficult
- In places, after an initial decrease of deformation rates long lasting creep deformations occurred



Recognizability of squeezing rock conditions

- Shear failure of lining if squeezing rock was not recognized soon enough



Refurbishment of sheared and damaged shotcrete shell

- instability of support system
- profile deficiencies

SPP

Criterion for installation of yielding elements on site

- Depending on deformation within 24 hours
  - up to 30 mm no deformation element
  - 30 mm to 60 mm → 2 rows (deformation allowance ~ 200 mm)
  - 60 mm to 120 mm → 4 rows (deformation allowance ~ 400mm)
  - more than 120 mm → 6 rows (deformation allowance ~ 600mm)

- Photo: intact shotcrete lining with use of yielding elements

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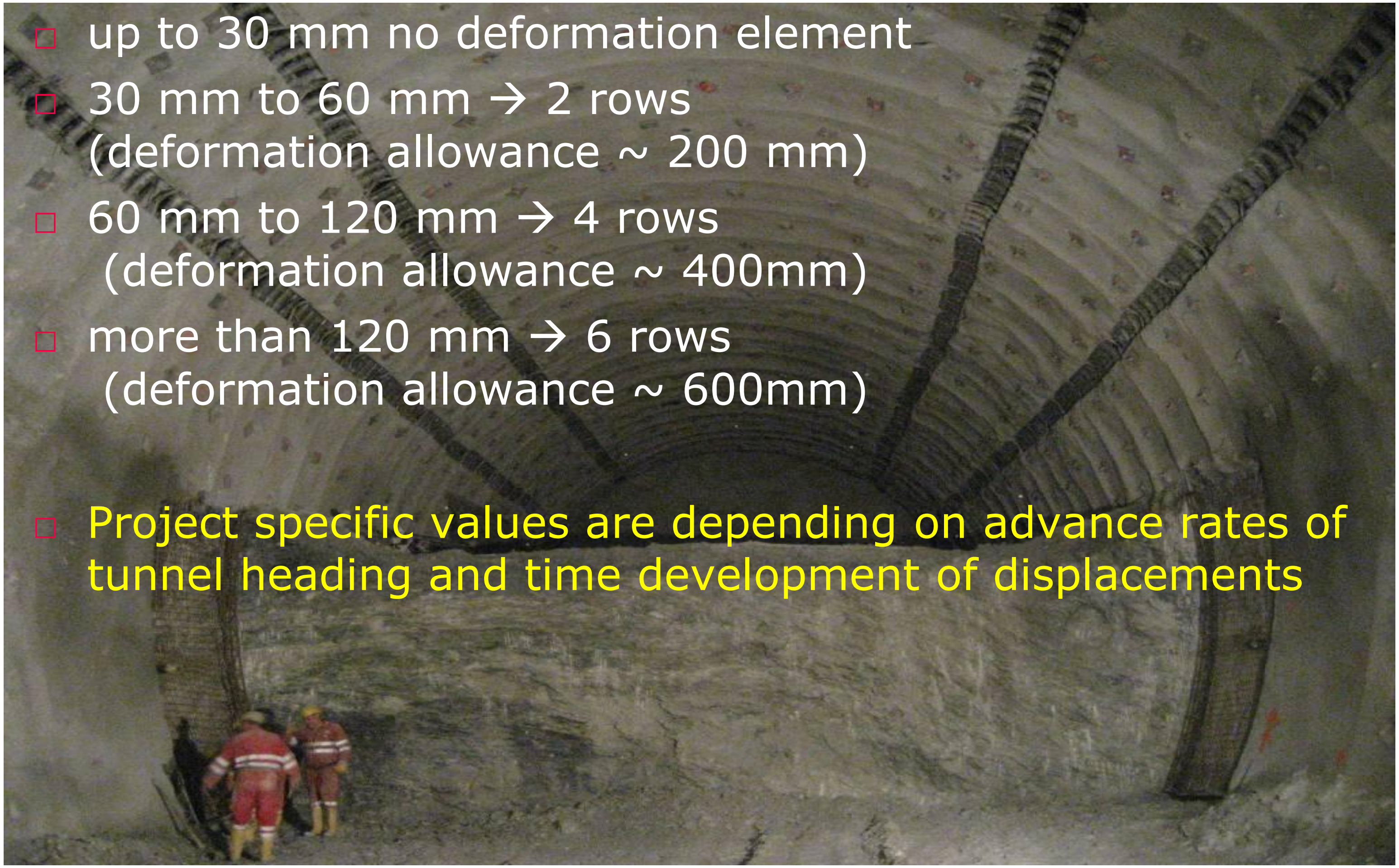

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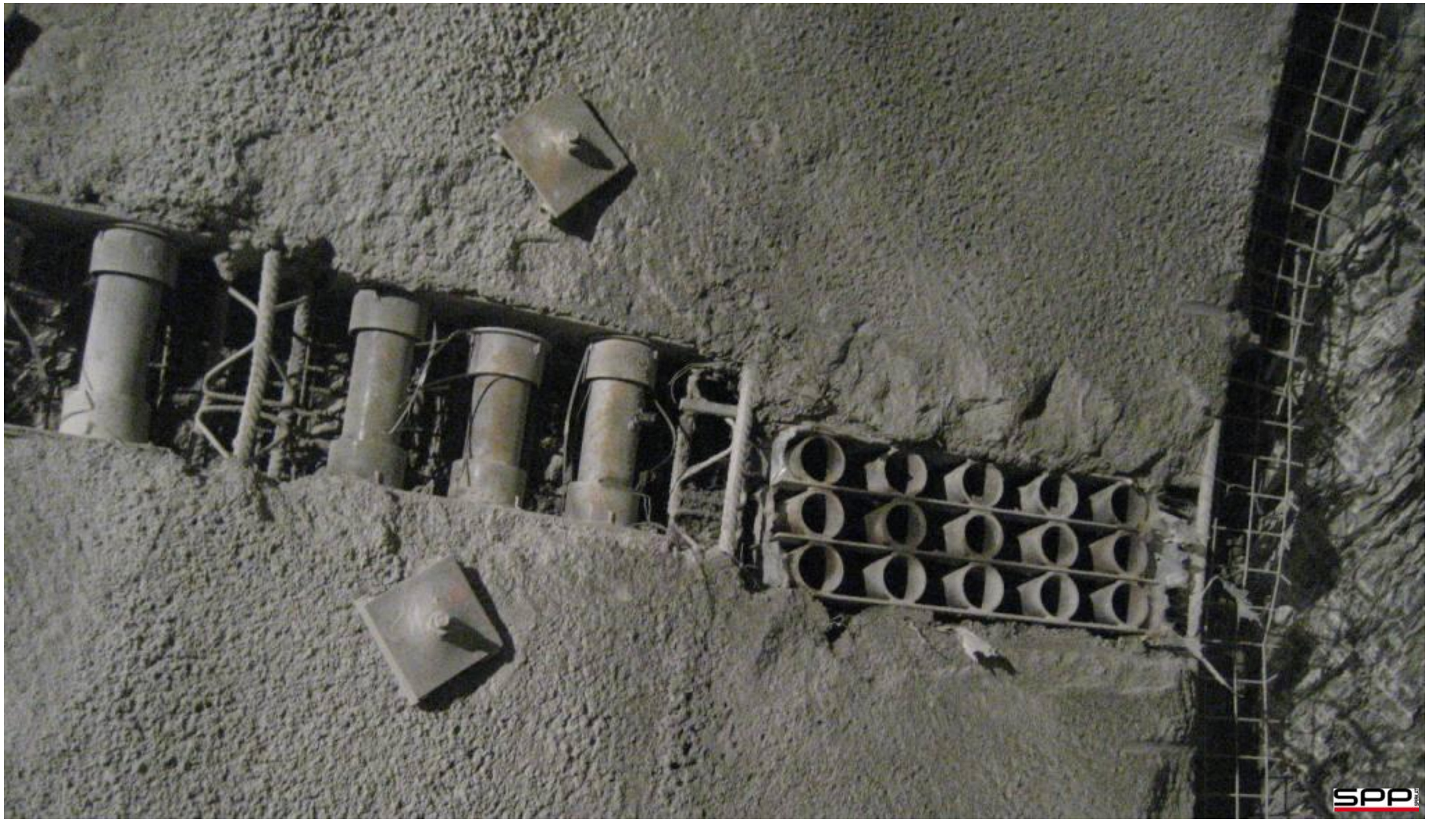
  - Project specific values are depending on advance rates of tunnel heading and time development of displacements

- Photo: intact shotcrete lining with use of yielding elements

Types of yielding elements used

- Lining stress controllers (LSC-elements; DSI)
- Honeycomb type WABE element (Bochumer Eisenhütte)



LSC element after consumption of displacements

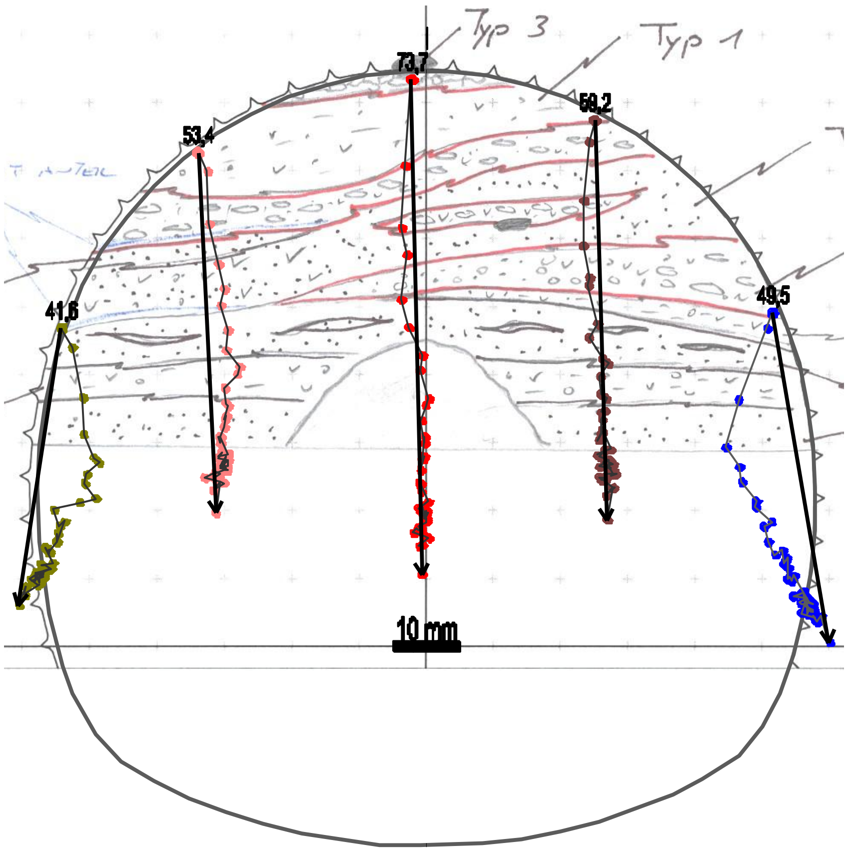
- Remaining gap to be closed with shotcrete

