ITA - AITES WORLD TUNNEL CONGRESS 2007 PRAGUE

The 3rd Training course
TUNNELLING IN URBAN AREA
Prague, 4-5th May 2007

Mechanized Tunnelling in Urban Areas General

TRAINING MATERIAL PREPARED BY

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ASSOCIATION INTERNATIONALE DES TRAVAUX EN SOUTERRAIN AITES

ITA INTERNATIONAL TUNNELLING ASSOCIATION

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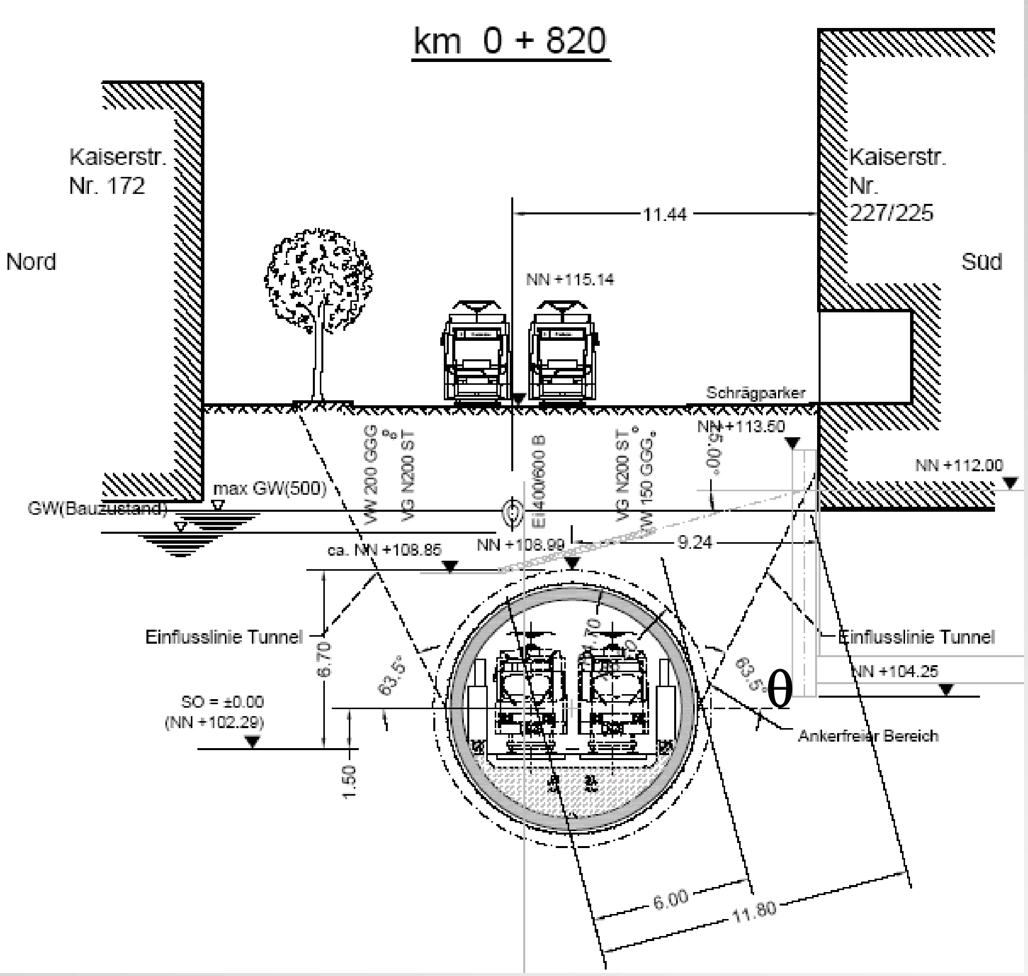
4 Execution of TBM Drives (20 min)

- Influence of TBM drives on Neighbour Buildings
- Face Stabilisation
- Precalculation of the necessary Face Pressure
- Survey during TBM drives and Guidance Systems

Influence on the neighbour buildings



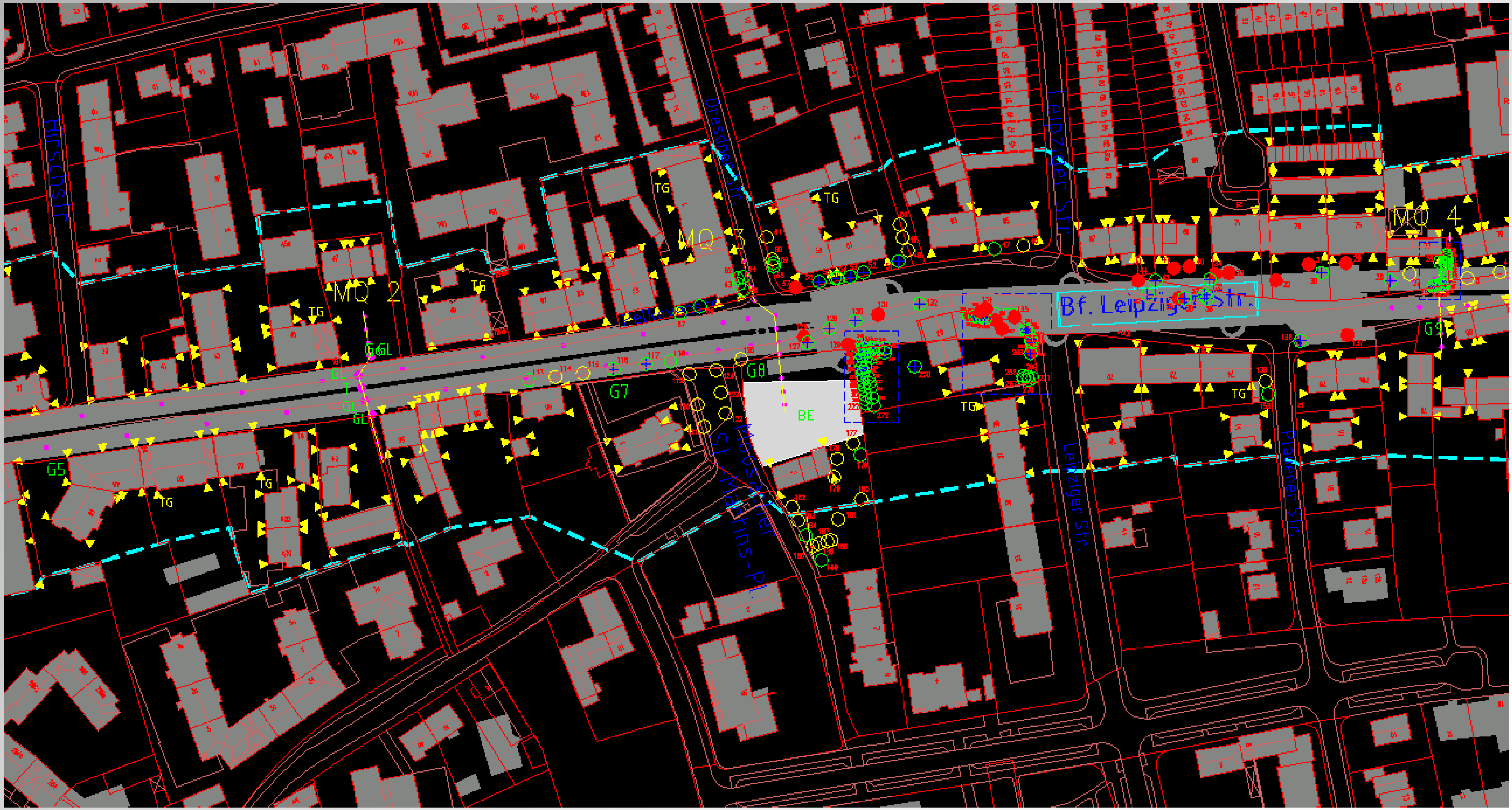
Calculation of the angle of influence θ:

a) Rough estimate: $\theta = 45°$
(sure side)

b) Rough estimate: $\theta = 60°$
(more realistic)

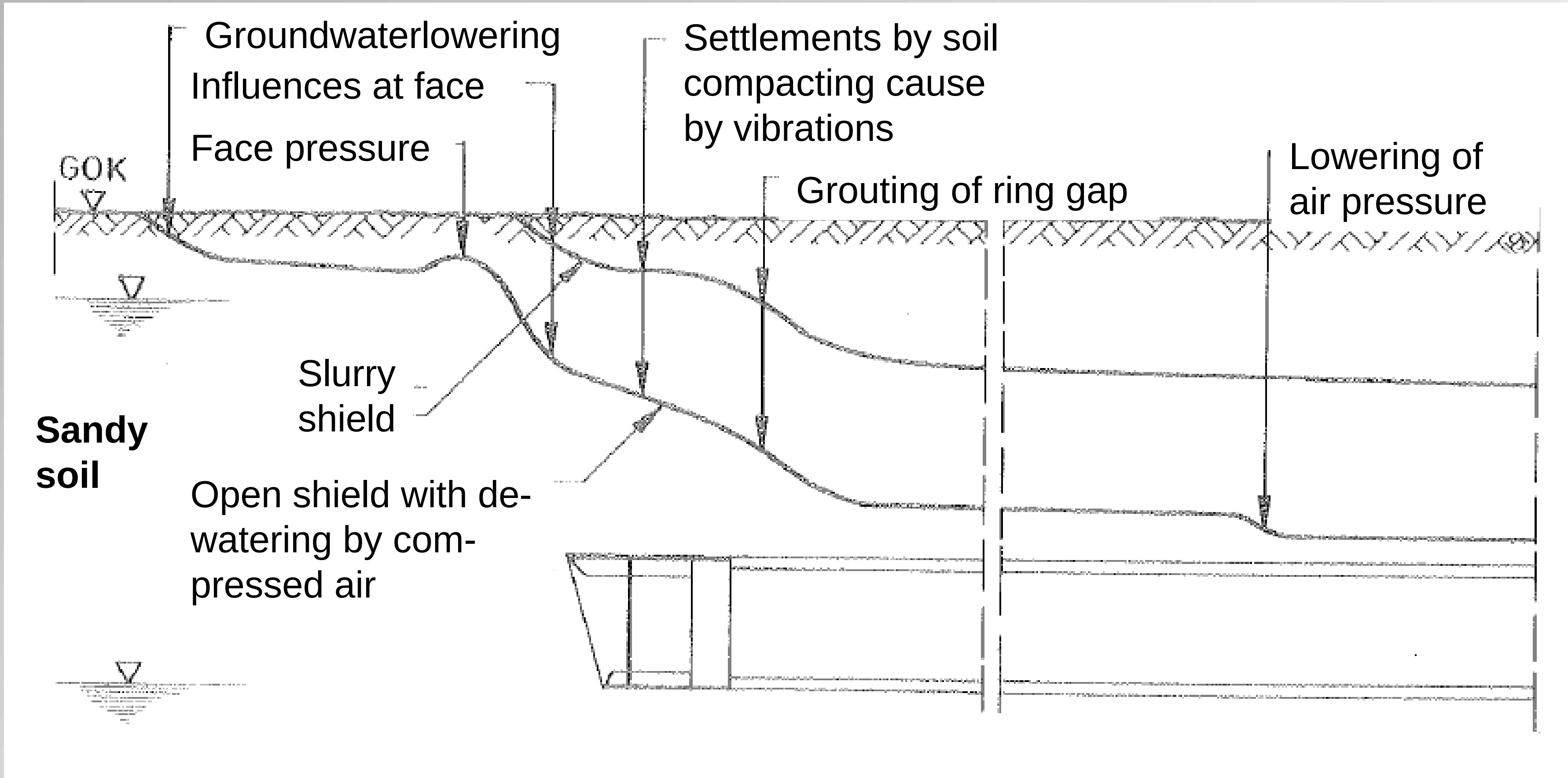
c) More exact: $\theta = 45° + 0,5 \cdot \varphi$
φ = angle of inner friction

Influence of a TBM drive on neighbour buildings



Limits of perpetuation of evidence

Settlements during excavation with shielded TBM (longitudinal section)



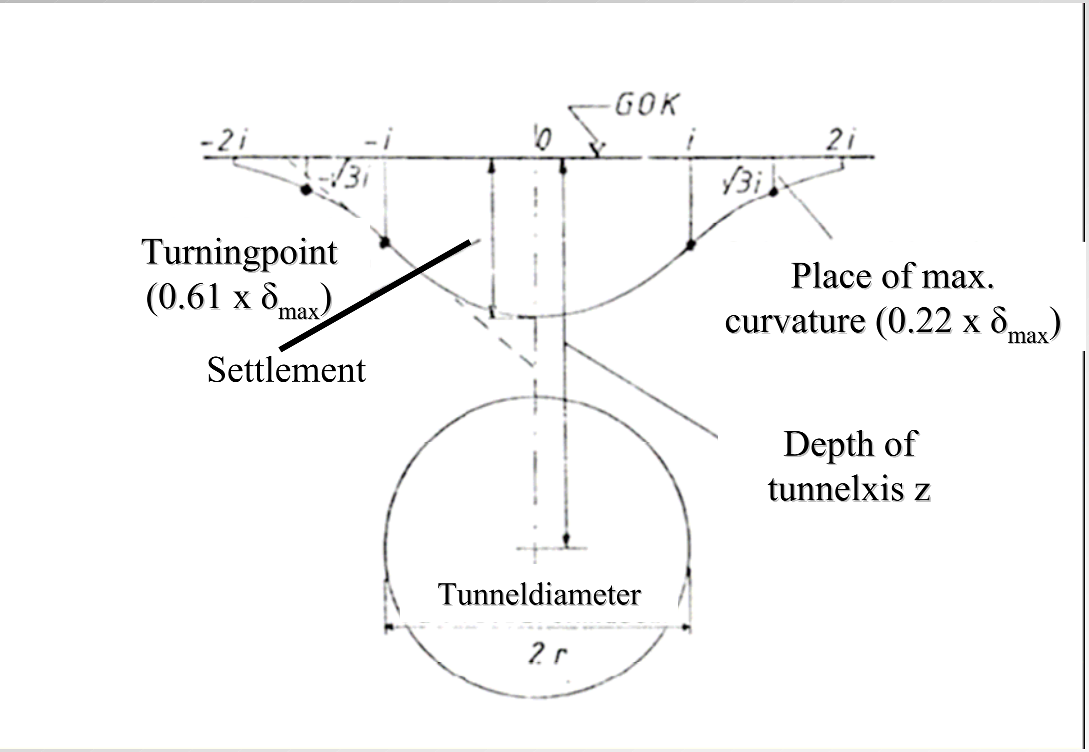
Influence of a TBM drive on the neighbour buildings

According to the soil conditions, the width of the settlement curve can be calculated.

Different calculation models and methods are available.

- **Volume Loss (V_l)** after Ralph Peck (1969)
  → Excavated soil volume (V_e) > displaced soil volume V_d)
  $\Delta V = V_e - V_d$ → $V_l = \Delta V / V_e$
  Examples: unsupported face in stiff clay: $V_l = 1.0 - 2.0$ %
  supported face (Slurry or EPBM) in soft sand: $V_l = 0.5 - 1.0$ %
  supported face (Slurry or EPBM) in soft clay: $V_l = 1.0 - 2.0$ %
  conventional shotcrete advance in London clay: $V_l = 0.5 - 1.5$ %

Settlement curve after Gauss normal distribution



Formulas for settlement calculation:

$$S = S_{max} \times e^{\frac{-x^2}{2i^2}}$$

(Form of the settlement curve)

$$S_{max} = \frac{V_L}{i \times \sqrt{2\pi}} \times \left(\frac{D_A}{2}\right)^2 \times \pi$$

(Maximal settlement)

$$\Delta V = \sqrt{2\pi \times i \times S_{max}}$$

(Volume loss)

i … coefficient for settlement

Coefficient i:

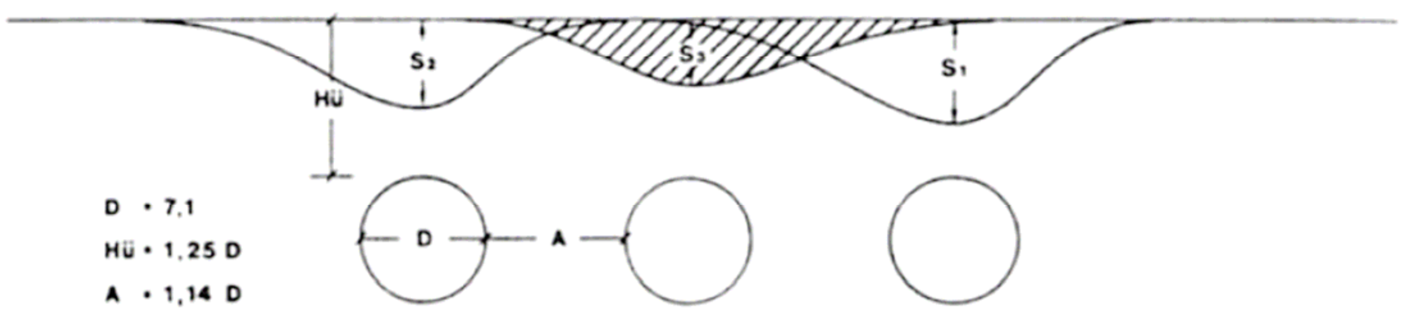
O'Reilly and New (1982):