Trigonometric measurement control of rock deformation

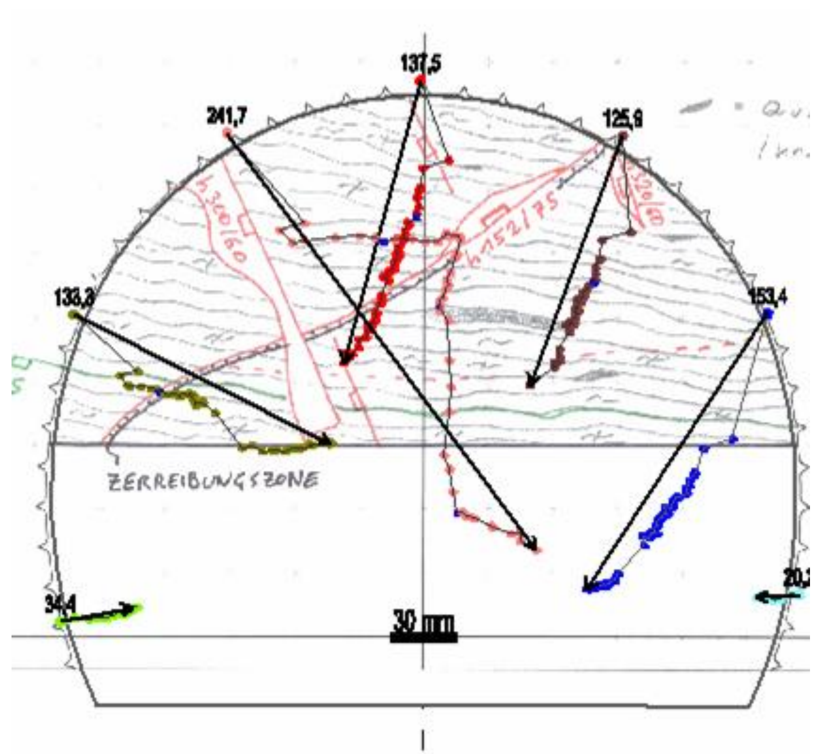
- Measurement control

Measurement control: vector plots of deformation

- typical deformation in gravel



- typical deformation in rock



Comparison of crown settlements

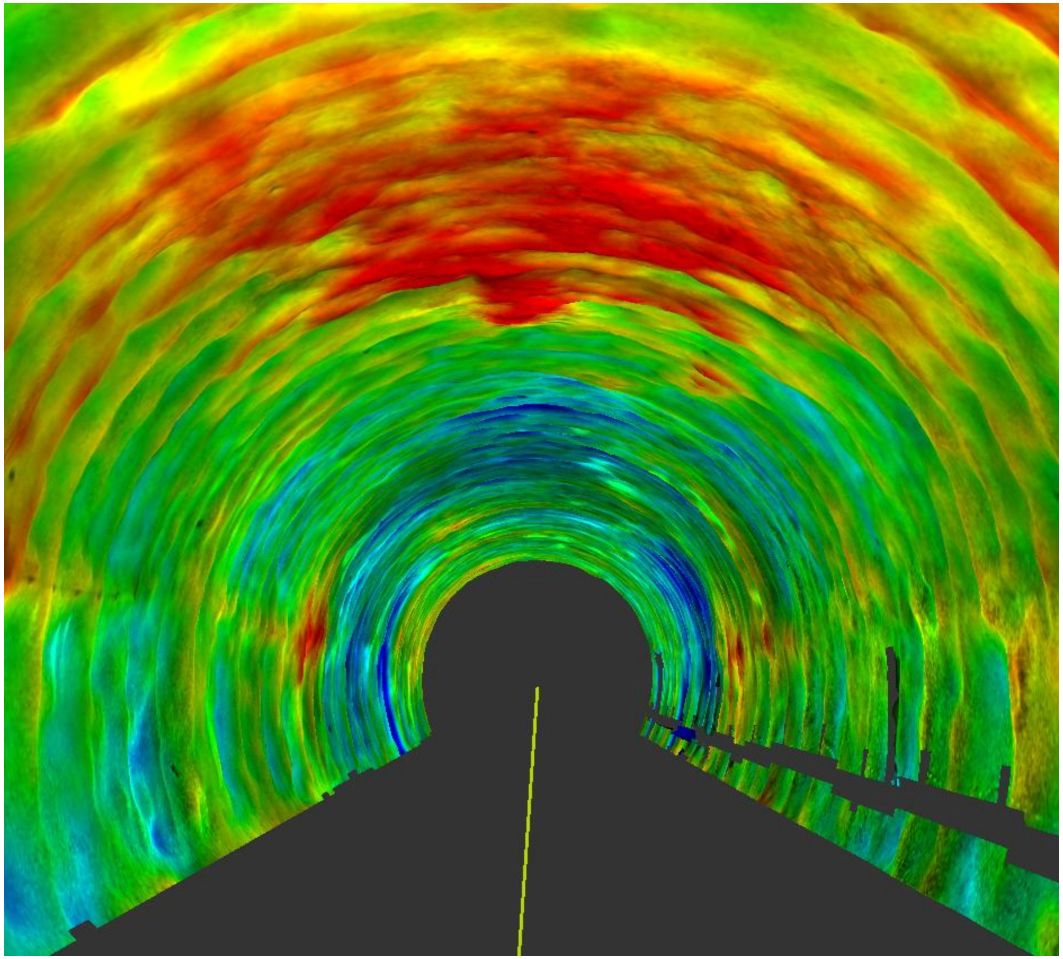
	1. tube	2. tube
Chainage 1100 from north	1300 mm	410 mm
Chainage 1800 from north	200 mm	30 mm
Southern Drive	Max. 200 mm	max. 50 mm

Reasons for less deformations in 2nd tube

- Increase of material quality and technology
- Yielding elements provide support pressure already as the deformations occur, while open deformation slots provide no support pressure at all (except of mobilized shear between shotcrete and rock surface)
- Quicker installation of support
- Higher quality in monitoring and evaluation of deformations
- Experience gained with tunnels in squeezing rock mass

Profile check

dibit 3DView



Inner lining

Moveable steel formwork

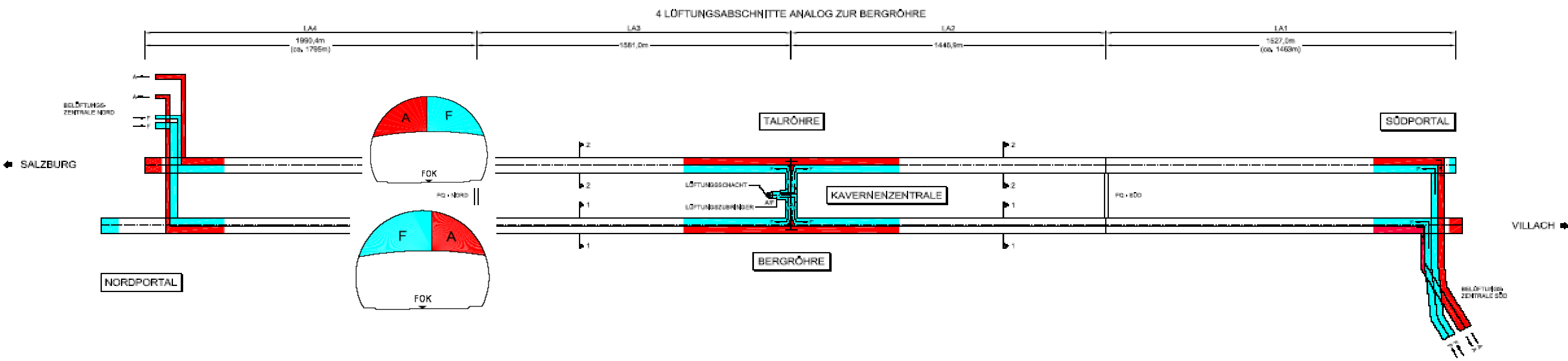
Cast in situ unreinforced concrete

Abutments for ceiling

Ceiling for ventilation ducts

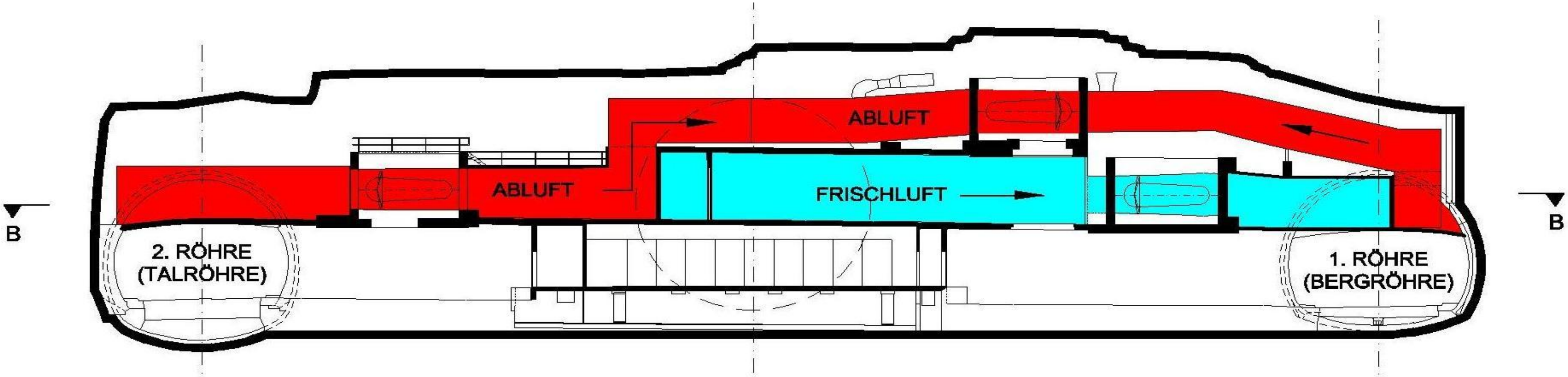
Ventilation system

- Fresh and exhaust air ducts
- 4 ventilation sections for each tube
- 2 inner sections for both tubes supplied + extracted through a 660 m high shaft
- Connection of shaft to tubes: via air supply tunnel + cavern