- cohesive soil: $3m < z_0 < 34m$ $\quad i = 0.43\, z_0 + 1.1m$
- non cohesive soil: $6m < z_0 < 10m$ $\quad i = 0.28\, z_0 - 0.1m$

O'Reilly and New for 2 layers (1991):

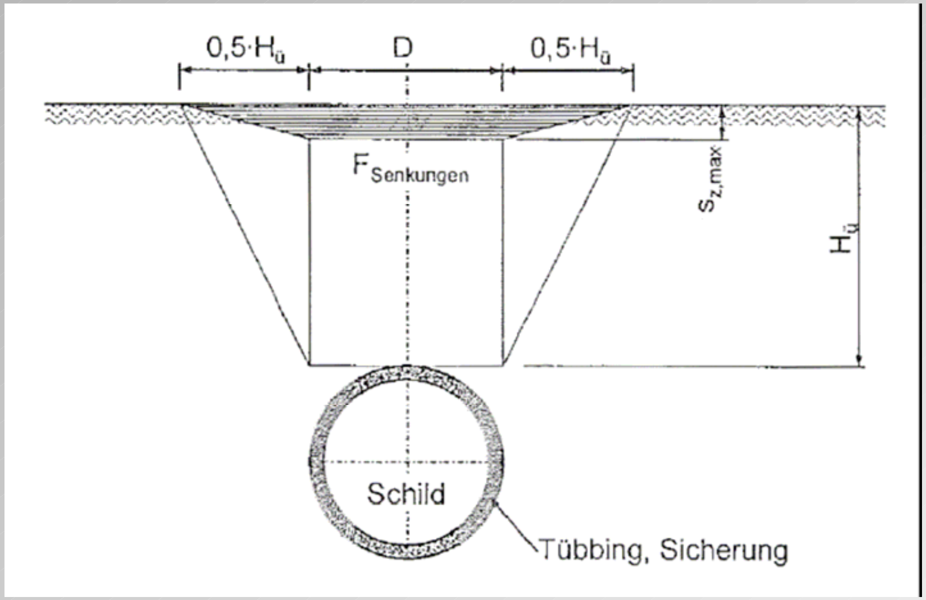
- tunnel in cohesive soil, non cohesive layer over the tunnel $\quad i = 0.43\, z_a + 0.28\, z_b + 1.1m$
- tunnel in non cohesive soil, cohesive layer over the tunnel $\quad i = 0.28\, z_a + 0.43\, z_b - 0.1m$

Settlement curve after "Köster" (1988):



$$S_1 = (X_1 \times D) \times e^{X_2 \times \lg E_S 3} \times e^{X_3 \times \lg E_S 4} \times e^{X_4 \times \lg E_S 5} \times e^{X_5 \times \lg E_S 6} \times e^{X_6 \times \lg E_S 7} \times \frac{\left(\ln \frac{H_u / D}{3{,}5} \right) - 0{,}1}{-0{,}02}$$

Settlement curve after "Scherle" (1977):

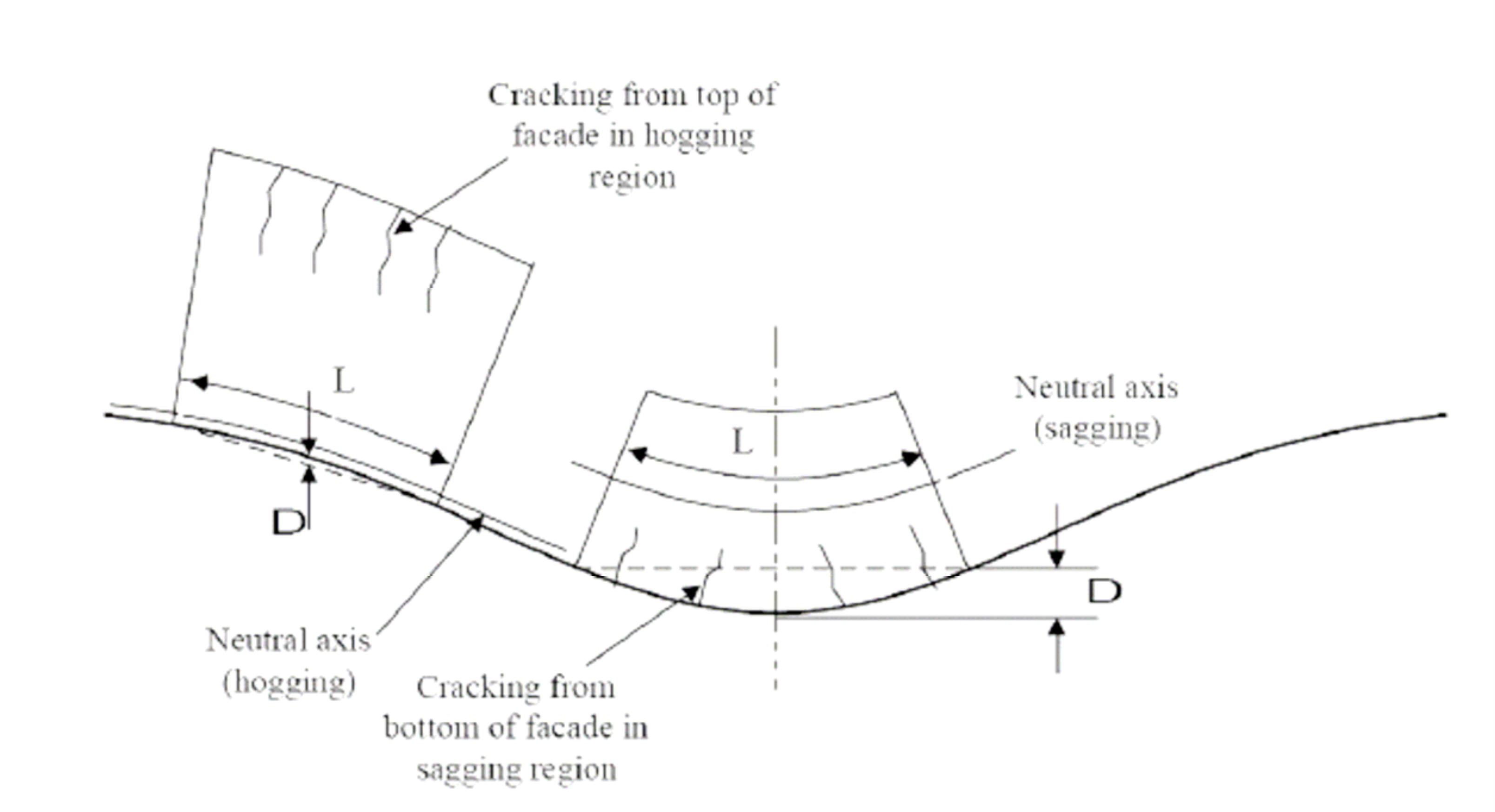


$$S_{z,\max} = \frac{D_A}{\left(1 + H_{\ddot{u}} / D_A\right)} \times B_K$$

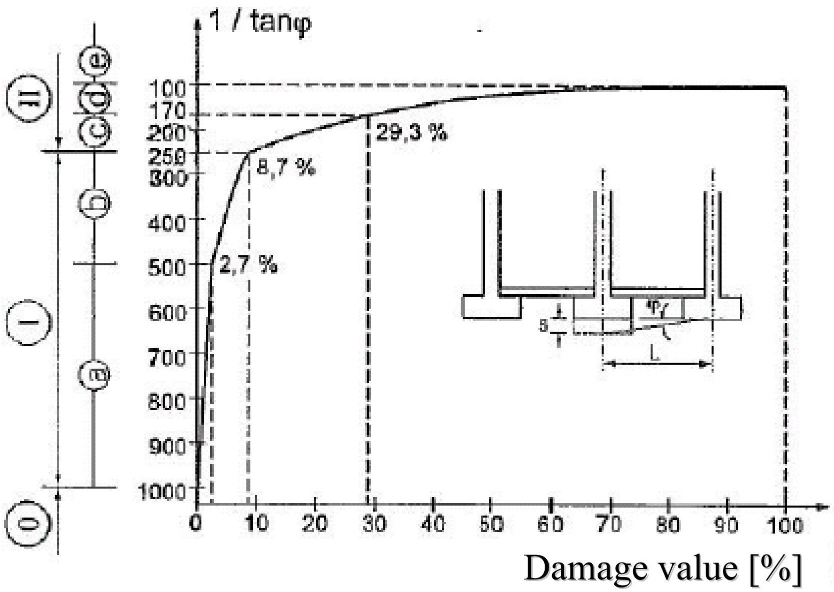
Parameter B_K:

non cohesive soils:	very compact 1.5	compact 2	loose 3	very loose 4
cohesive soils:	semi solid 2	stiff 3	soft 4	pulp 6

Damages caused by settlements



Damages caused by settlements



Area 0: No damages

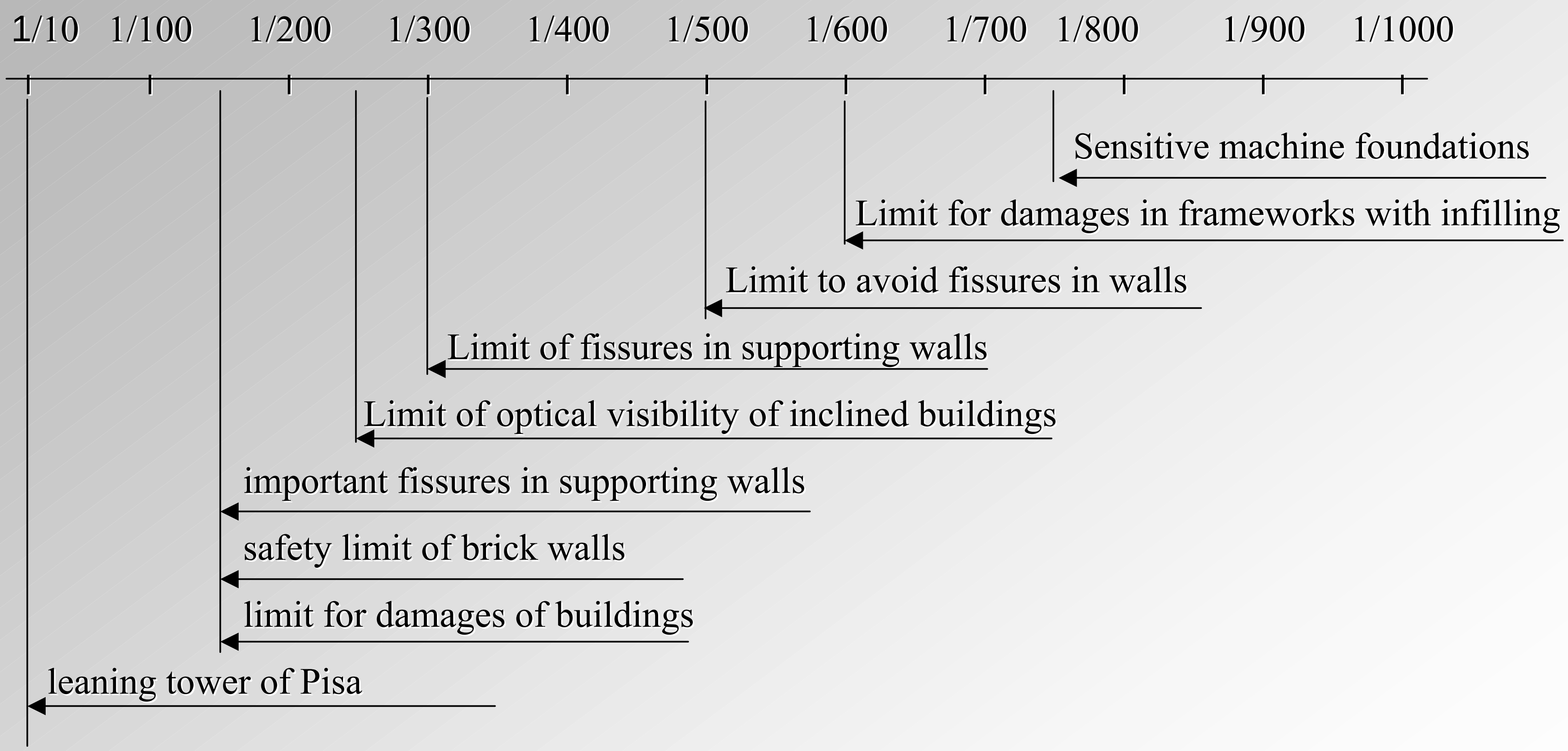
Area 1: architectural damages

- a) light damages (fissures in plaster)
- b) middle to strong damages (fissures must be filled, windows and doors must be repaired)

Area II: constructive damages

- c) light structure damages (new levelling of floors, additional strengthening of floors, new finishing, loss of value of the building
- d) strong structural damages but repairable
- e) collapses or demolition of the building, complete reconstruction necessary

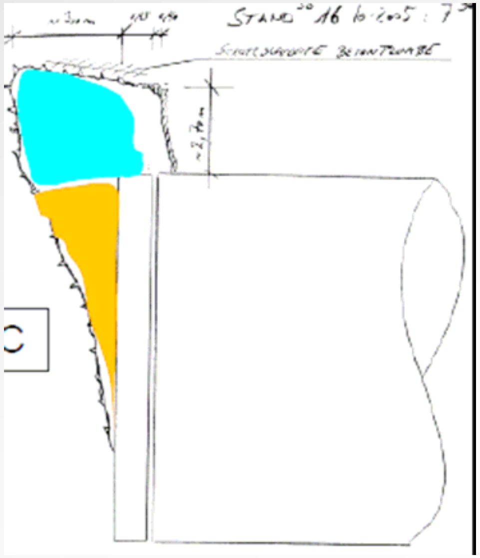
Damages caused by settlements



Possible events at the face during advance:

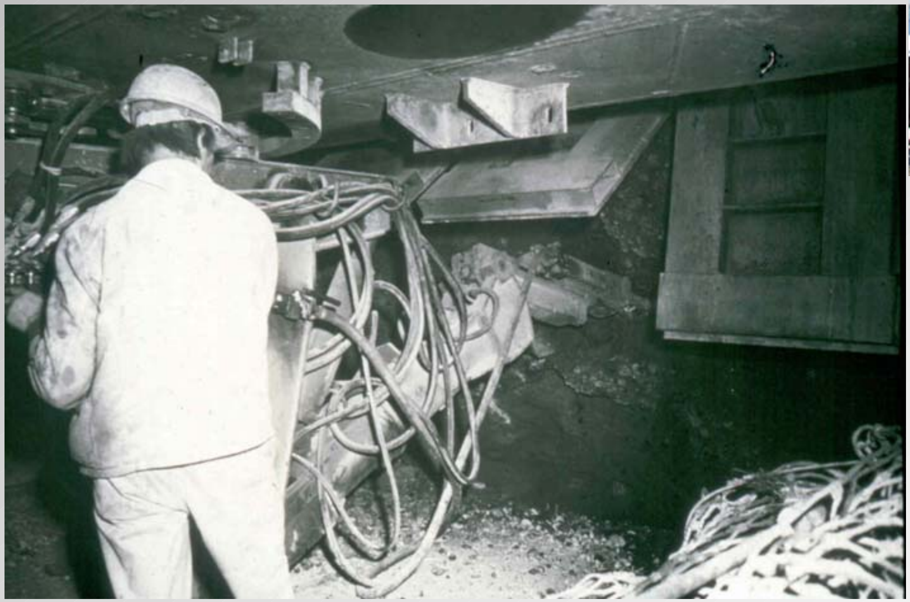
- Face collapses
  → change of penetration rate (advance [cm] per rotation [-])
  → change of rotation speed
  → change of blade pressure

- Collapses <u>over</u> face
  → no interrupts in advance (optimisation of all installations)
  → no turning of the cutting wheel without moving forward
  → closing of radial openings in cutting wheel



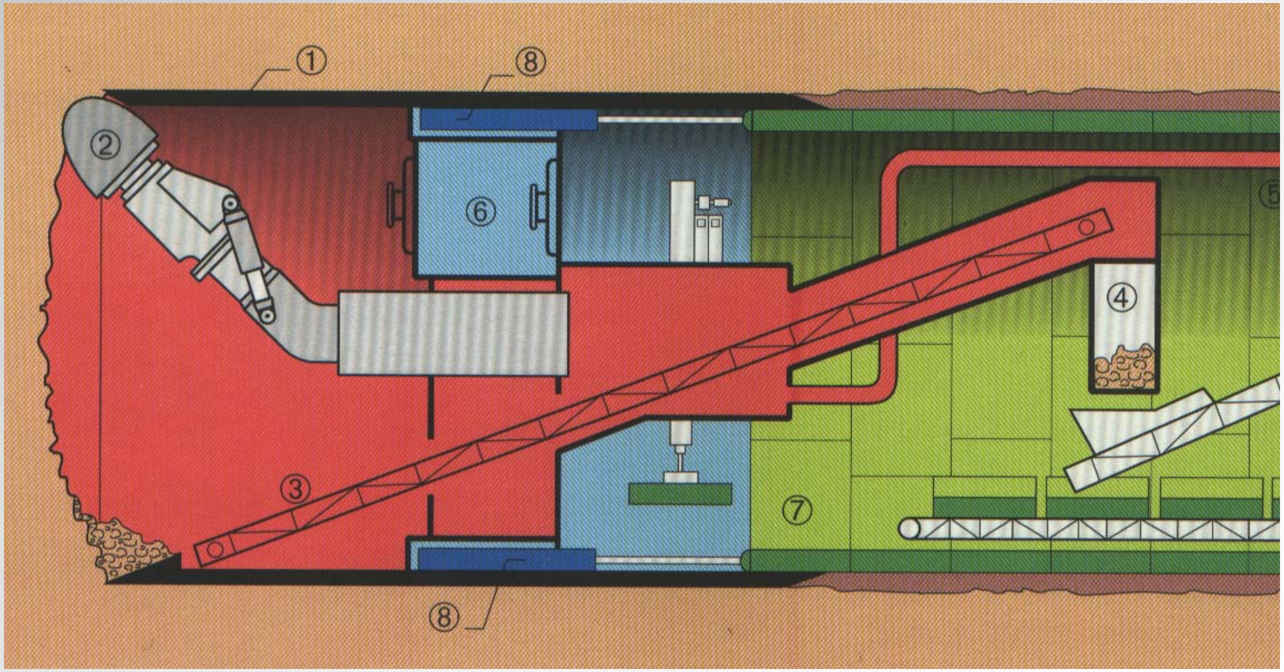
Systems for face stabilisation:

- Blade pressure



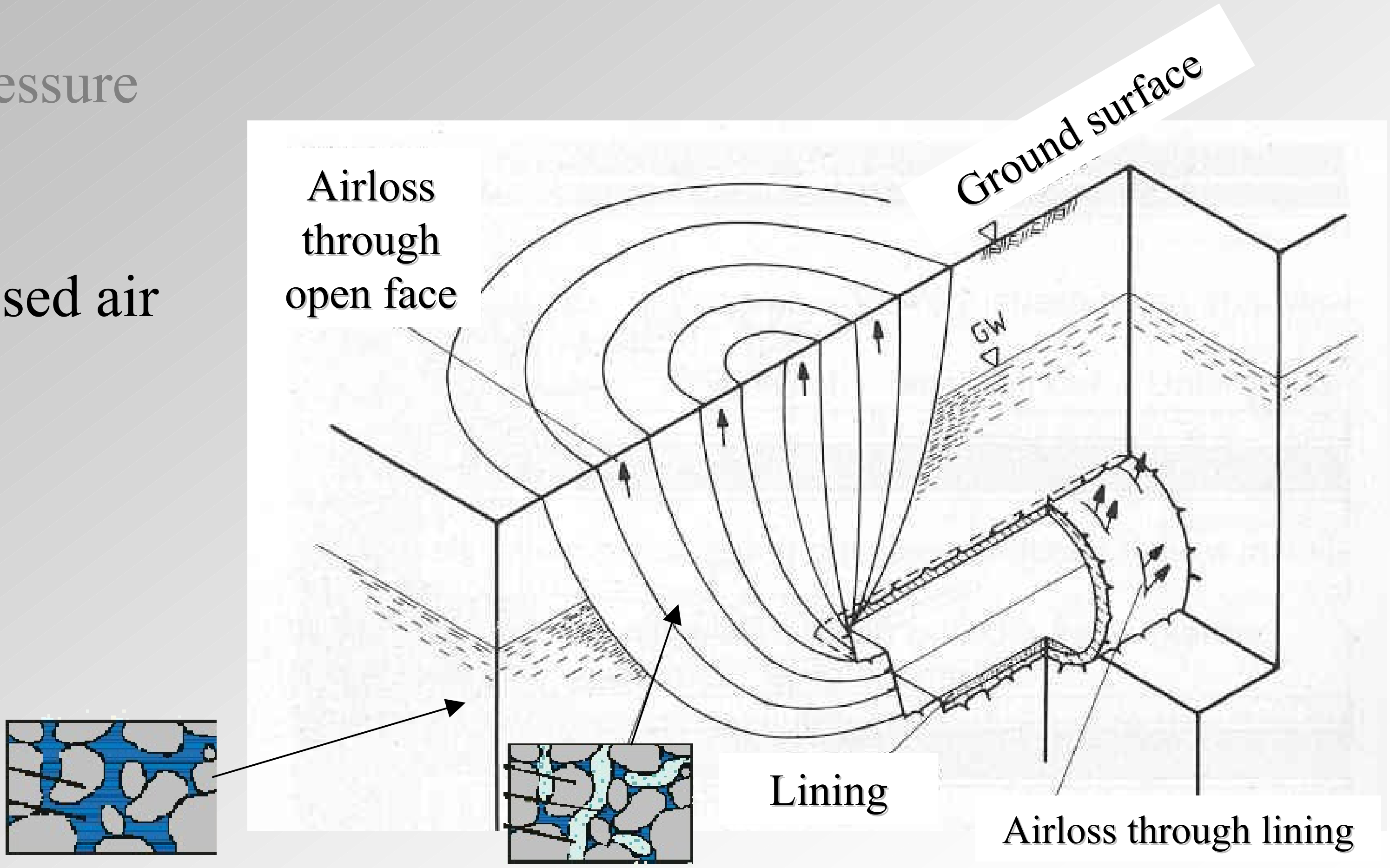
Systems for face stabilisation:

- Blade pressure
- Compressed air



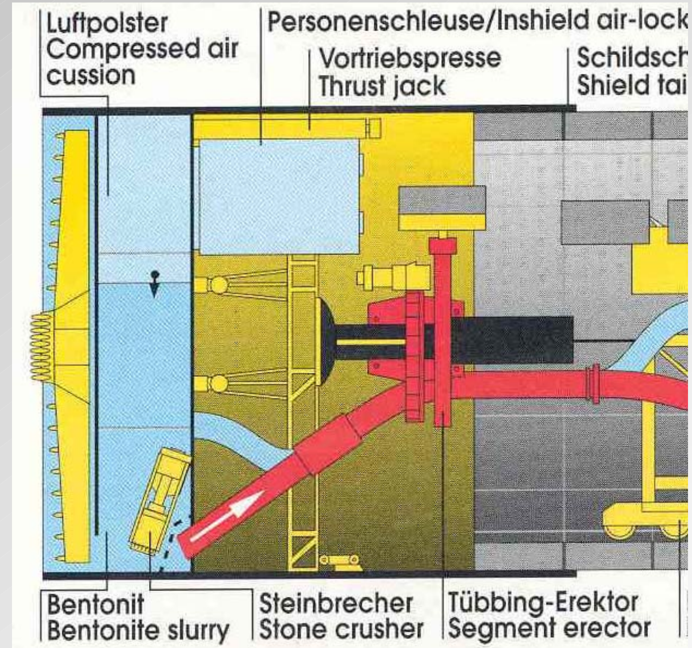
Systems for face stabilisation:

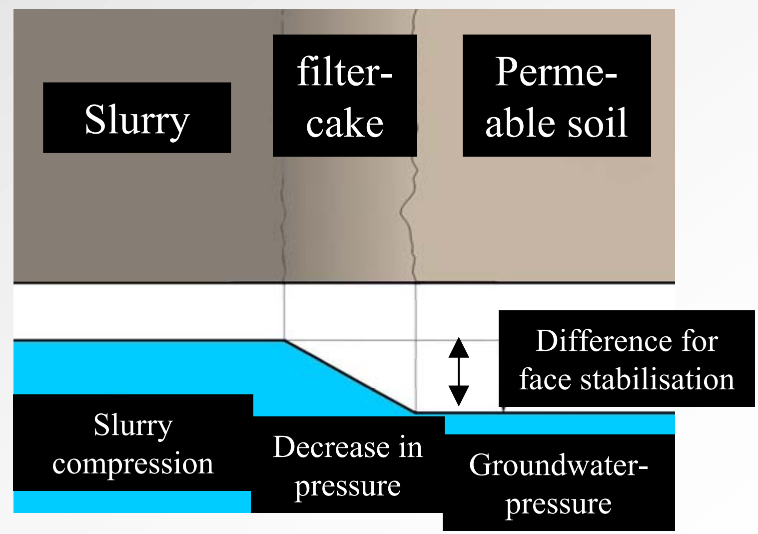
- Blade pressure
- Compressed air



Systems for face stabilisation:

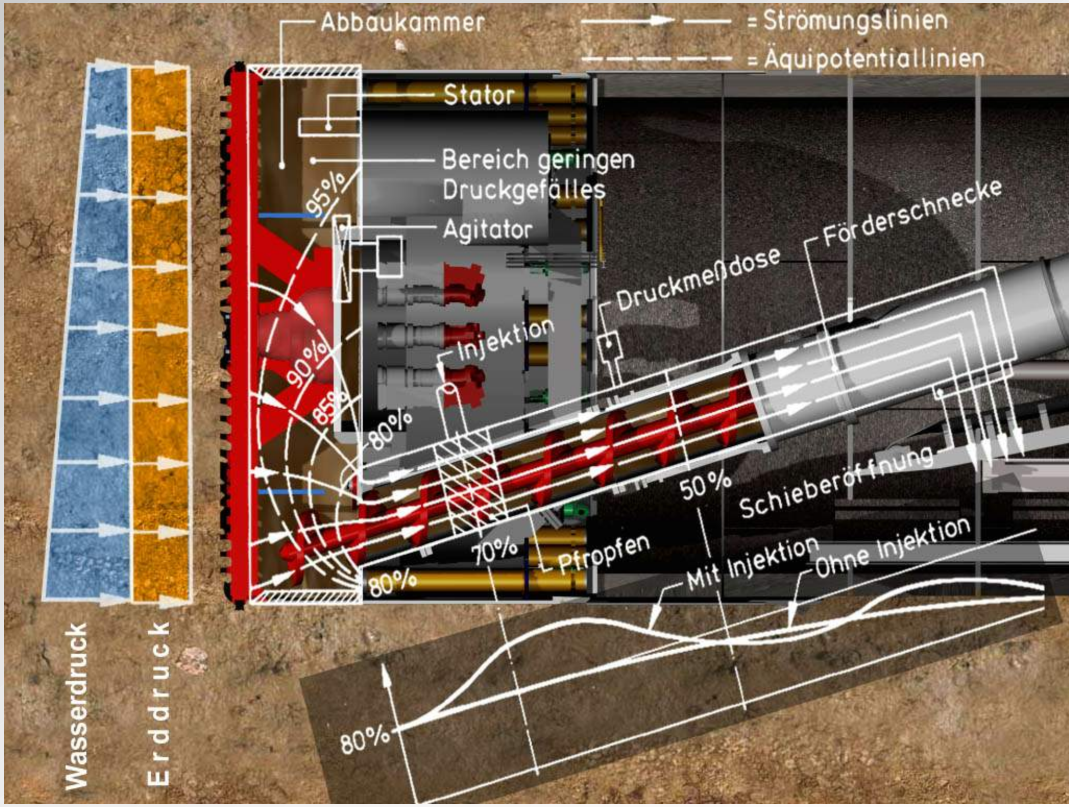
- Blade pressure
- Compressed air
- Slurry (bentonite mixture)





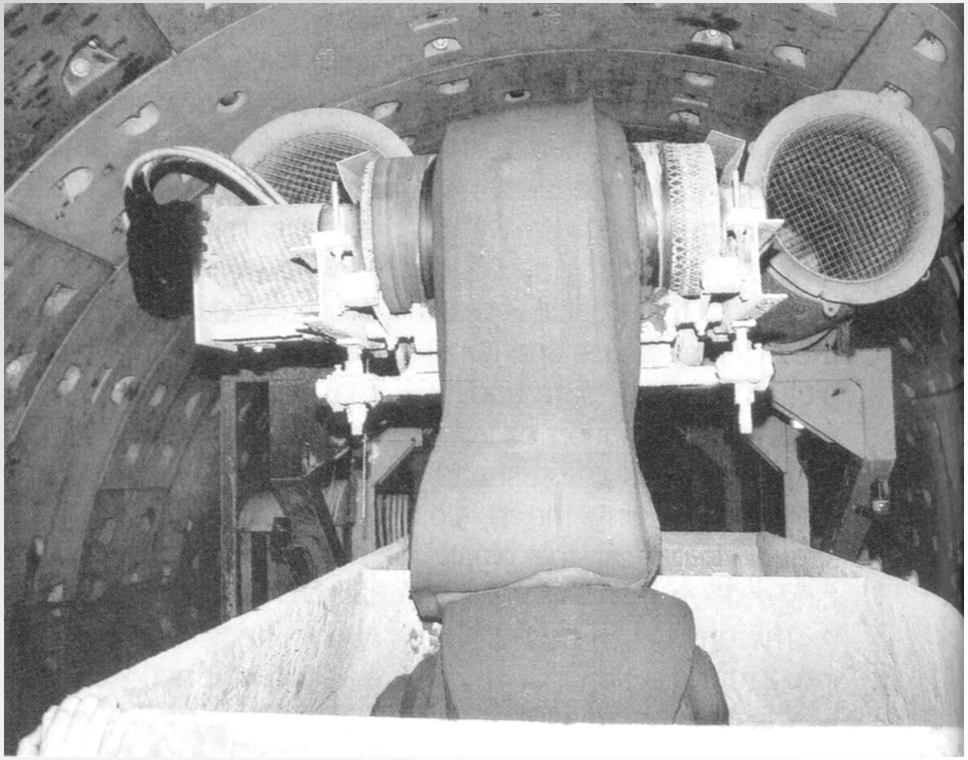
Systems for face stabilisation:

- Blade pressure
- Compressed air
- Slurry (bentonite mixture)
- EPB



Systems for face stabilisation:

- Blade pressure
- Compressed air
- Slurry (bentonite mixture)
- EPB

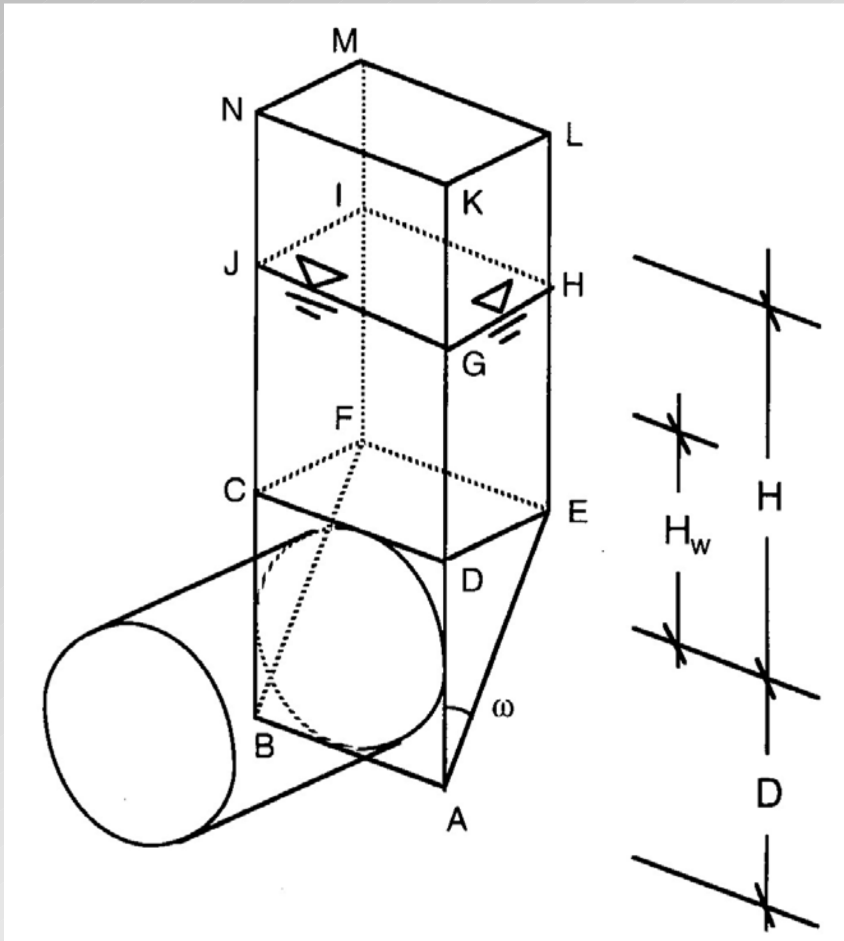


Precalculation necessary Face Pressure

Calculation Models:

- Anagnostou / Kovari
- Horn
- Jancsecz
- Muramay
- DIN 4085

Calculation Model "Horn"



Calculation Model "DIN 4085"

Face pressure is calculated according to

DIN 4085

(Spheric earth pressure on a slurry wall)

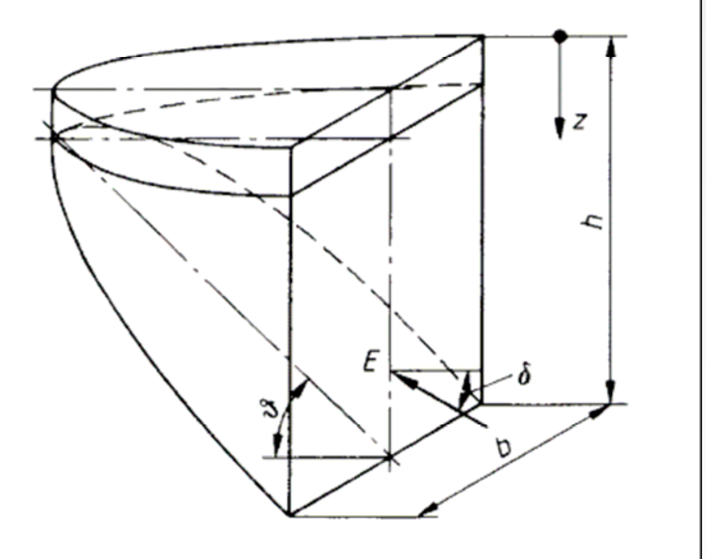


Bild 10. Bruchkörpermodell nach Piaskowski/Kowalewski, Beispiel eines Bruchkörpers