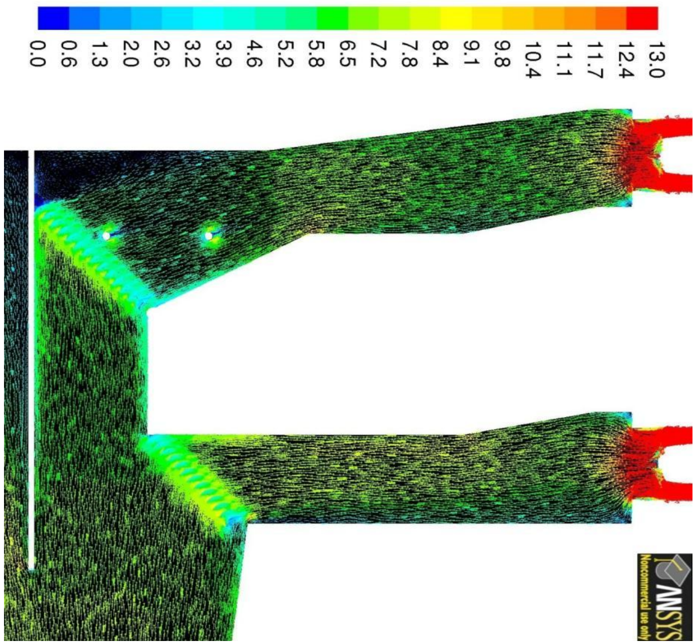
Ventilation Cavern

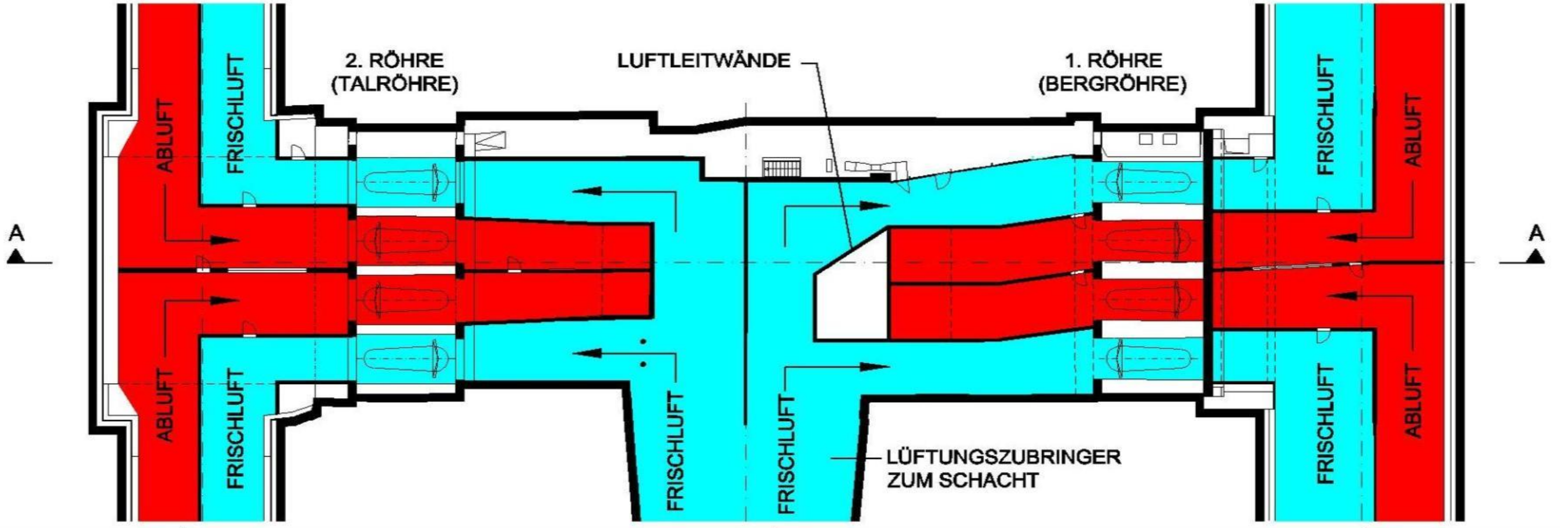
- 1970: emphasis on supply of fresh air
- 2005: emphasis on extraction of smoke in case of fire
- Redesign of air ducts in cavern was necessary



Redesign of air ducts in cavern

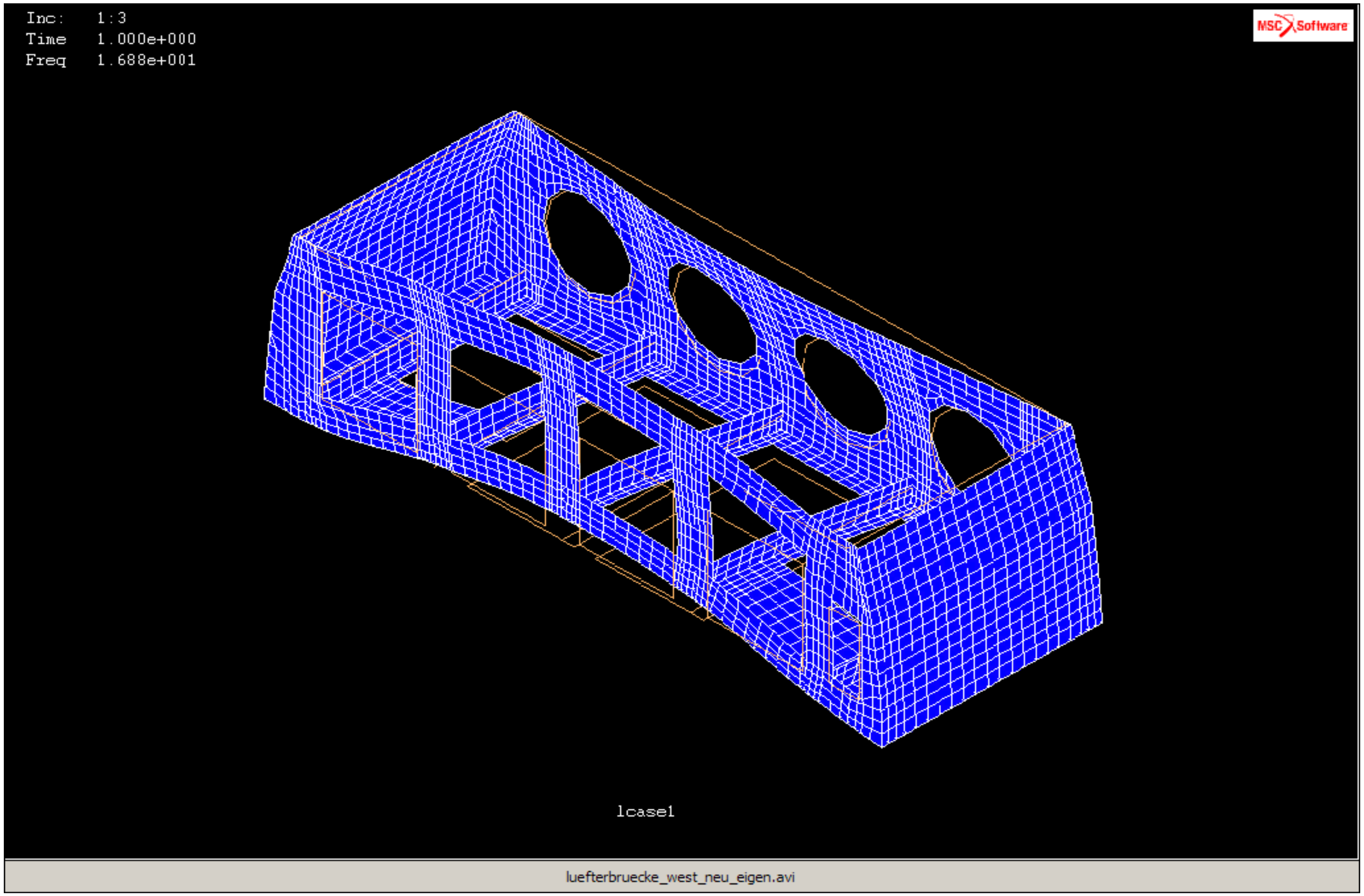
- Maintenance of traffic → operation of ventilation of at least one tube
- Statical analyses in combination with aerodynamic aspects





Redesign of cavern

- Oscillations had to be taken into account for the fan bridges → determination of natural frequency

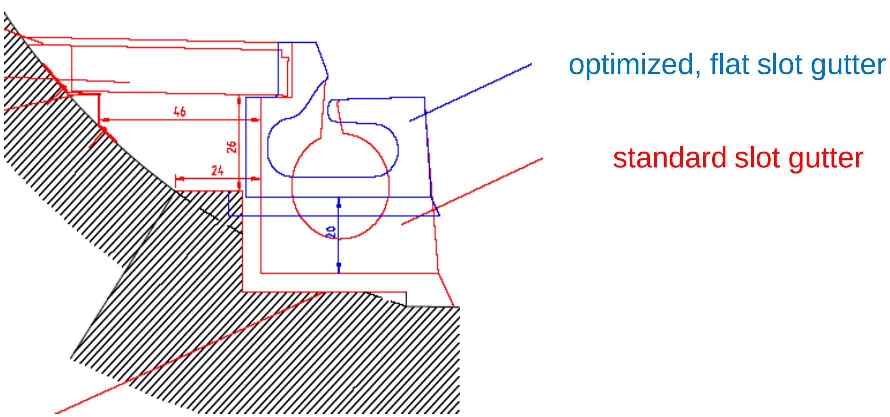


Design of 2nd Tube – Excavation Material

- 1.000.000 m³ excavation material
- Projects for reuse of material
- Tauernalm service area:
  - 235.000 m³ filled within 3 months
  - raising level by max. 7m
- Intermediate stockpiling necessary

Drainage System – Design aspects rehabilitation of 1st tube

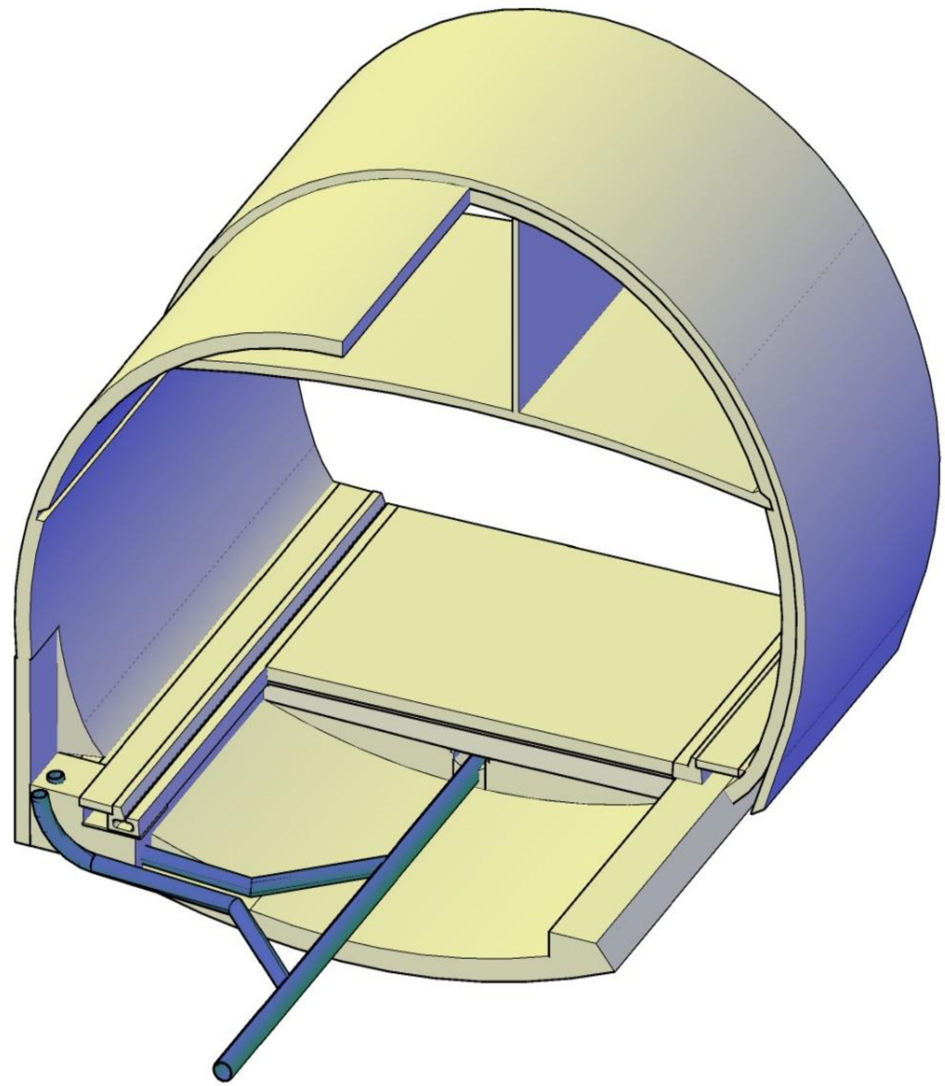
- Restrictions of existing abutment
- Avoidance of extensive milling of abutment
- → optimized flat slot gutter (Δh = 200 mm)
- Maintainability: culverts



Maintainability & Safety – Refurbishment of 1st tube

- existing drainage duct located unfavourably → tunnel closure for maintenance works
- problems with man hole covers

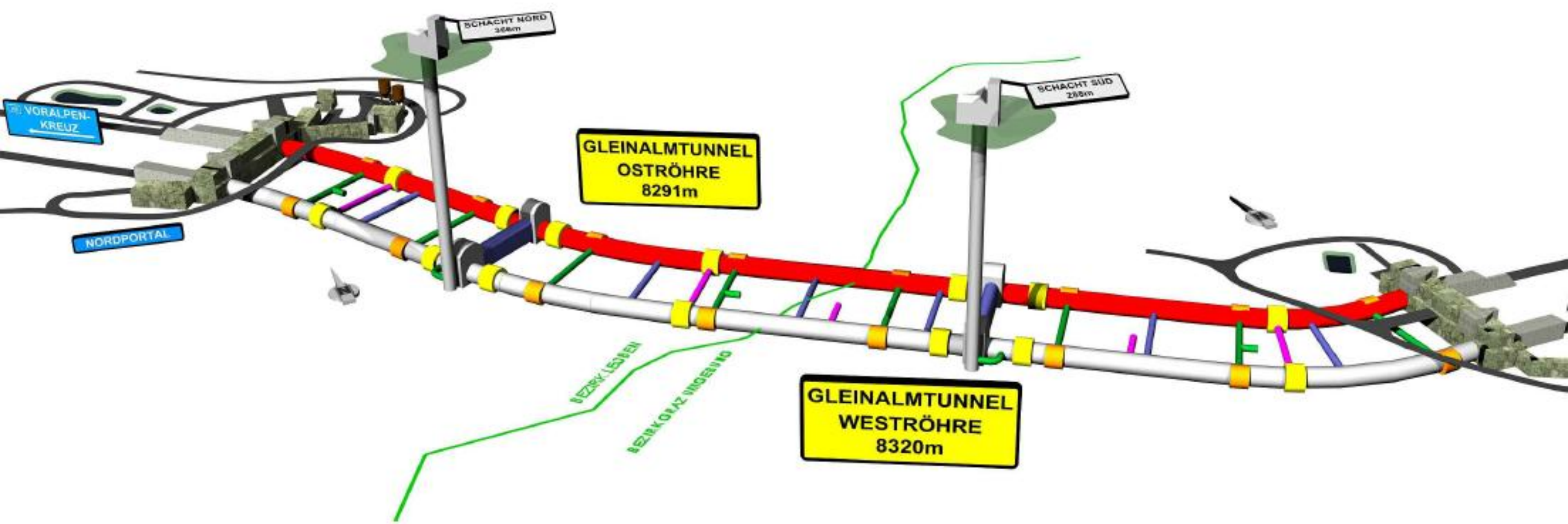
- → new drainage pipe in existing duct
- → flushing pipes for maintenance



- Easily accessible
- Increased safety

- Both tunnel tubes opened to traffic in 2011

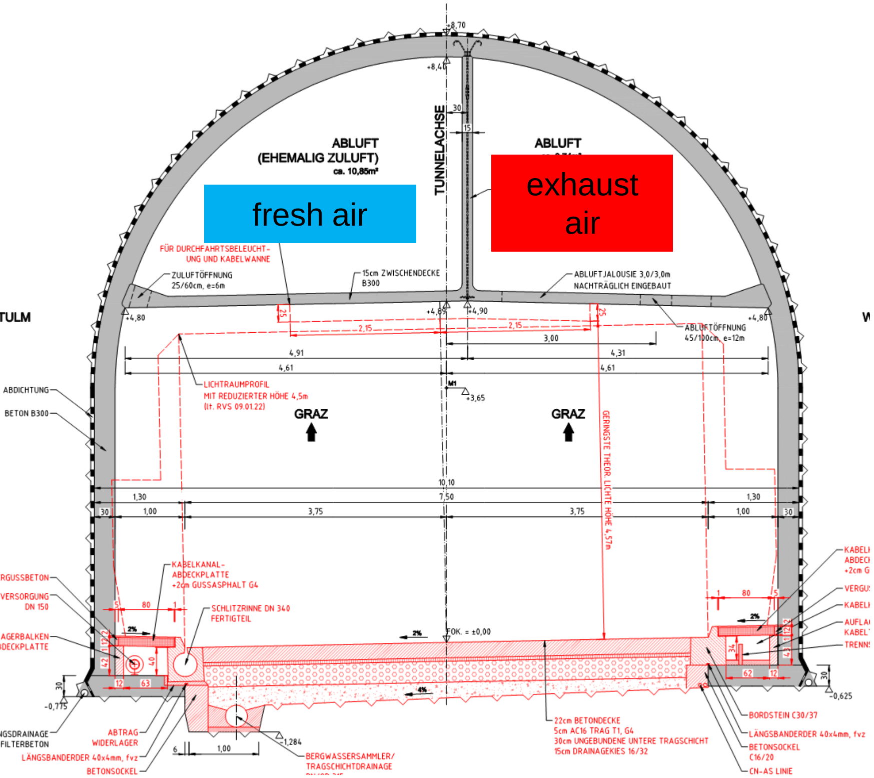
GLEINALMTUNNEL – 3D view



- L=8320m (third longest road tunnel in Austria)
- 1st tube opened to traffic 1978
- 2nd tube under construction

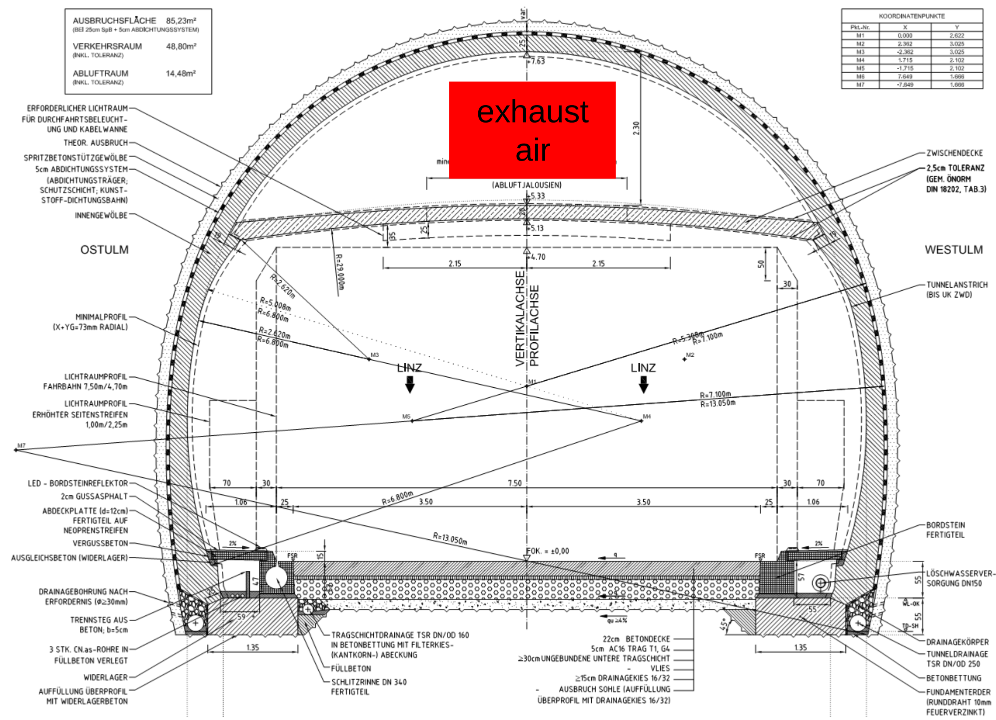
Typical cross sections

- 1st tube



- Excavation area 102 m²

- 2nd tube



- Excavation area 85 m²

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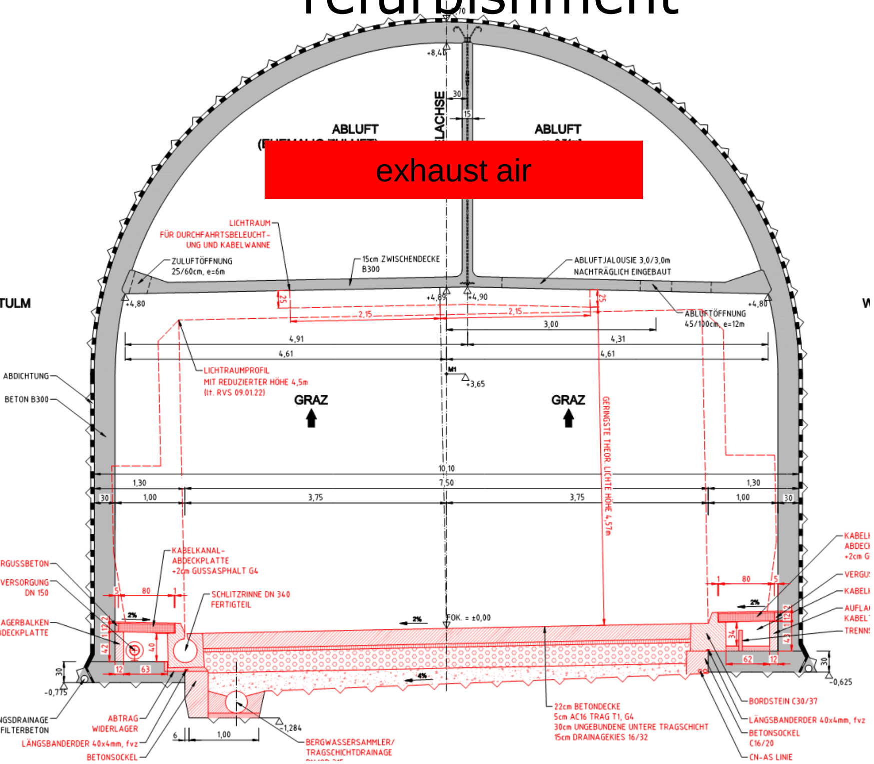
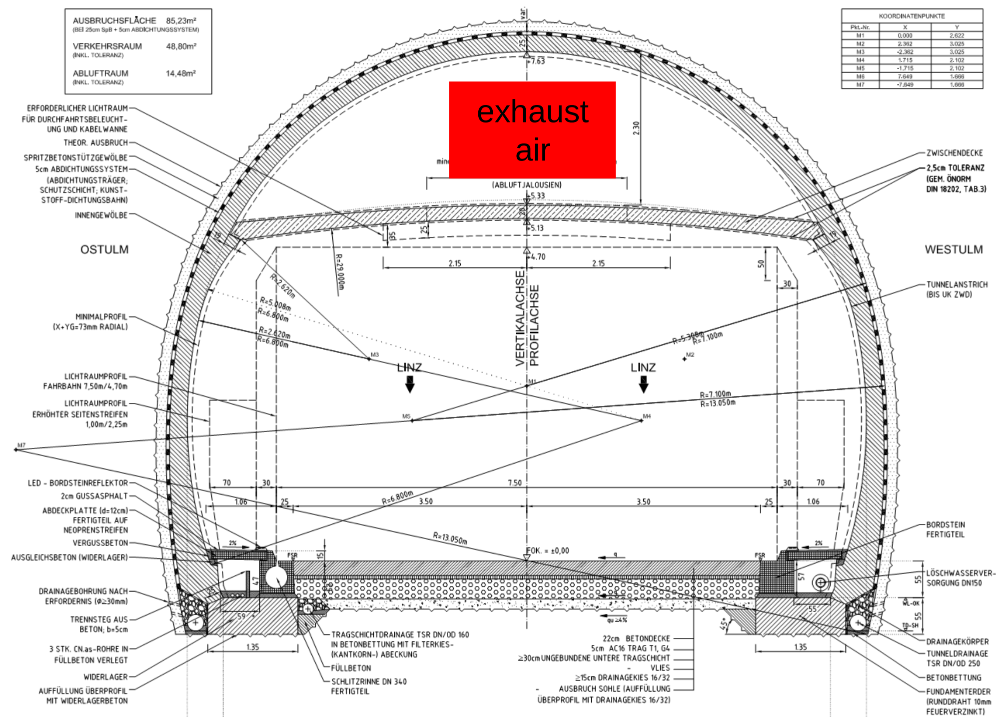
Typical cross sections