Parameters:

cal φ'..........angle of inner friction (calculated) of the drained soil
cal γ.......... Spezific weight (calculated) of the soil
cal c'..........cohasion (calculated) of the drained soil
z................ depth
Δh..............Hight of the calculated lamell
p................Load on surface

Face pressure according to DIN 4085:

Way of calculation:

1. calculation of horizontal earth pressure

   (active earth pressure)

   k_{agh} from weight of soil $$k_{agh} = \tan^2\left(45° - \frac{cal\ \varphi^I}{2}\right)$$

   k_{ach} from cohasion $$k_{ach} = 2 \cdot \tan\left(45° - \frac{cal\ \varphi^I}{2}\right)$$

Face pressure according to DIN 4085:

2. Form parameter for spheric calculation

z … depth   b … tunnel diameter

z/b	0	1	2	3	4	6	8	10
$\mu_{agh} = \mu_{aph}$	1	0,82	0,70	0,59	0,50	0,37	0,30	0,25

Face pressure according to DIN 4085:

3. Calculation of pressure coefficient

$$\text{spa } e_{ah} = \text{cal}\,\gamma \cdot z \cdot \mu_{agh} \cdot k_{agh} + p \cdot \mu_{aph} \cdot k_{agh} - \text{cal}\, c^{I} \cdot \mu_{ach} \cdot k_{ach}$$

Face pressure according to DIN 4085:

4. Resulting force at the face (from earth pressure)

$$\text{spa}\ E_{ah} = b \cdot \sum_{0}^{D} \text{spa}\ e_{ah} \cdot \Delta h$$

5. Resulting force at the face (from water pressure)

$$p_W = \gamma_W \cdot t_W$$

γ_W.... spezific weight of water (γ_W=10 [KN/m³])
t_W..... Depth under groundwater level

Face pressure according to DIN 4085:

6. Verifications

a) Stability of face

$$S \geq \eta_W \cdot W + \eta_E \cdot E_{ah}$$

S …… pressure for face stability
W …… waterpressure
E_{ah}…… sum of active earthpressure
η_W…… security factor for waterpressure $\eta_W = 1{,}05$
η_E…… security factor for earthpressure $\eta_E = 1{,}5$

$$\left(\eta = \frac{S}{(\eta_W \cdot W + \eta_E \cdot E)} \geq 1{,}0\right)$$

Face pressure according to DIN 4085:

b) Stability in top of tunnel

$$S \geq 1{,}1 \cdot \left(W + E_{ah}\right)$$

S …… pressure for face stability
W …… waterpressure
E_{ah}…… sum of active earthpressure

$$\left(\eta_{top} = \frac{S}{\left(W + E\right)} \geq 1{,}1\right)$$

Face pressure according to DIN 4085:

c) Stability in bottom

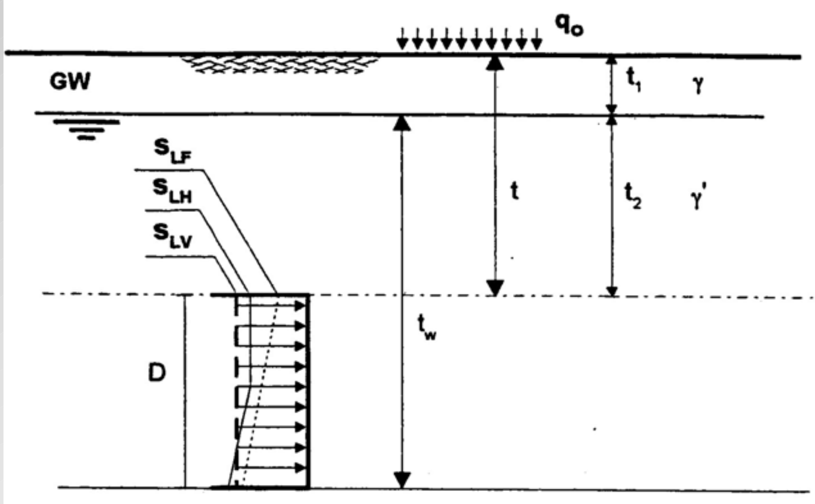
$$S - (W + E_{ah}) \geq 10...20 \text{ KN/m}^2$$

S …… pressure for face stability
W …… waterpressure
E_{ah}…… sum of active earthpressure

Face pressure according to DIN 4085:

d) Stability against blow outs

$$\eta = \frac{\left(\sigma_Z + p_{W0}\right)}{p_0} \geq 1{,}1 \ldots 1{,}2$$

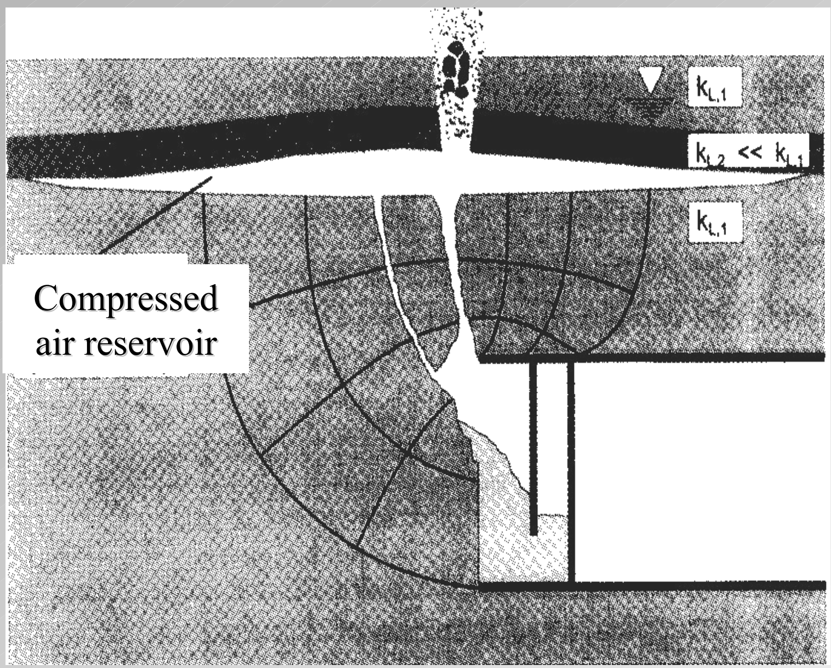


$$\eta = \frac{\gamma \cdot t_1 + \gamma' \cdot t_2 + \gamma_W \cdot \left(t_W - D\right)}{s_{LF,LH,LV}} \geq 1{,}1 \ldots 1{,}2$$

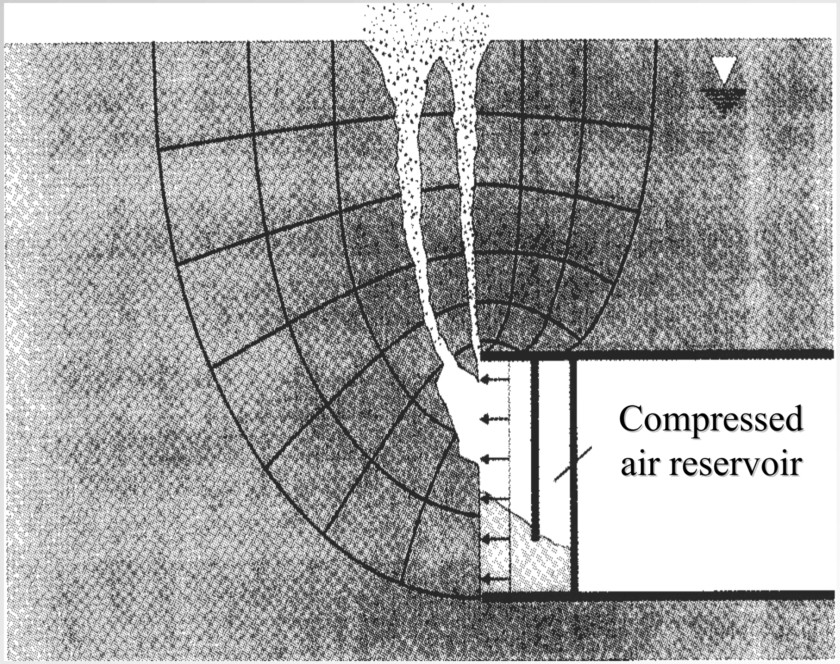
1.1 …… Security factor for normal advance