- 1st tube - after refurbishment
- 2nd tube

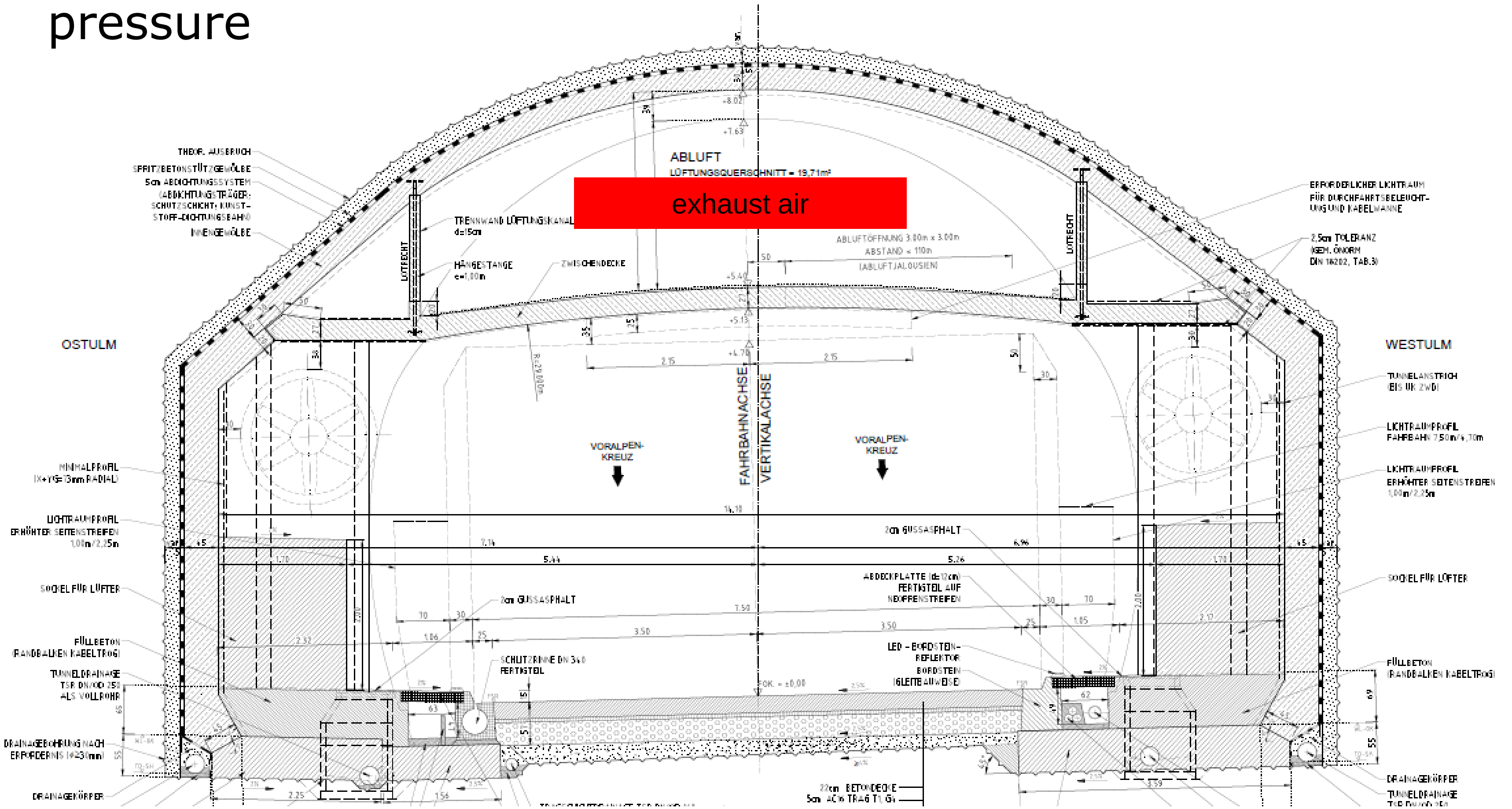




- Excavation area 102 m²
- Excavation area 85 m²

Ventilation bays for jet fans

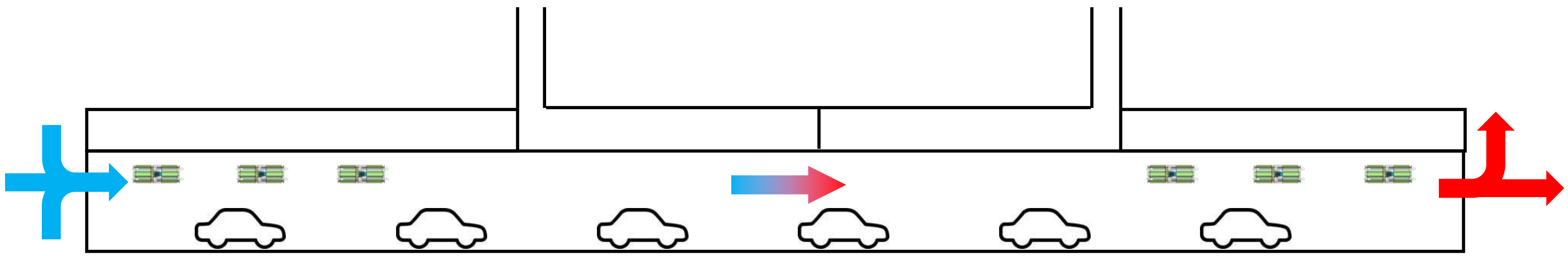
- to control longitudinal velocity of air and to create excess pressure