1.2 …… Security factor during air pressure at face

Blow outs

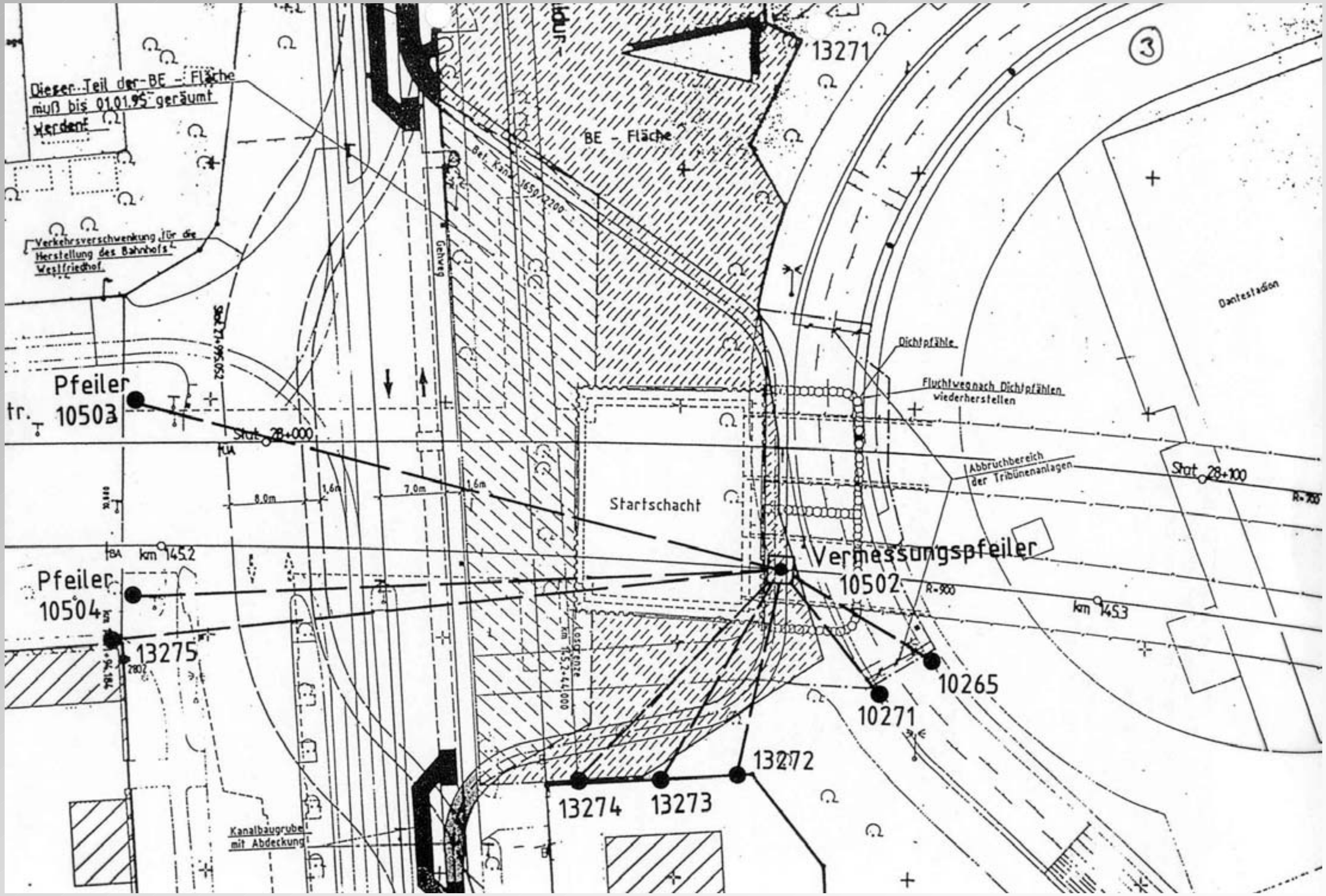


k_{L,1}
k_{L,2} << k_{L,1}
k_{L,1}
Compressed air reservoir



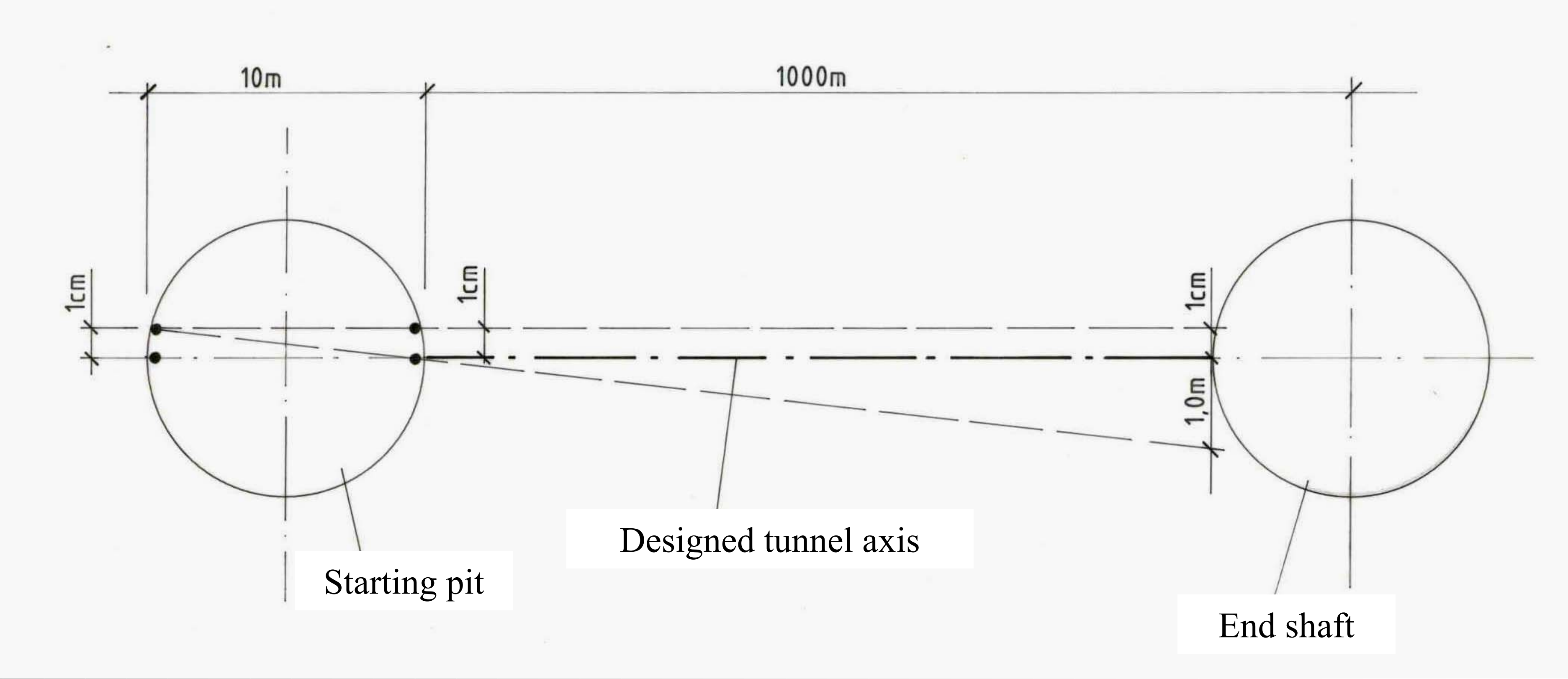
Compressed air reservoir

Survey during TBM drives and Guidance Systems



Coordinated site system with fixed survey points

Result of direction fault in the starting pit



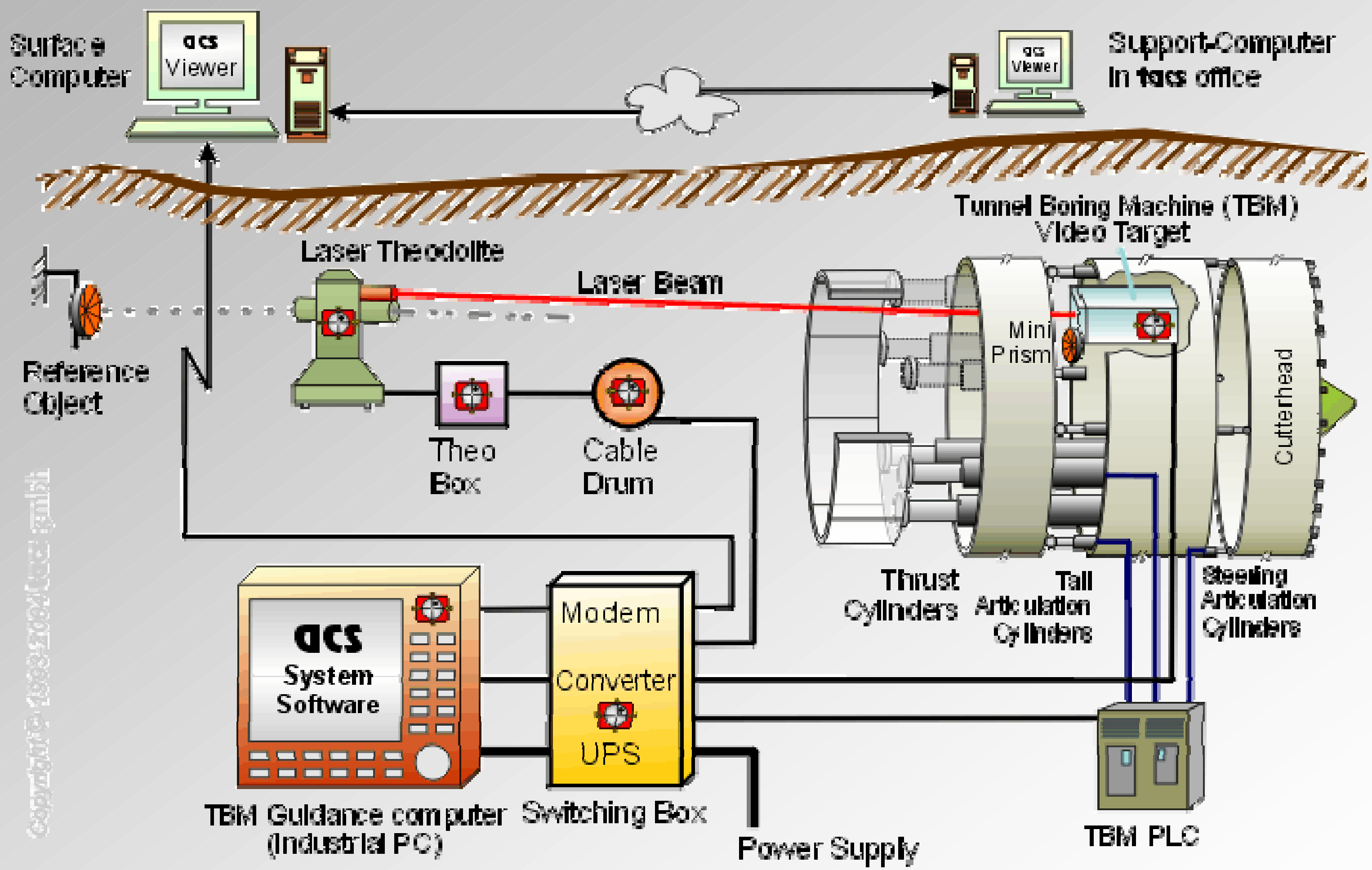
Guidance systems

1. Laser – target - system:
   The „guiding line” is a laser beam. It hits on a special target fixed in the TBM. The target measures the exact position of the hit points and sends it to the computer. There the position of the TBM is calculated.

2. Measuring of reflectors fixed in the TBM with theodolite:
   A motor theodolite searches and measures in short time several reflectors fixed in the TBM and calculates the 3D-coordinates. The computer calculates the position and tendency of the TBM from this coordinates.

3. Giro-theodolite and rubber tube level:
   The tendency of the TBM is measured permanently by a north-finding giro-theodolite and an inclinometer. From the stationing of the TBM, the position is calculated from the last position.

acs Guidance System
- System Overview -

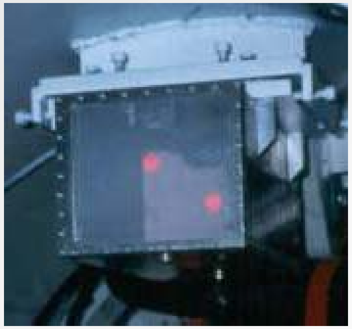


Guidance system - components

1. Laser (-theodolite):
   - provides an exposed guiding beam in the tunnel
   - is equipped with an electronic distance measuring device: → Result: Coordinates of each point

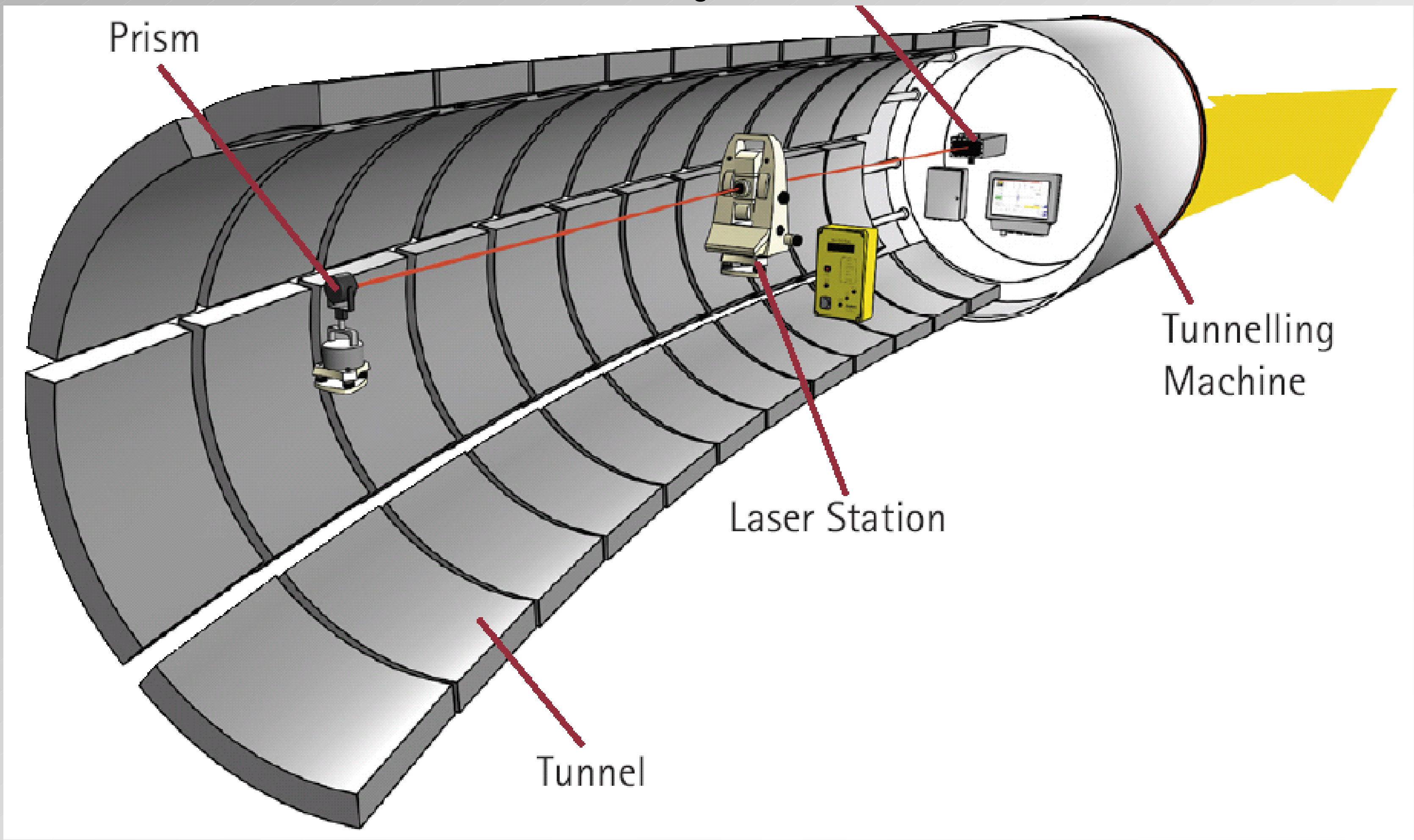
2. Target:
   - Measures the point where the laser hits the TBM
   - Measures rolling and inclination

3. Computer:
   - Stores all informations
   - Calculates the TBM position
   - Compares real position with DTA
   - Offers several working tools for the shift engineer and the surveyor

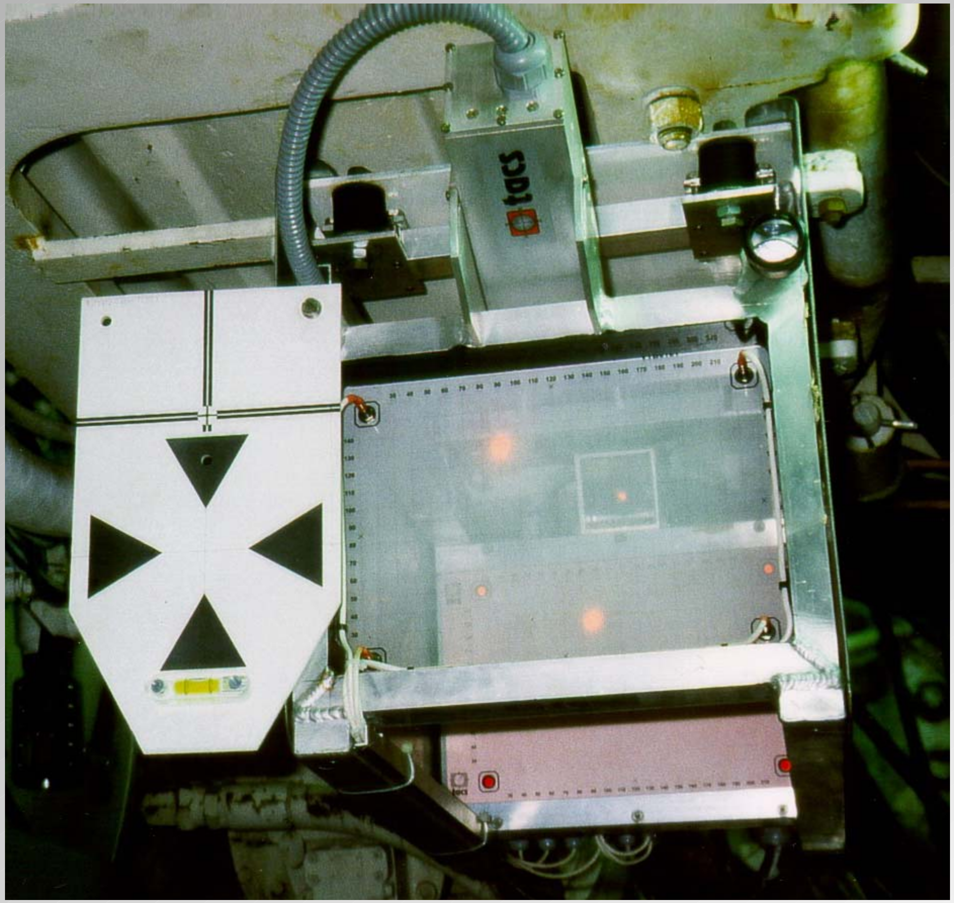


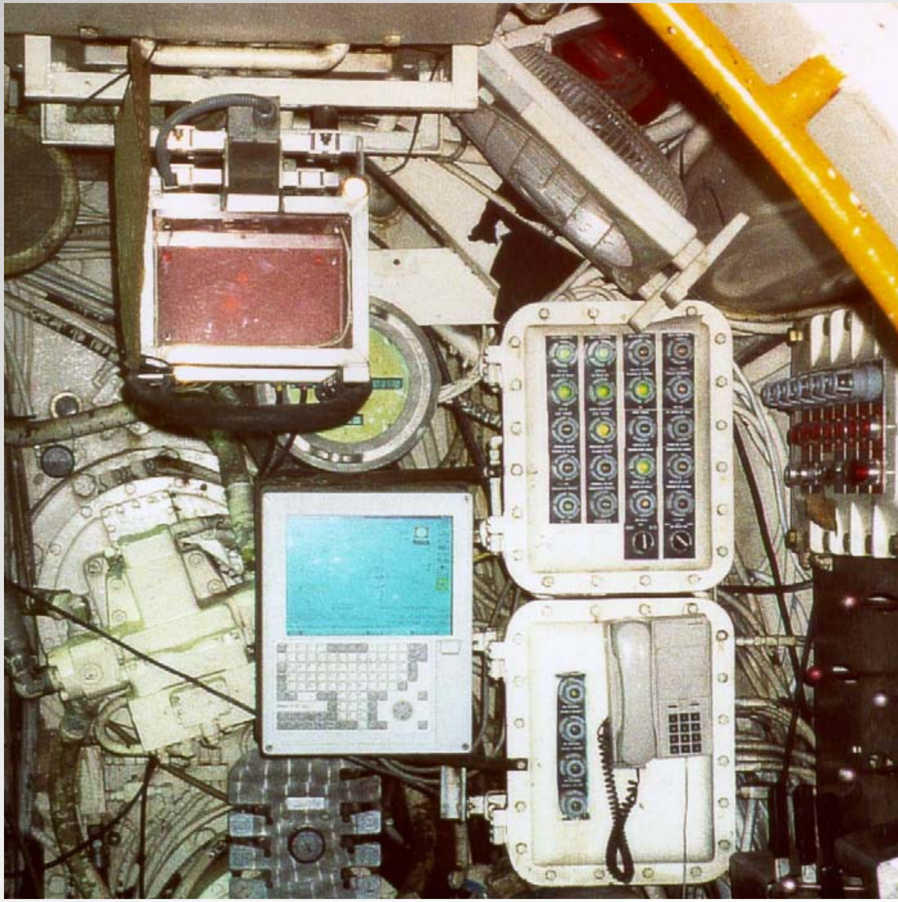
Components

Target unit

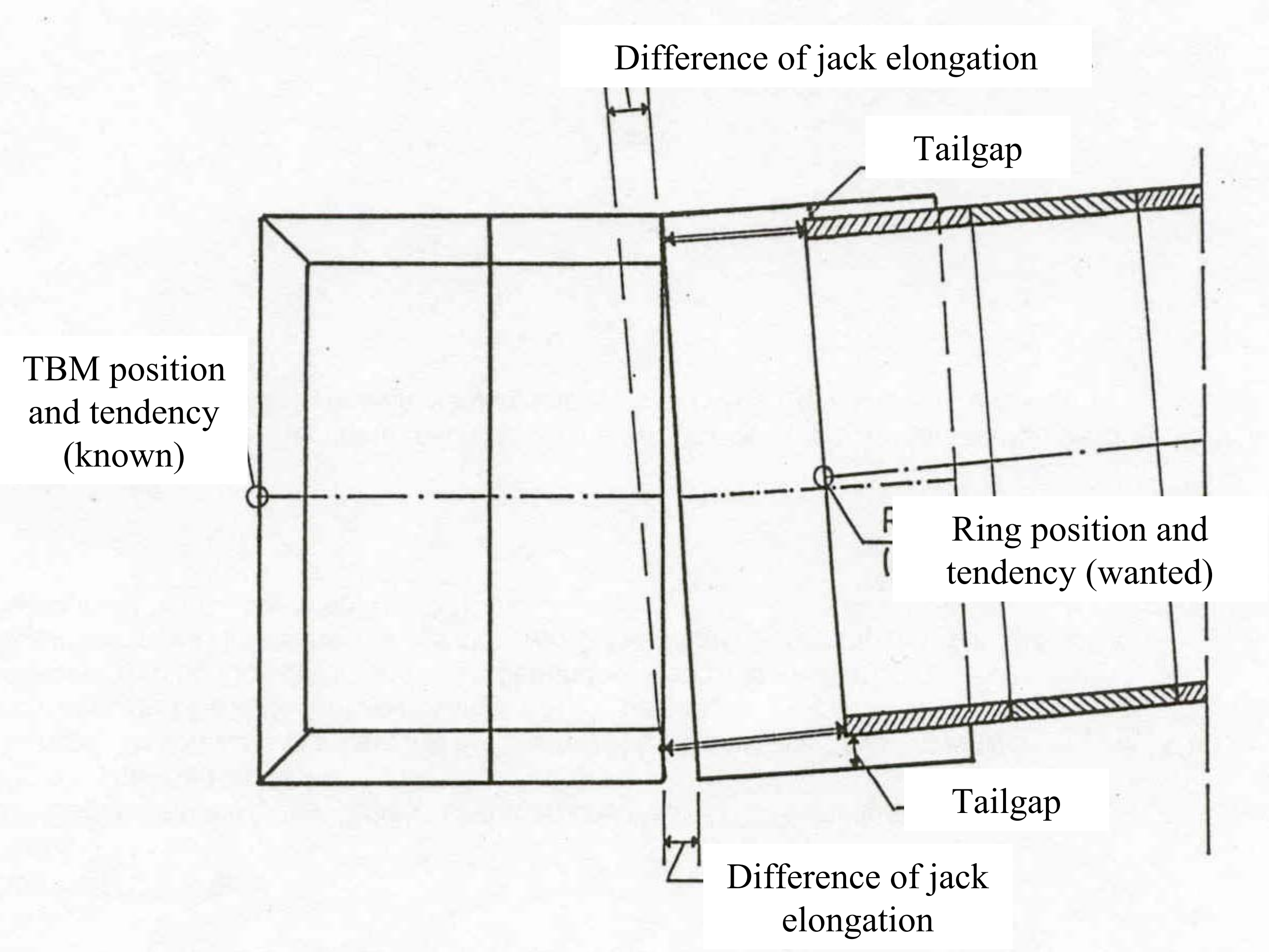


Double target unit (tacs gmbh)

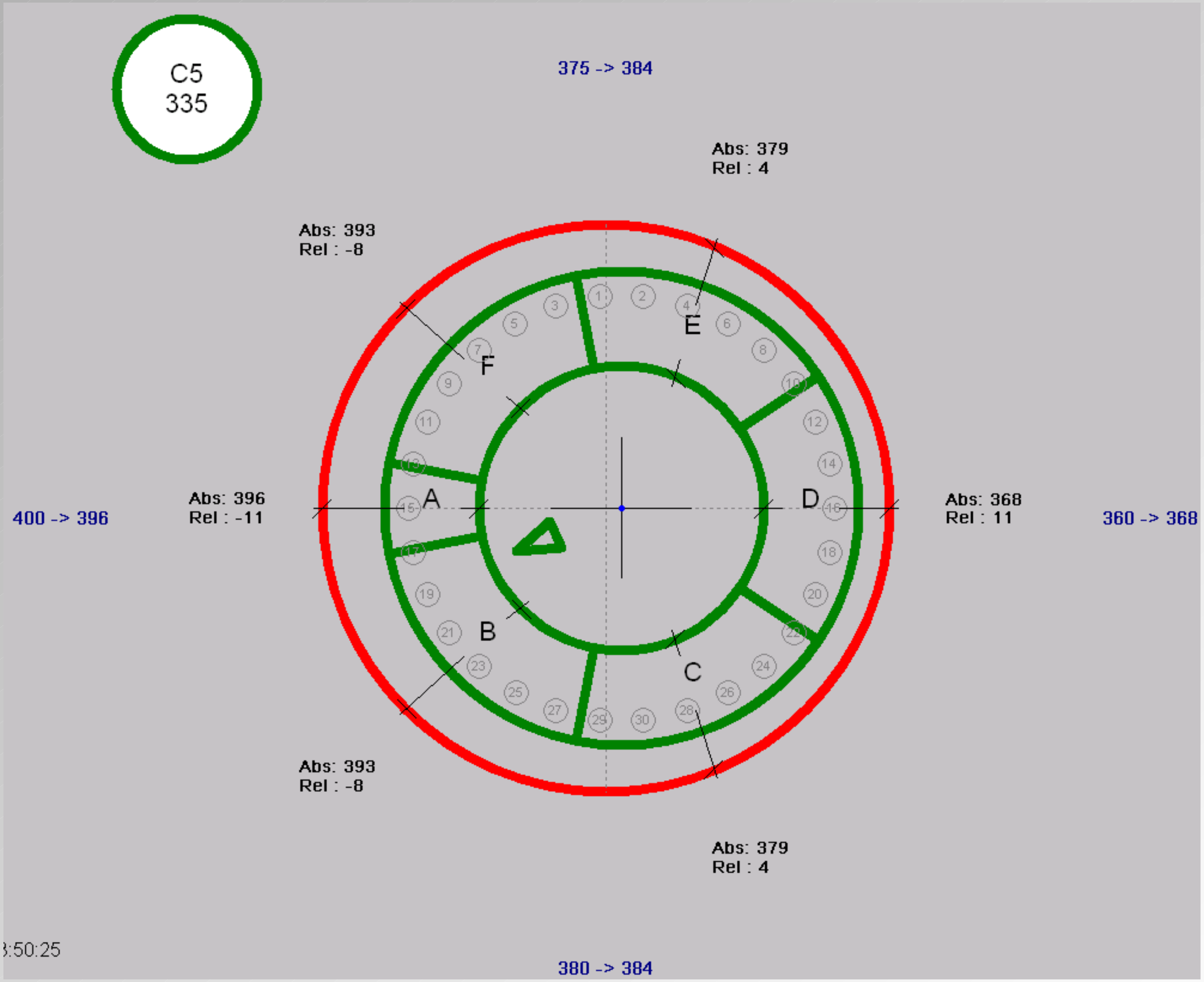




Computer (Industrial - PC)

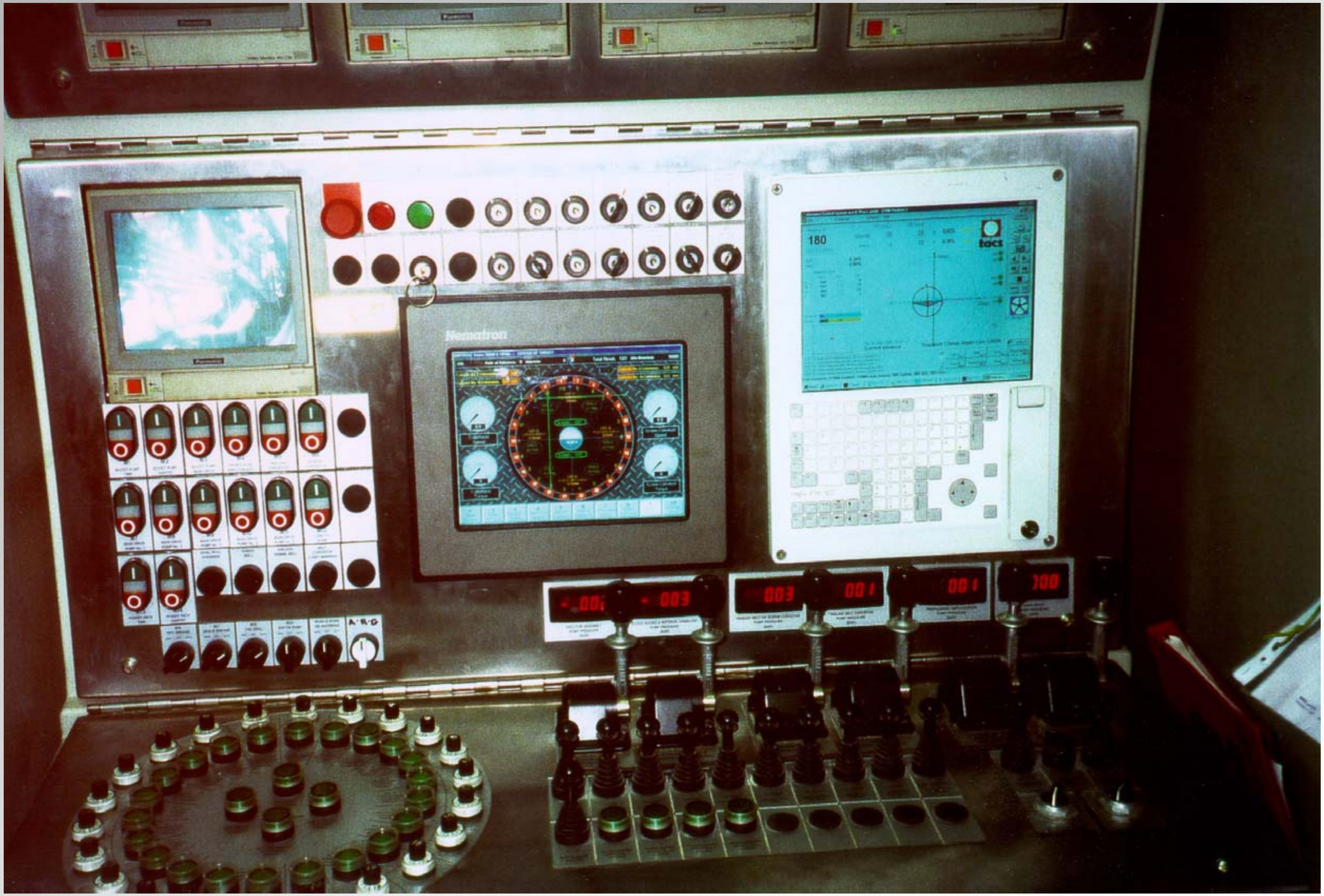


Guidance system – measuring of the segmental ring

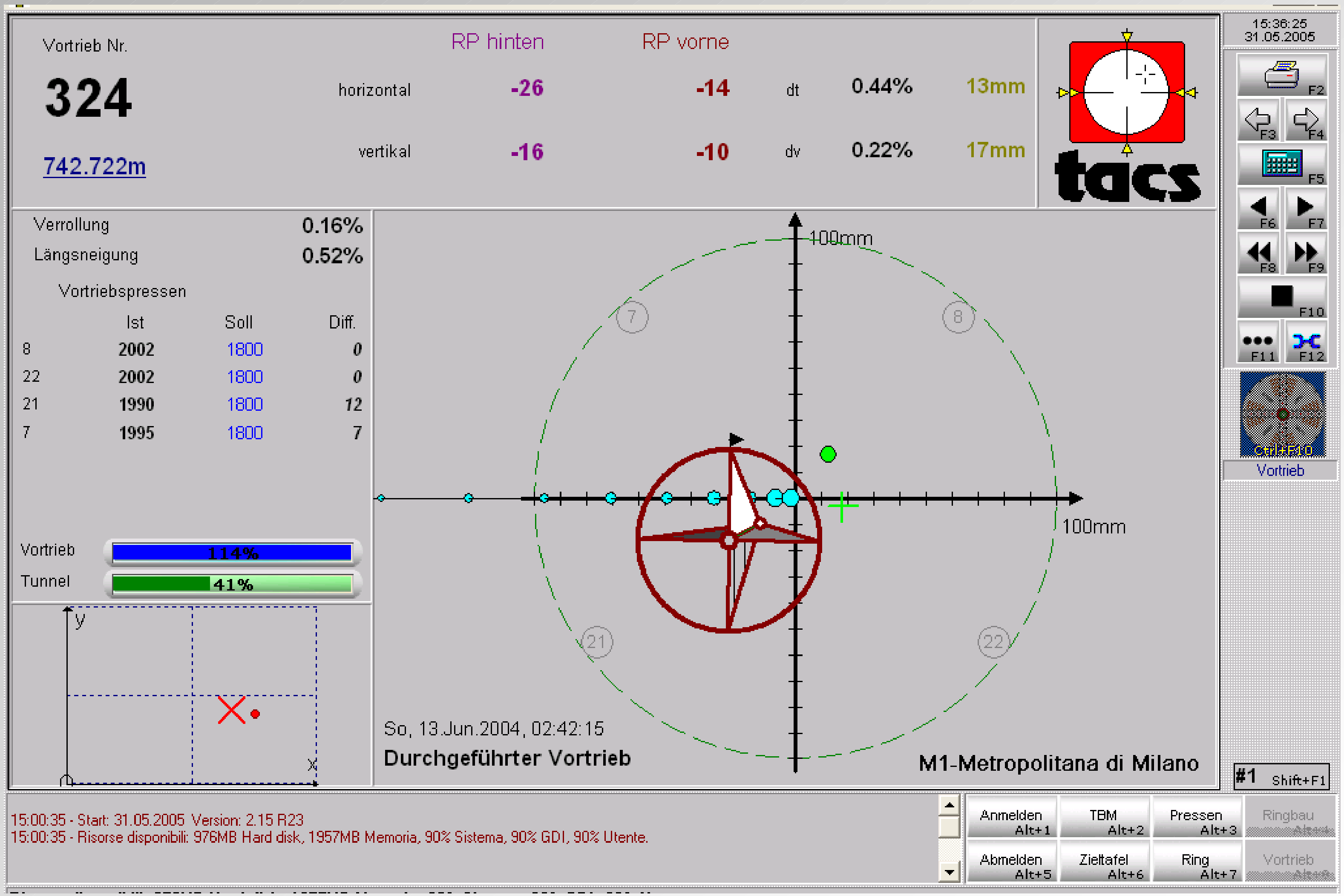


Measuring of the segmental ring

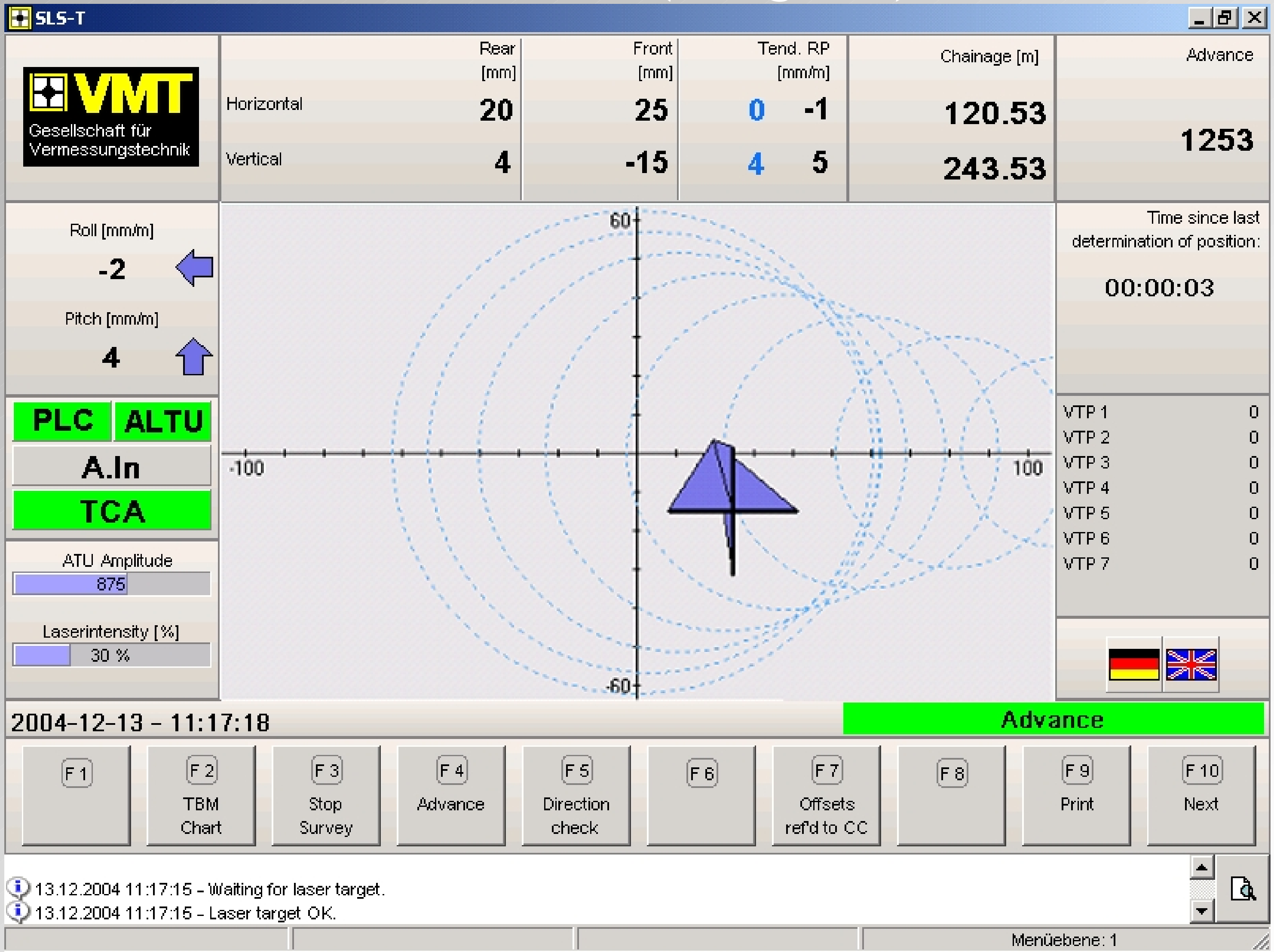
Control pannel (LOVAT)