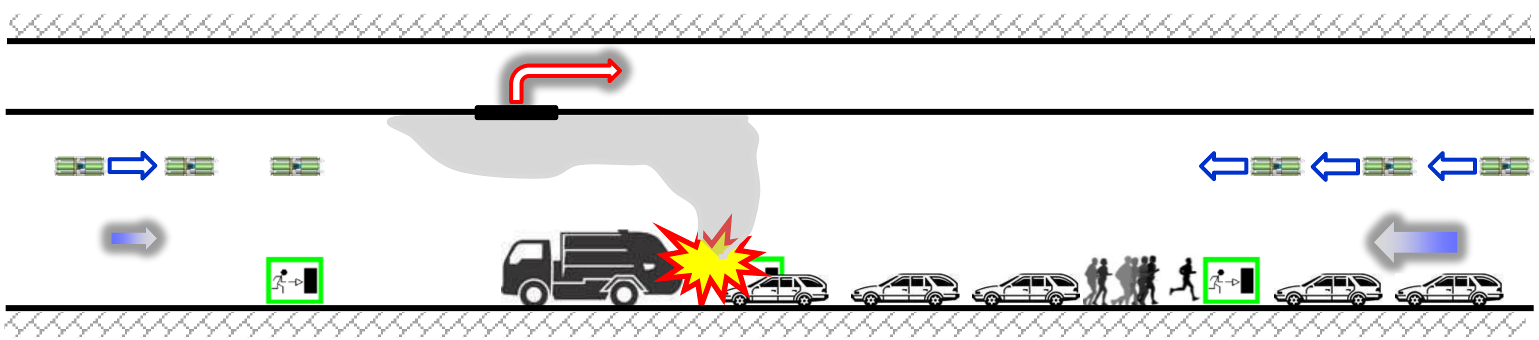
  - Excavation area 127 m²

Ventilation system

- Standard operation

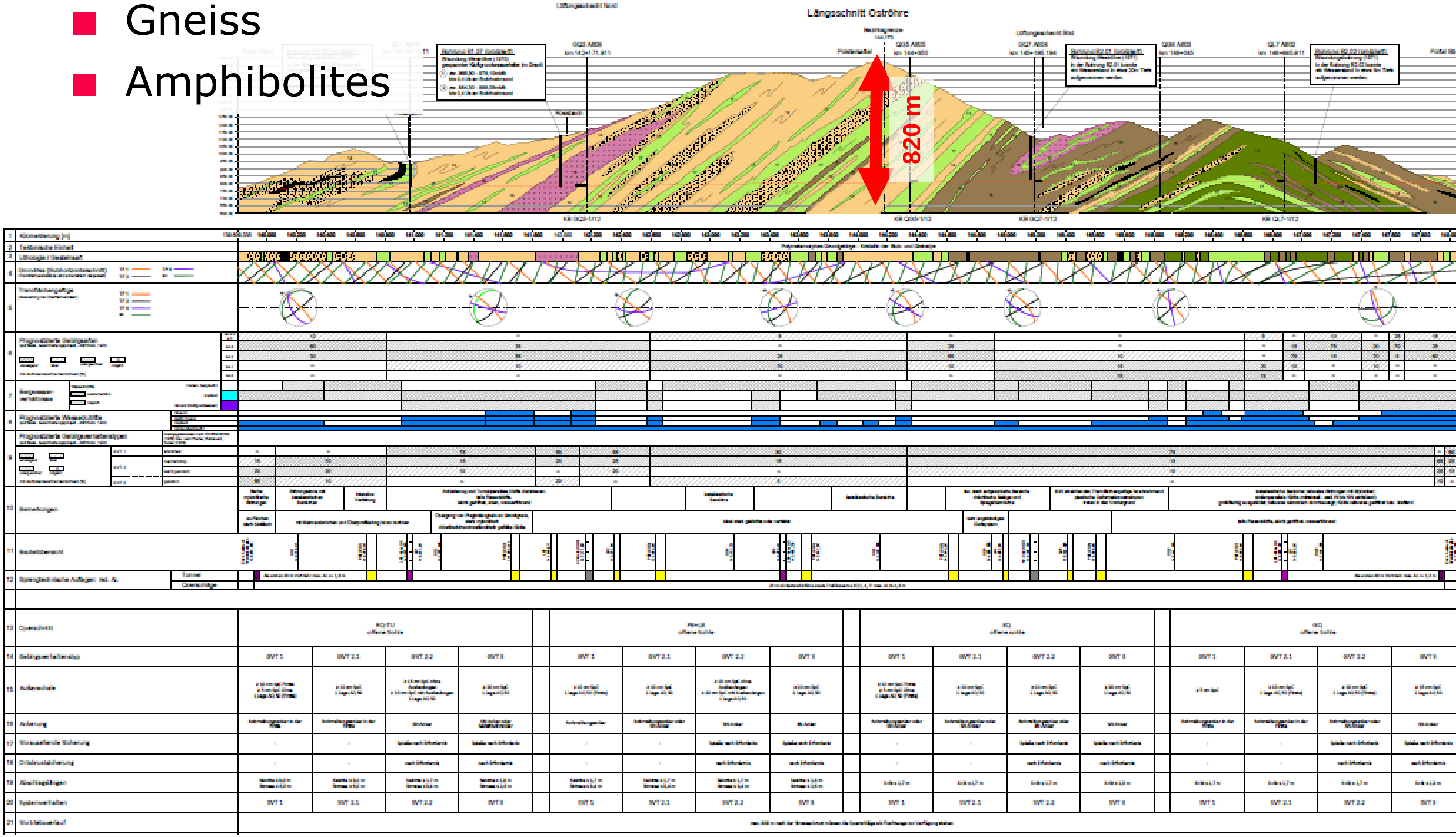


- Incident operation



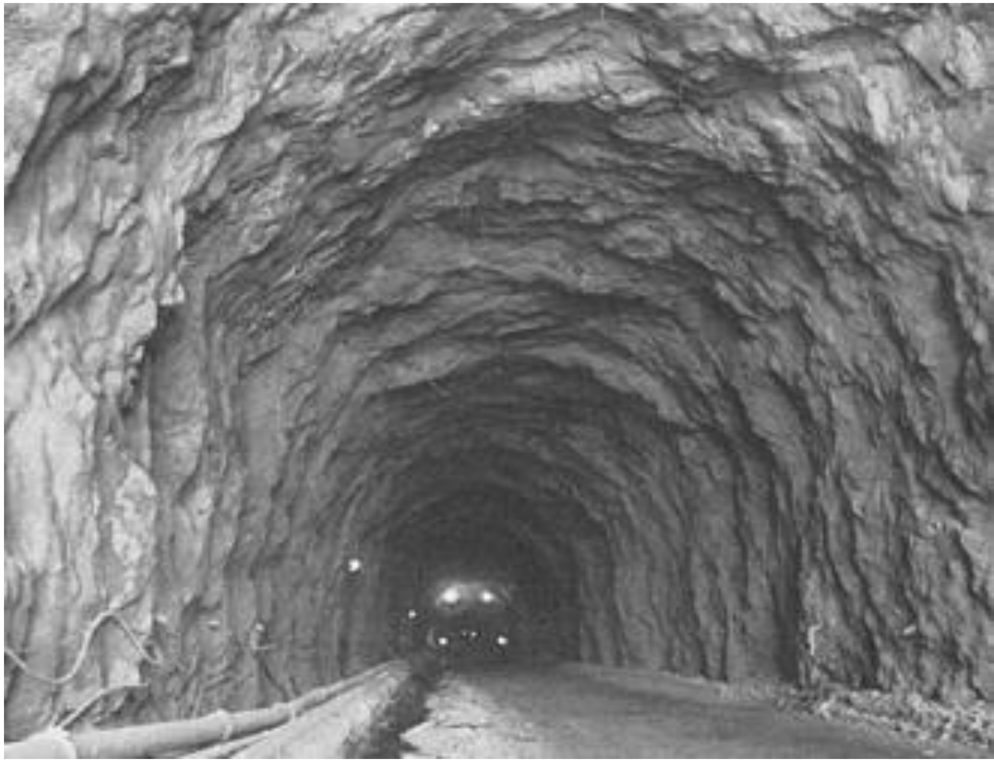
GLEINALMTUNNEL – Geotechnical Long Section

- Gneiss
- Amphibolites



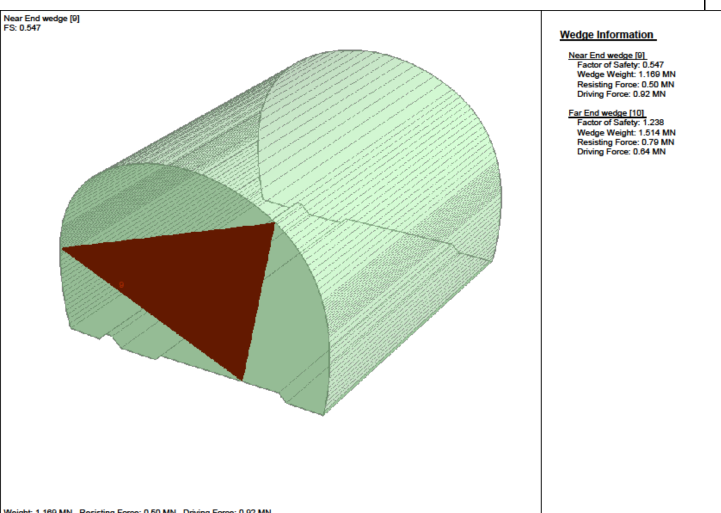
Design of 2nd Tube - Geotechnics

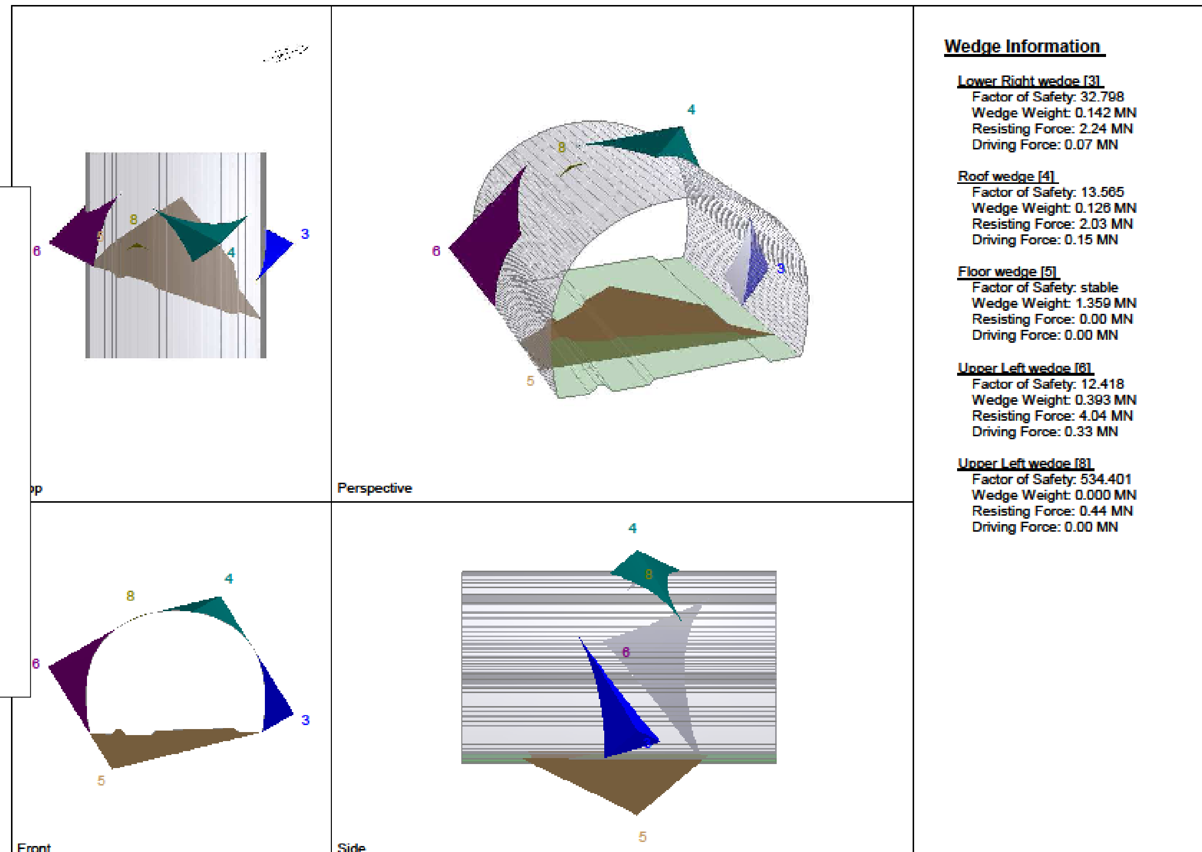
- Basis for the design
  - Geological documentation of 1st tube and prognosis of 2nd tube
  - Generally no major displacements in 1st tube except in isolated fault zones
  - Testing programme
- Geotechnical design focus
  - joint induced failure
  - rock burst due to high overburden and brittle rock
  - Analysis of fault zones and areas with weak rock (ground reaction curve)



Design of 2nd Tube – Wedge analysis

- Analysis of potentially falling wedges and blocks
  - Identification of governing joint sets
  - 3D stability analysis using „Unwedge“ by Rocscience