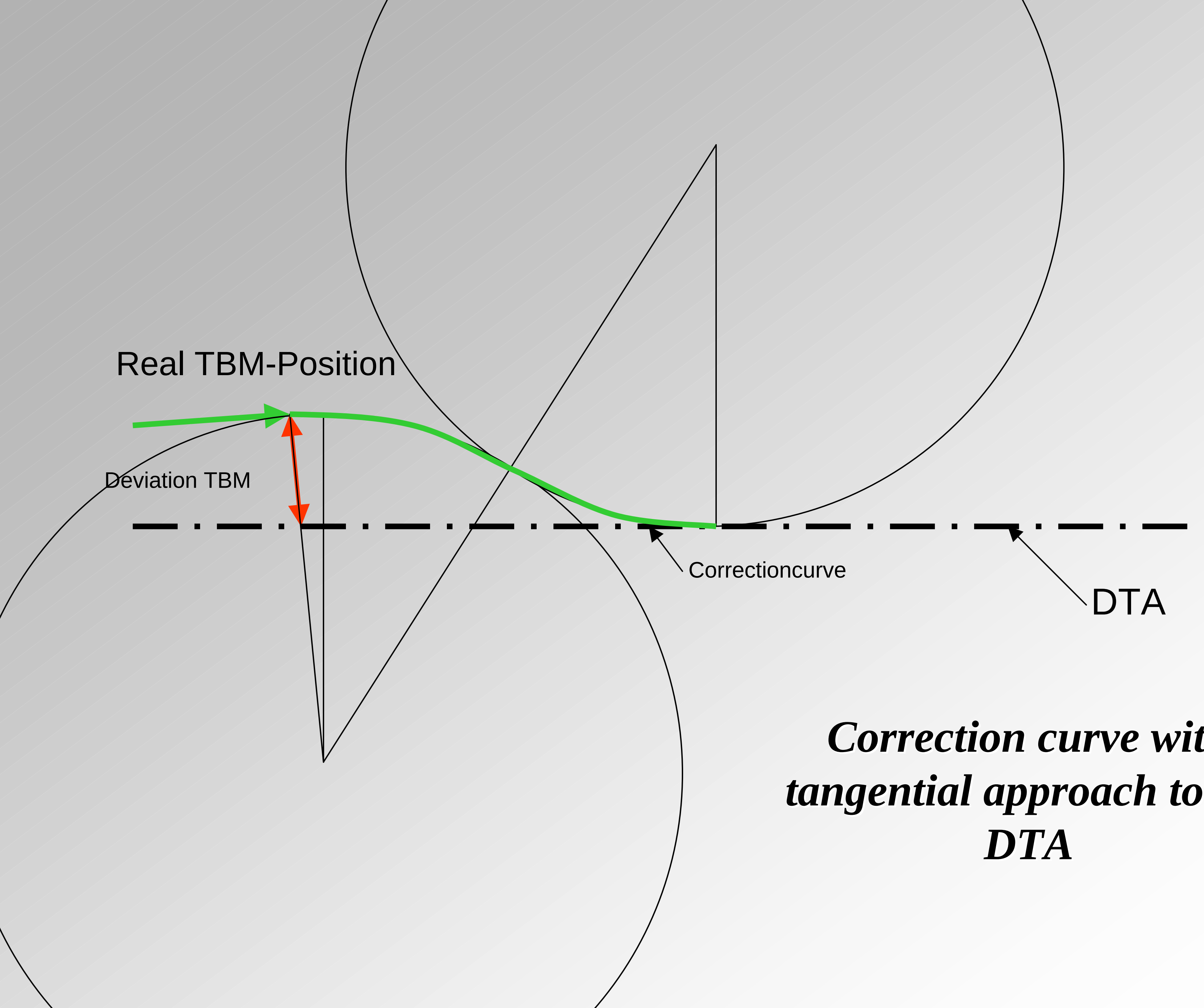


Main screen (tacs gmbh)



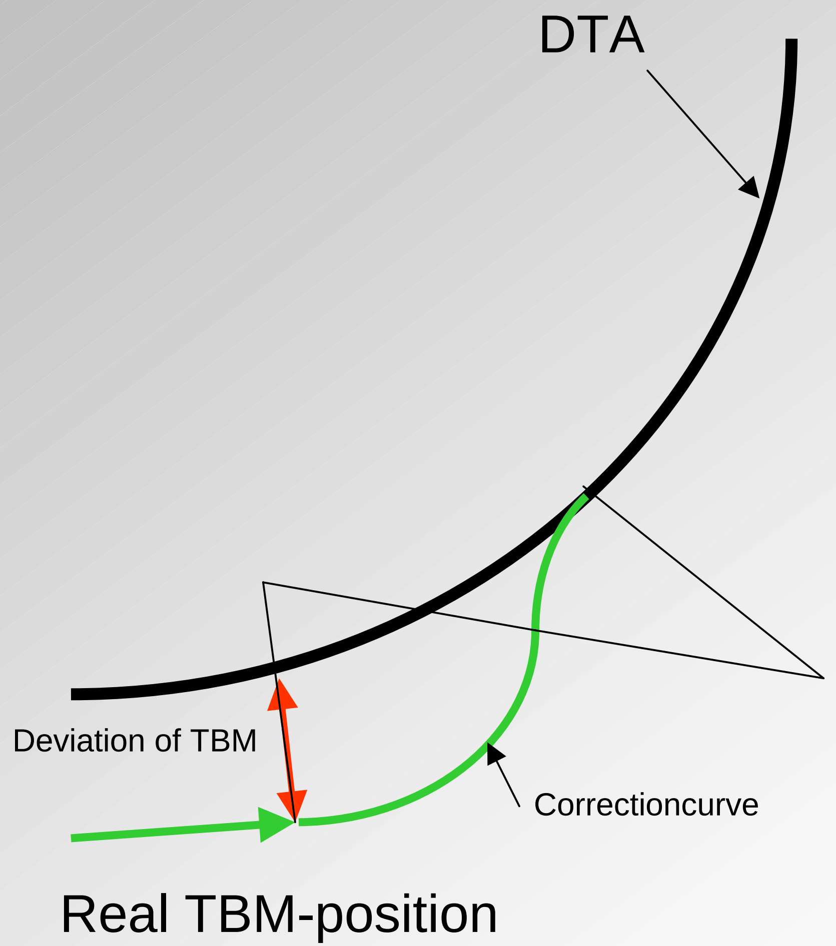
Main screen (vmt gmbh)



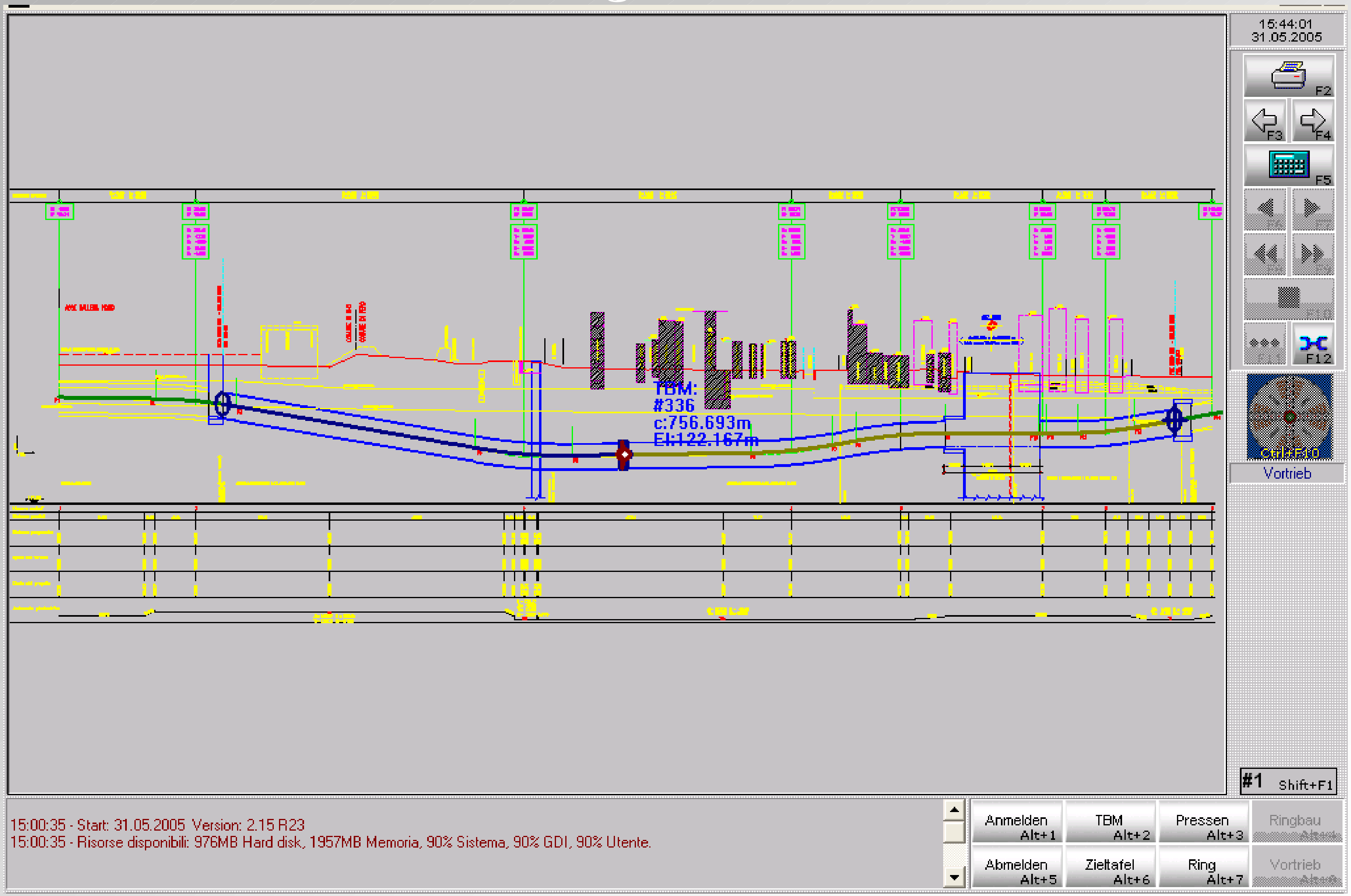


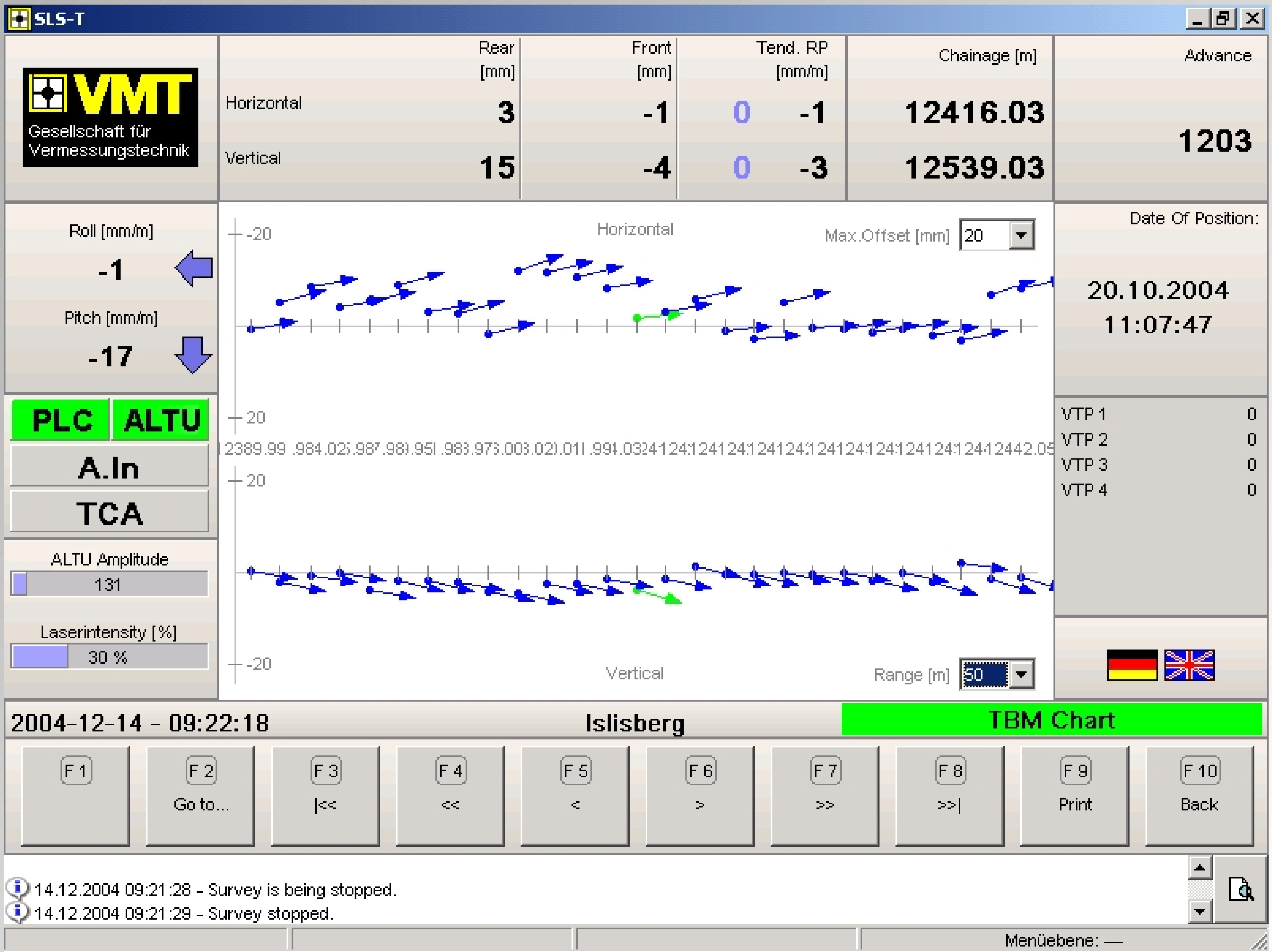
Correction curve with tangential approach to the DTA

Correction curve with tangential approach to the DTA



Screen – longitudinal section



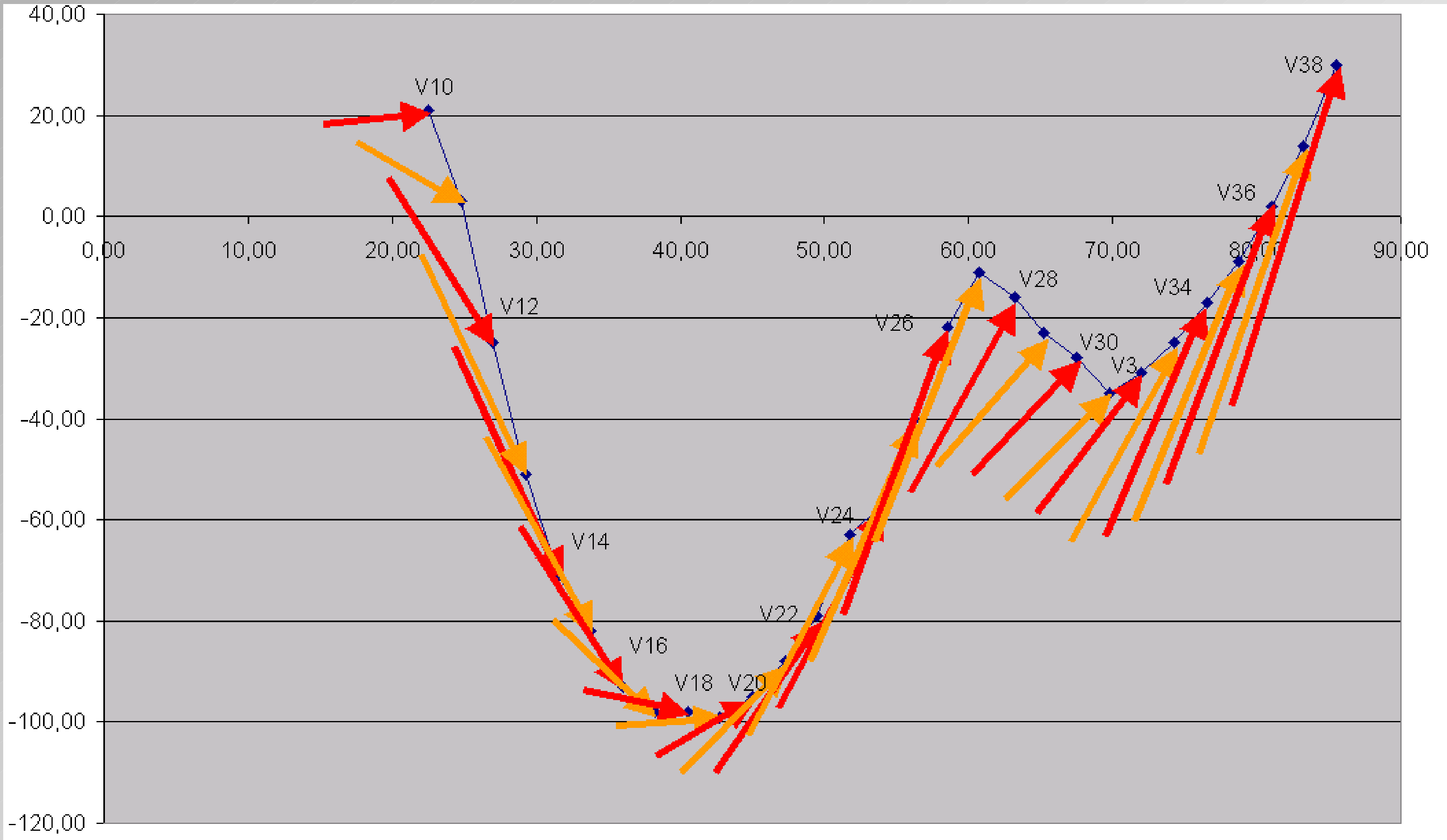


TBM position

Problems concerning advance controll

- Inaccurate survey of the TBM before start of tunnelling
- Incorrect definition of tunnel axis in reference to rail axis (consider of cant)
- Mistake during input of DTA
- Problems with control of direction (refraction at tunnel wall)
- Incorrect driving back to the DTA after a deviation

Refractions - Laser near lining



TBM drive in the start phasis (riding)

Monitoring of advance and ring erection

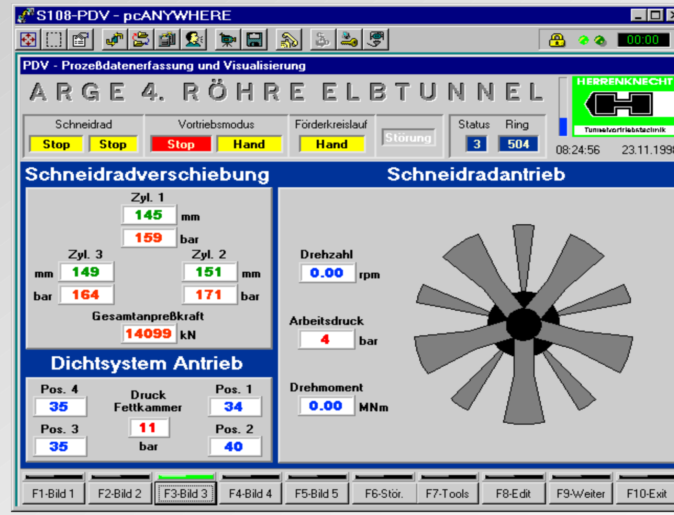
During the whole tunnel drive, the advance team should make a report for each erected ring and for each advance (of one ring).