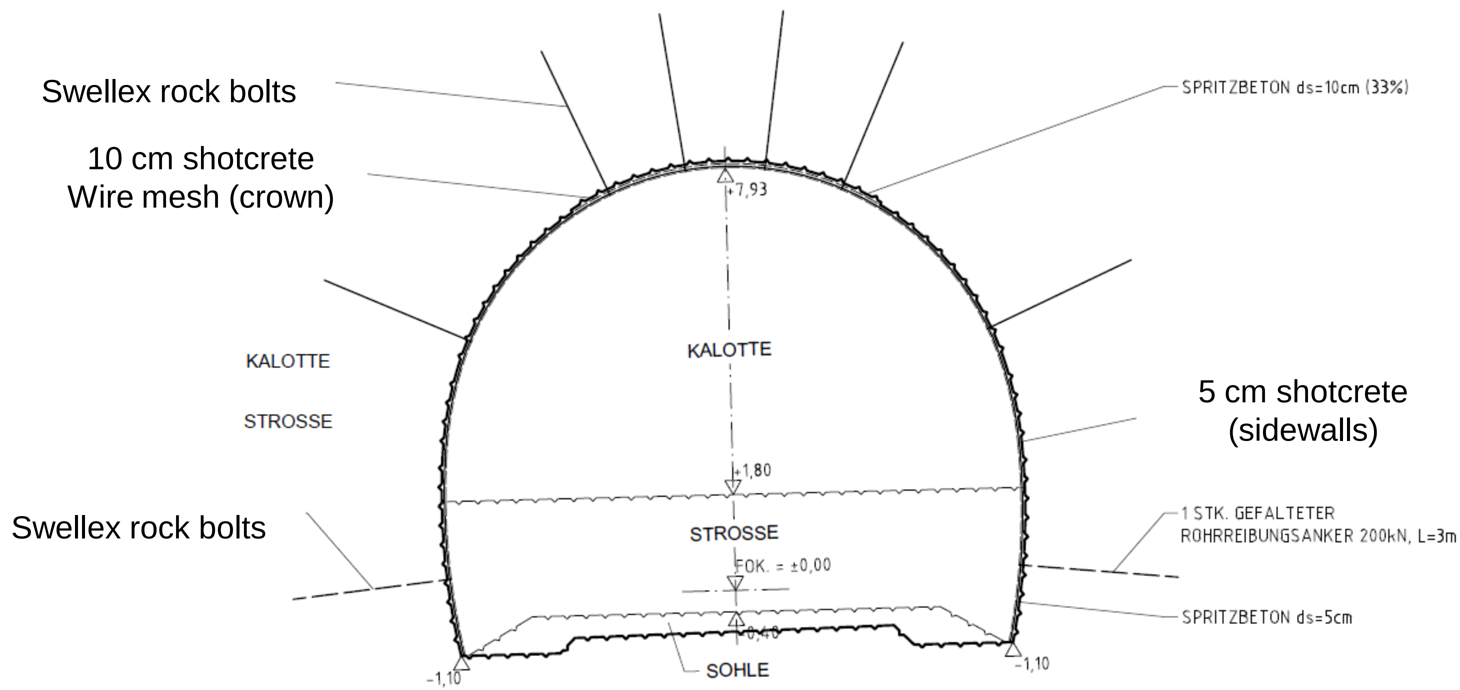




Design of 2nd Tube - Wedge analysis

- Min. support to prevent falling wedges and blocks
  - Tunnel: 10 cm shotcrete + wire mesh in crown, 5 cm in sidewalls
  - Lay-bys, ventilation bays: 10 cm shotcrete +w.m.
  - Cavern: 20 cm shotcrete + 2 layers of wire mesh

} Systematic bolting



Design of 2nd Tube – Rock burst

- Spontaneuos fracture of brittle rock
  - Sudden release of stored elastic strain energy
- Rock burst – prerequisites according to Steiner (TU Graz, 2005)
  - Potential of rock to store elastic strain energy
    $PES = UCS_{intact}^2/2xE_{s,intact} < 50$
  - Brittleness of the rock
    $BRIT = UCS_{intact} / \boldsymbol{\sigma}_{tensile} < 40$
  - High tangential stress level around tunnel
    $TANG = \boldsymbol{\sigma}_{tan} / UCS_{intact} > 0{,}47$

    $\boldsymbol{\sigma}_{tan}$ ... tangential stress around tunnel
    $\boldsymbol{\sigma}_{tensile}$ ... tensile strength of intact rock
    UCS_{intact} ... uniaxial compressive strength of intact rock
    $E_{s,intact}$ ... Young's modulus of intact rock

- Additional criterion adopted from expert group Semmering base tunnel: GSI min > 75

Design of 2nd Tube – Rock burst

- Details for classification of rock burst potential (Steiner)

P. e. Strain Energy		Limits	Category	Potential for Rock Burst
PES	<	50	1	very low
PES	<	100	2	low
PES	<	150	3	moderate
PES	<	200	4	high
PES	>=	200	5	very high

Strength Utilization Factor		Limits	Category	Potential for Rock Burst
TANG	<	0.47	1	no
TANG	<	0.6	2	weak
TANG	<	0.7	3	strong
TANG	>=	0.7	4	violent

Rock Brittleness		Limits	Category	Potential for Rock Burst
BRIT	>	40.0	1	no
BRIT	>	26.7	2	weak
BRIT	>	14.5	3	strong
BRIT	<=	14.5	4	violent

Remark: other authors propose lower limits, e.g. Russenes, Guo

Design of 2nd Tube – Rock burst

- Situation for ground types of Gleinalmtunnel
  - analysis of rock potential

Ground Type		γ [kN/m³]	ν [-]	ROCK MASS UCS [MPa]	c [MPa]	φ [°]	E [GPa]	GSI [-]	INTACT ROCK UCS [MPa]	E [GPa]	c [MPa]	φ [°]	σtensile [MPa]	POTENTIAL OF ROCK BURST PES [UCS²/(2*Ei)]		BRIT [UCS/σtensile]	
GA3	amphibolit, granit-gneiss	27	0,25	30	2,5	44	9,5	55	50,0	30,0	n.v.	n.v.	2,6	42	very low	19	STRONG
GA2	amphibolit, granit-gneiss	27	0,25	30	4	46	15	65	80,72	44,56	27,7	44,0	10,5	73	low	8	VIOLENT
GA1	gneiss	27	0,25	30	5	48	25	75	150,82	37,89	12,0	38,0	12,7	300	very heigh	12	VIOLENT
GA0	gneiss	27	0,25	40	5	48	33	80	217,36	57,31	46,0	55,1	9,9	412	very heigh	22	STRONG

  - Comparison of max. overburden (820m) to tangential stresses for various values of K_0 → rock burst not expected

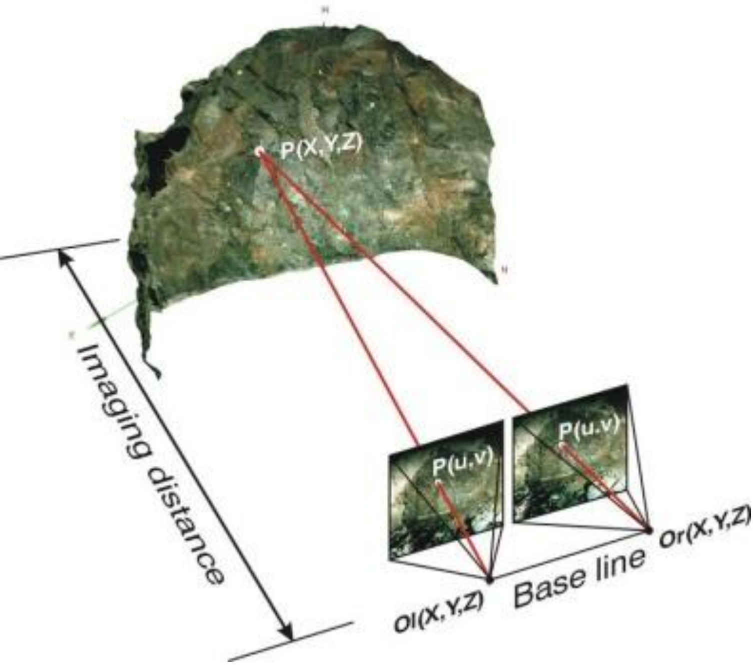
Ground Type	$\sigma_t = 2{,}66 \cdot \sigma_v$ $K_0 = 0{,}33$		$\sigma_t = 2 \cdot \sigma_v$ $K_0 = 1{,}0$	
	H_{crit}	σ_{crit}	H_{crit}	σ_{crit}
GA1	985 m	26,58 MPa	1313 m	35,44 MPa
GA0	1419 m	38,31 MPa	1892 m	51,08 MPa

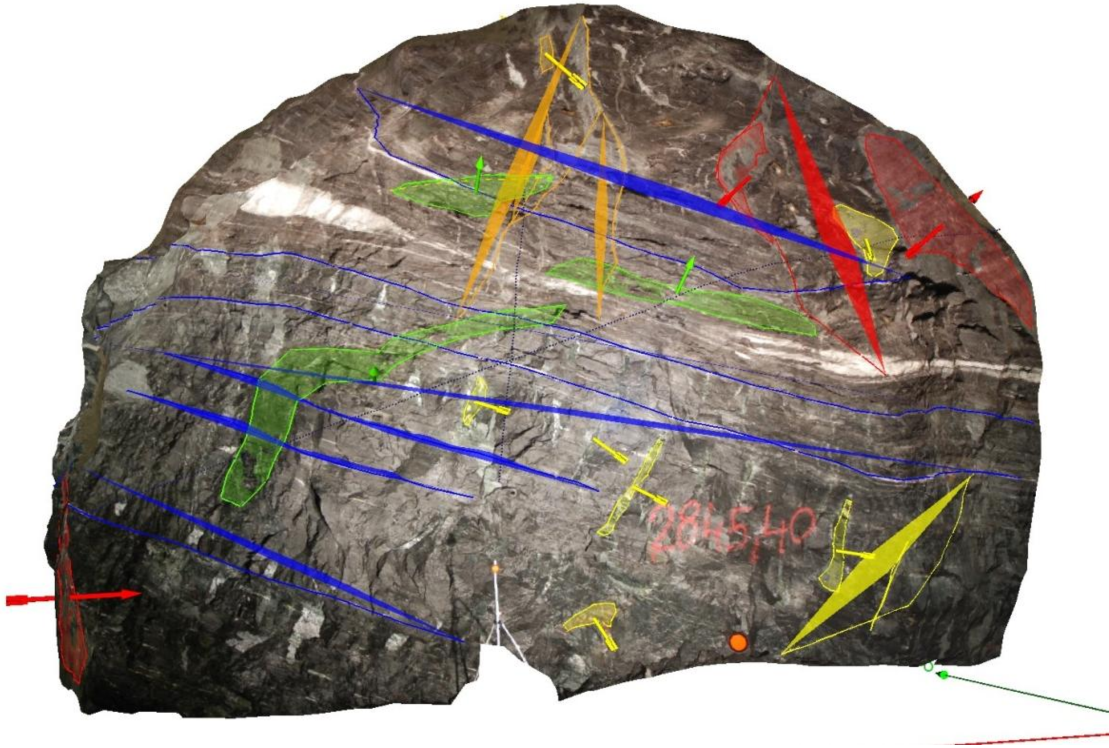
Experience of construction of 2nd Tube

- Drill and blast NATM heading
- Predominantly full face excavation, if rock conditions allowed

Experience of construction of 2nd Tube

- Rock burst was not detected
- Regular assessment of rock surfaces and joint orientation → 3D image ShapeMetriX^{3D} → assessment of discontinuities





3GSM pictures courtesy of G. Pischinger, Geoconsult

Experience of construction of 2nd Tube

- Rock burst was not detected
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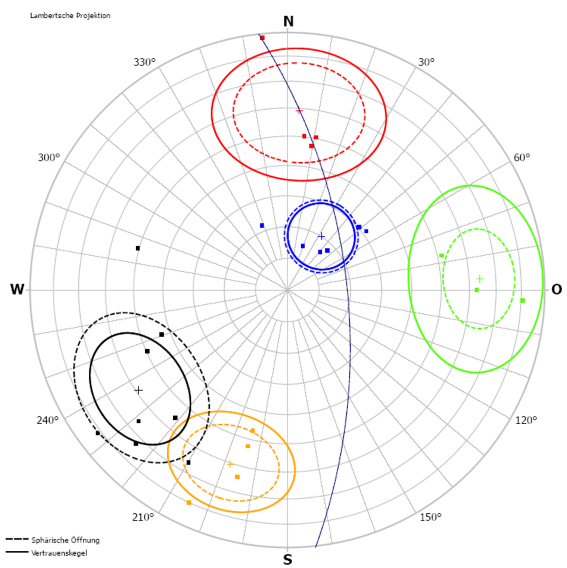
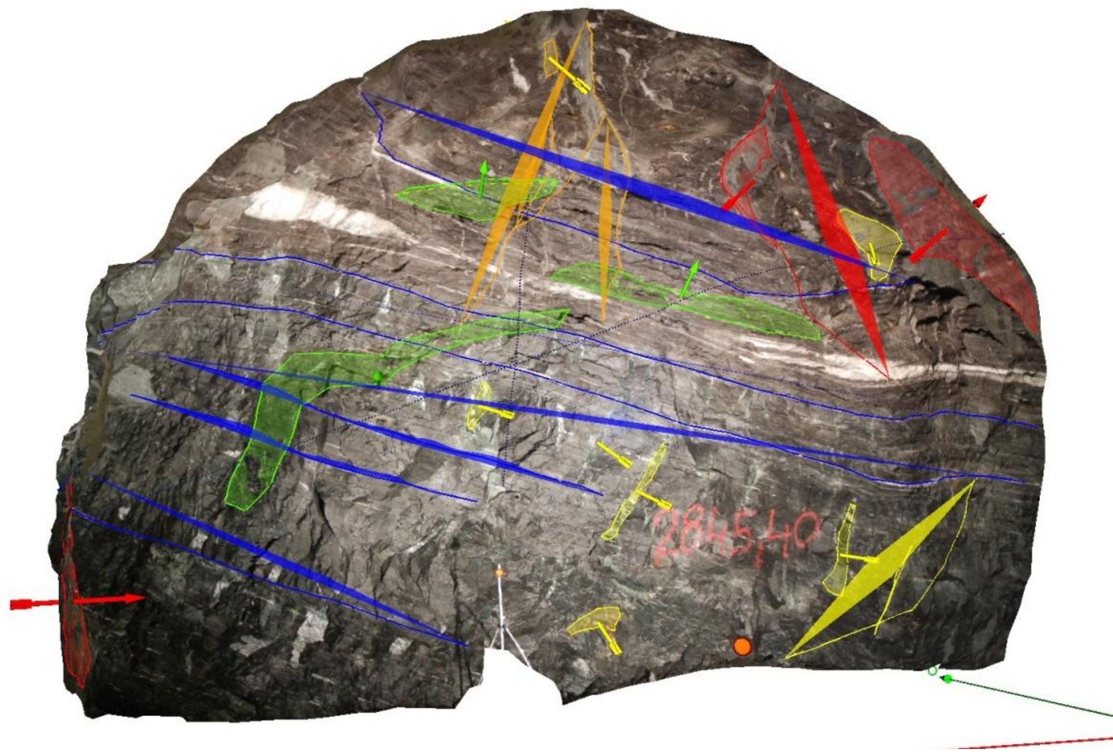
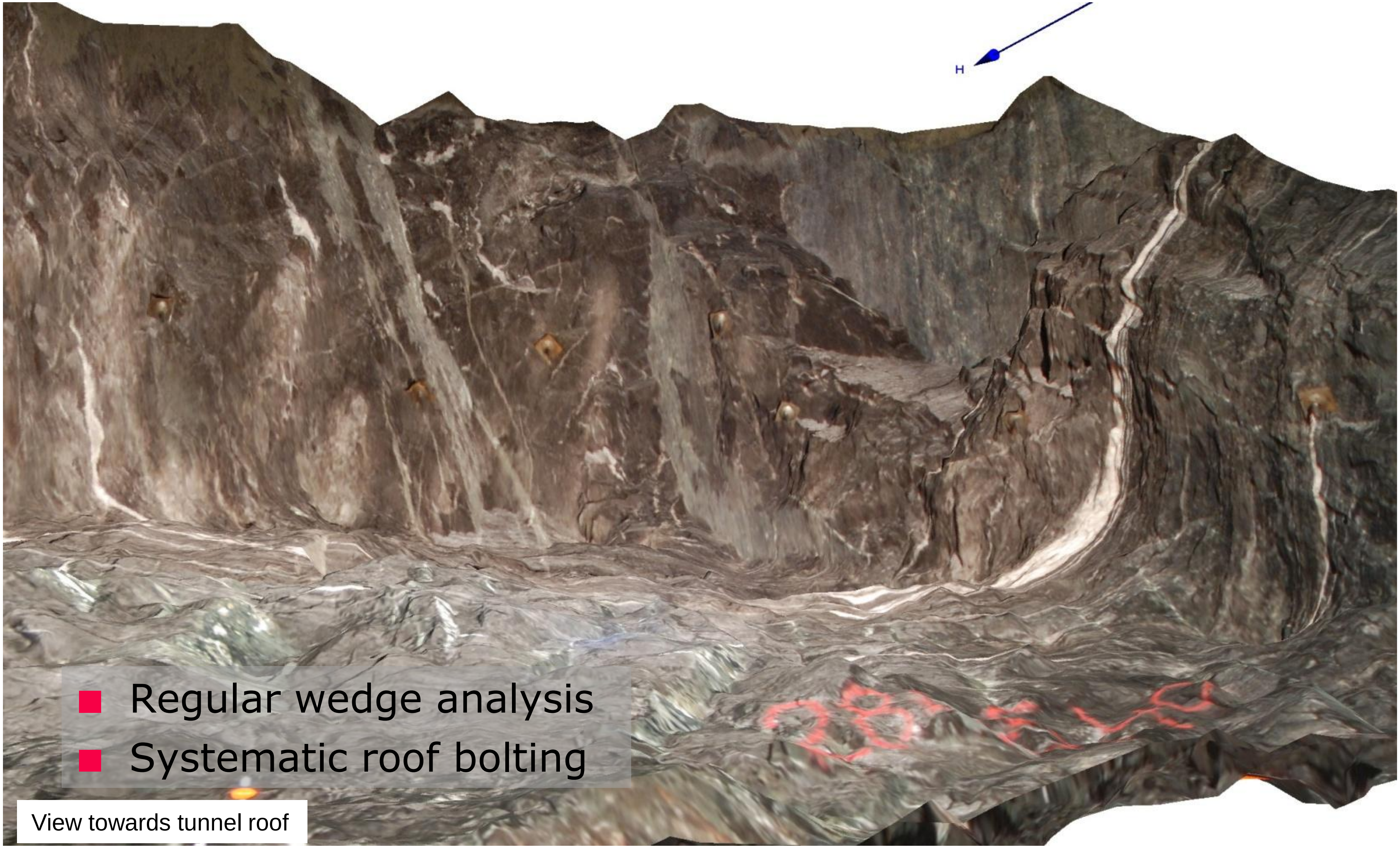


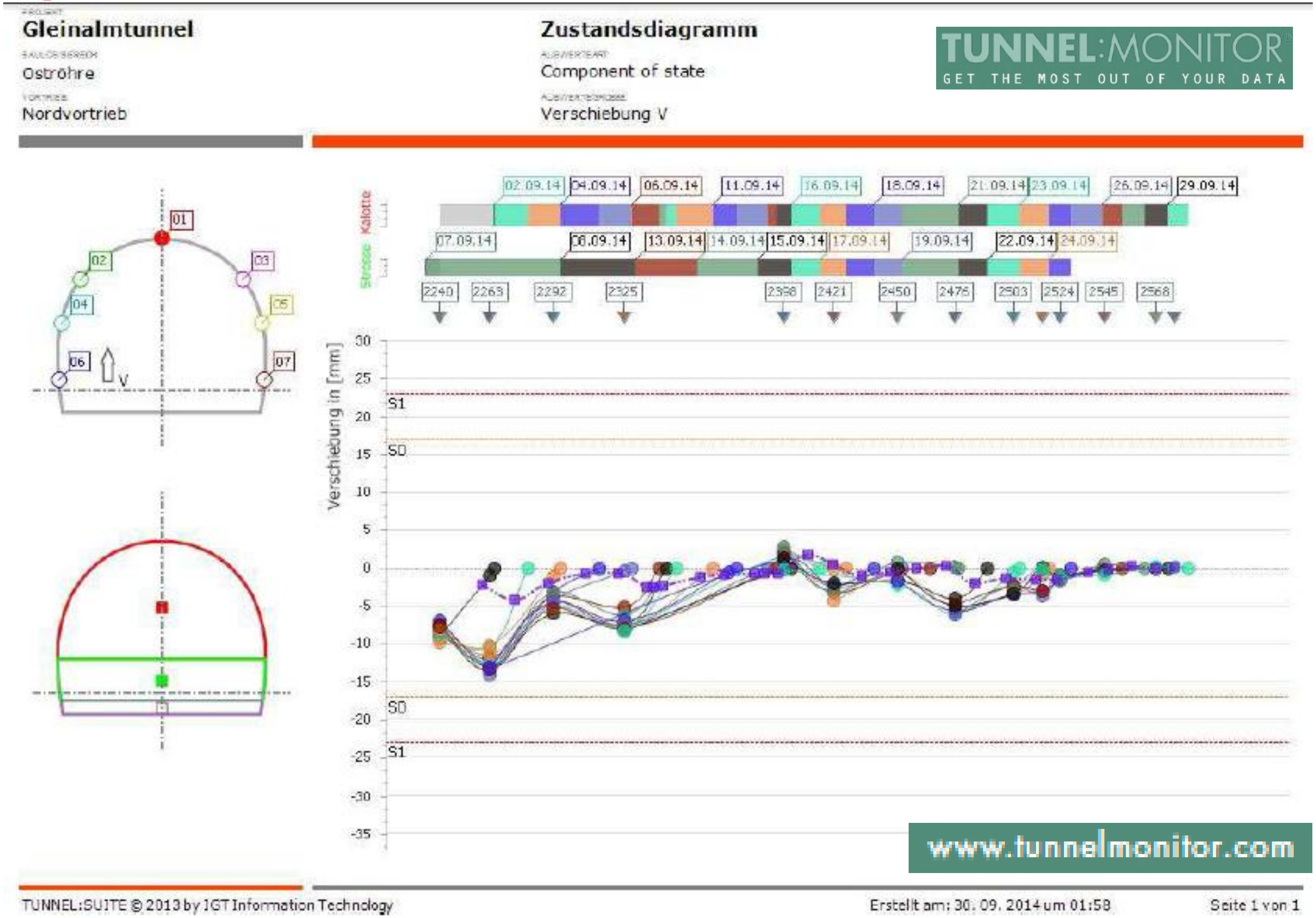


3GSM pictures courtesy of G. Pischinger, Geoconsult

Experience of construction of 2nd Tube



Experience of construction of 2nd Tube



THANK YOU FOR THE ATTENTION !

Credits and proposed Literature

- Criteria for the determination of ground behaviour types
  Alois Steiner, Master‵s thesis, TU Graz (2005)
- Tunnel design and prediction of system behaviour in weak ground
  Nedim Radoncic, Doctoral Thesis, TU Graz (2011)
- Practical Rock Engineering, Evert Hoek
  www.rocscience.com