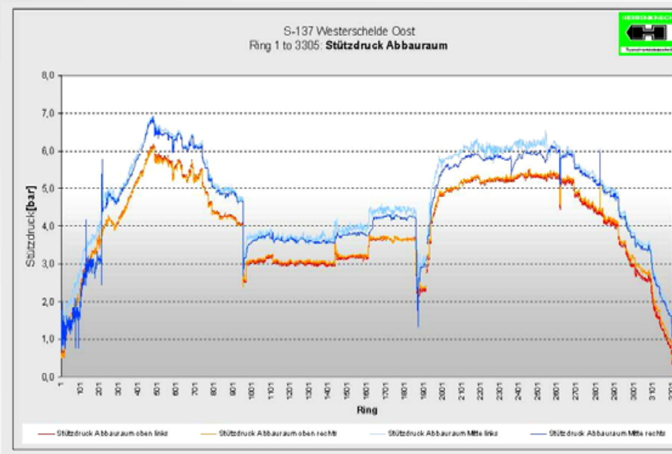
The reports should be part of the construction log book. Form and content should be agreed by the client.

Following items should be part of the report:

- Start and end of advance
- Measured tail gap (4 places), before and after ring erection
- Jack elongations
- Position and form of the built ring
- Special events during advance
- Start and end of ring erection
- Damages at the ring during ring erection
- Results of face inspection (cutters, face)
- Accidents during advance and ring erection (time, cause)

Monitoring of TBM data





5

Lining behind TBMs

- Shotcrete behind hardrock TBMs
- Precast Concrete Lining behind shielded TBMs
- Ringerection

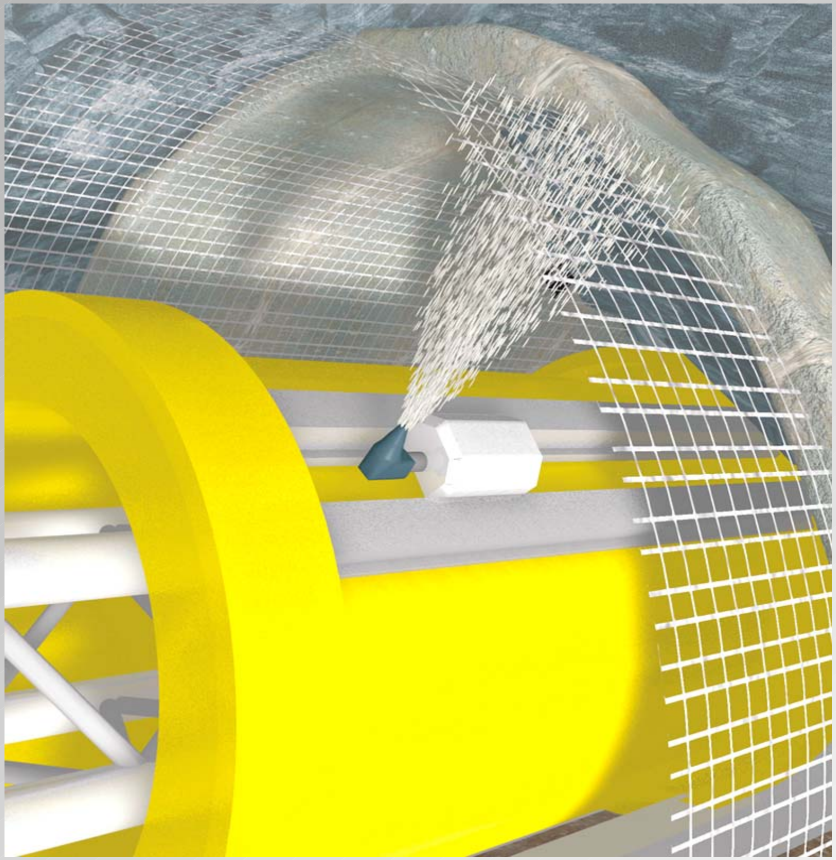
Shotcrete behind hard rock TBMs

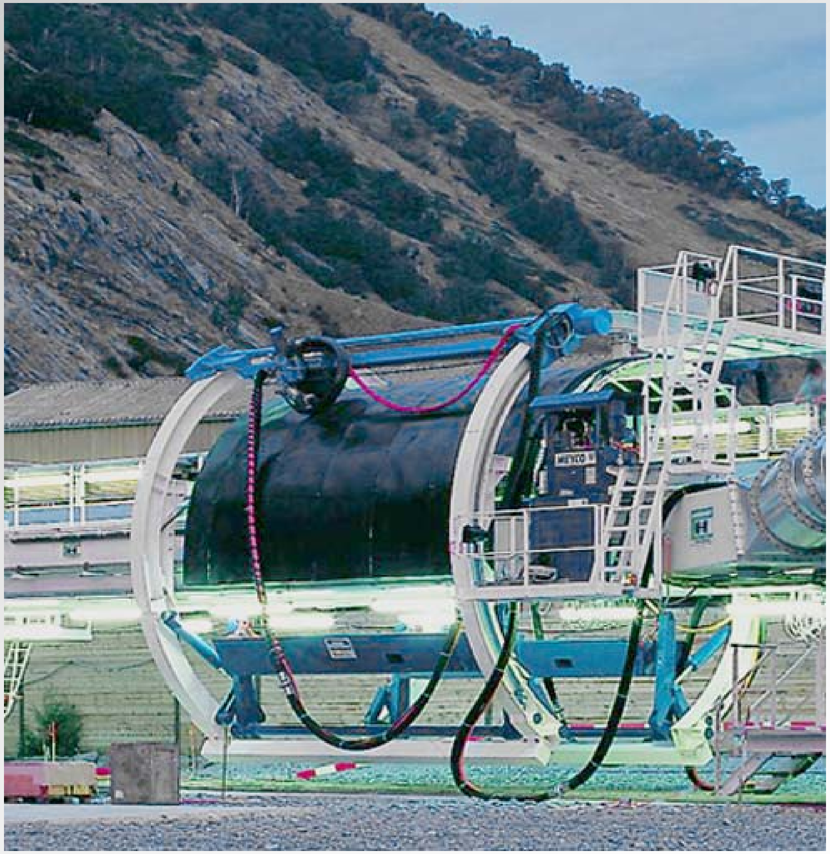
- Shotcrete is creating dust

Shotcrete behind hard rock TBMs

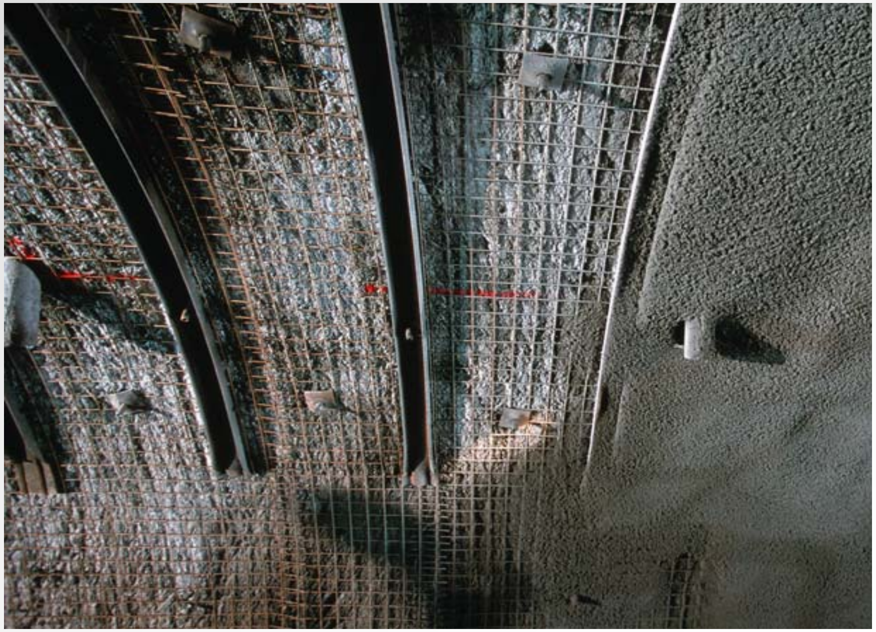
- Shotcrete should be used in the back part of the trailer (>60m from face)

Shotcrete behind hard rock TBMs





Shotcrete behind hard rock TBMs



Advantages of concrete segmental rings:

- After leaving the TBM tail and grouting, the segmental ring can take the final loads. No hardening time is necessary.
- The constant quality of the concrete can be easily tested in the segment factory.
- Ring erection is done by the help of machines, is done in short time (20 to 40 minutes per ring) and has a high quality
- Each ring is positioned with a high precision in the shield tail
- The ground is stabilized by the ring and may not fall down

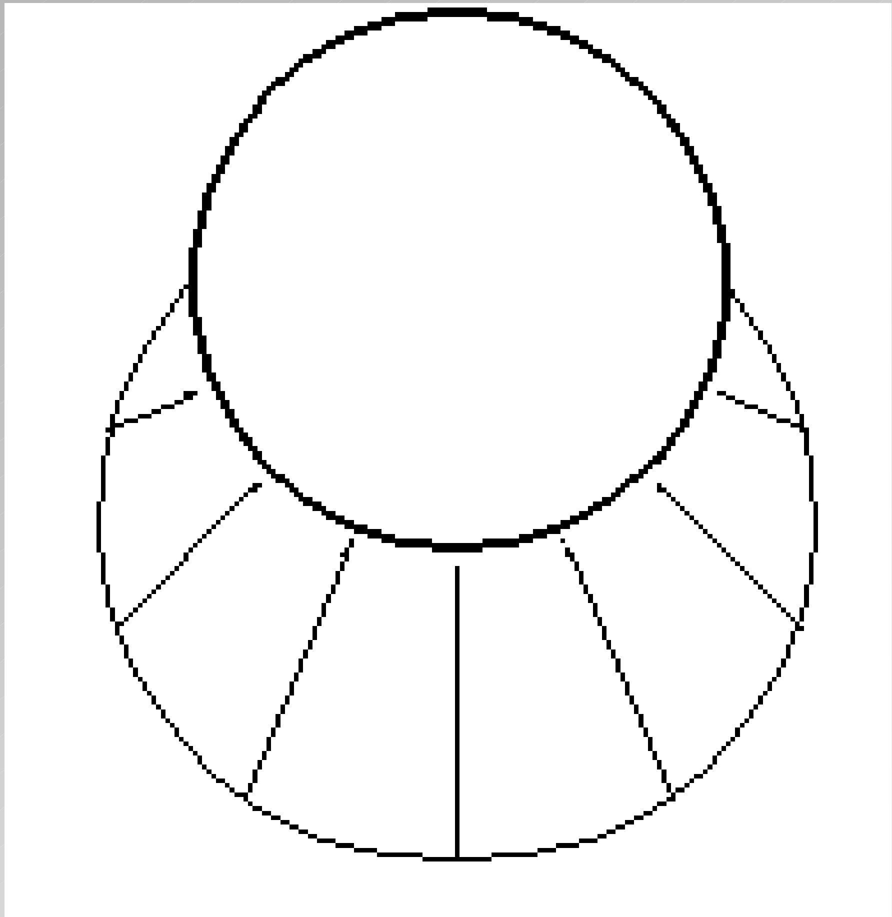
Advantages of the single shell segmental lining

- High quality of the precast segments
- High load capacity shortly after ring erection
- Easy detection of leakages and easy repair work
- Lower costs than for a double shell lining (no inner lining)
- Real loads on inner lining are not clear

Special loads after end of advance

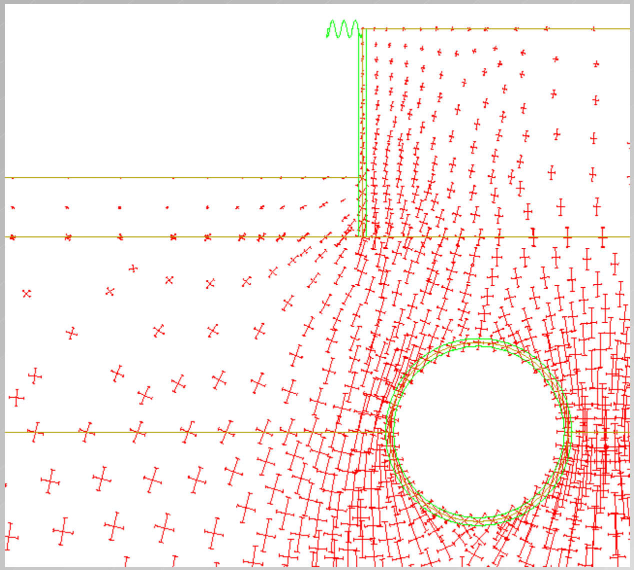
- Exterior loads who appear later (swelling pressure, later constructions near the tunnel)
- Relaxation over or aside of the tunnel (later pits)
- Two near running tunnels
- High outer water pressure
- Small distance between parallel tunnels
- Possible high water pressure around the tunnel (>15 bar)

Special loads which may occur after end of advance

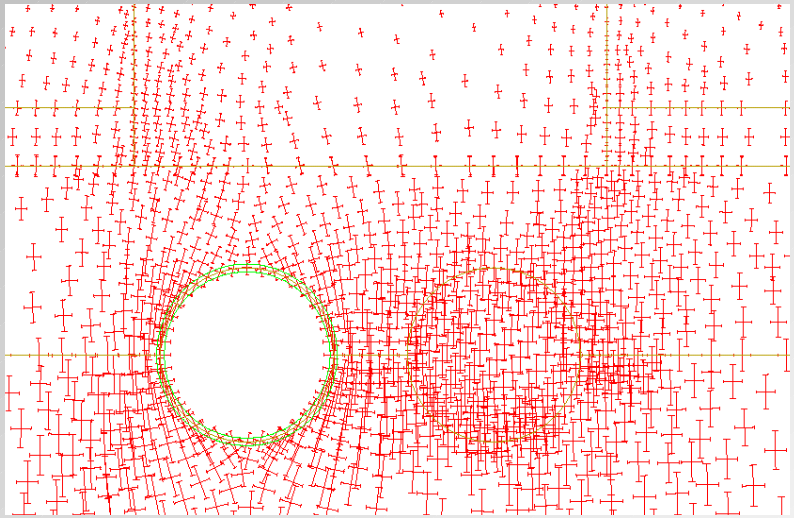


Swelling pressure
(anhydrite, clay)

Unfavourable loads on a single shell lining



Deep pits over / aside a tunnel → normal forces are reduced, moments get higher



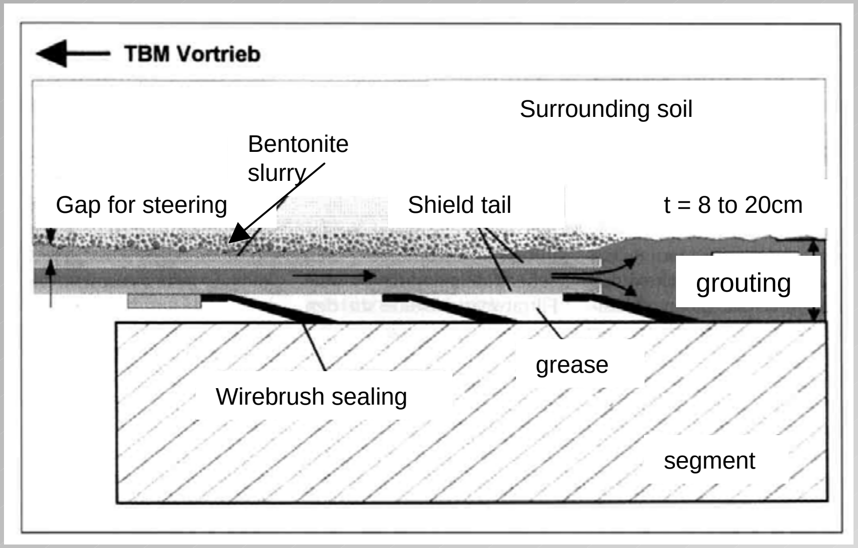
Parallel tunnels with small distance between both tubes (<1/2 D)

Insufficient bedding of first tunnel when second machine passes

Following loads are important for the quality of the rings:

- Ram forces
- Loads from trailer rolls
- Loads resulting from squeezing in the tail sealing
- Stresses induced by grouting of the annular space

Special loads



Segmental ring Design

Segmental rings are used from 2 to 16m outer diameter

Rings normally consist of 5 to 8 segments

Continuous longitudinal joints in Europe only usual if inner lining is used (German railway standard RiL853 demands staggered joints for single shell lining)

Possible problems if continuous longitudinal joints are used:

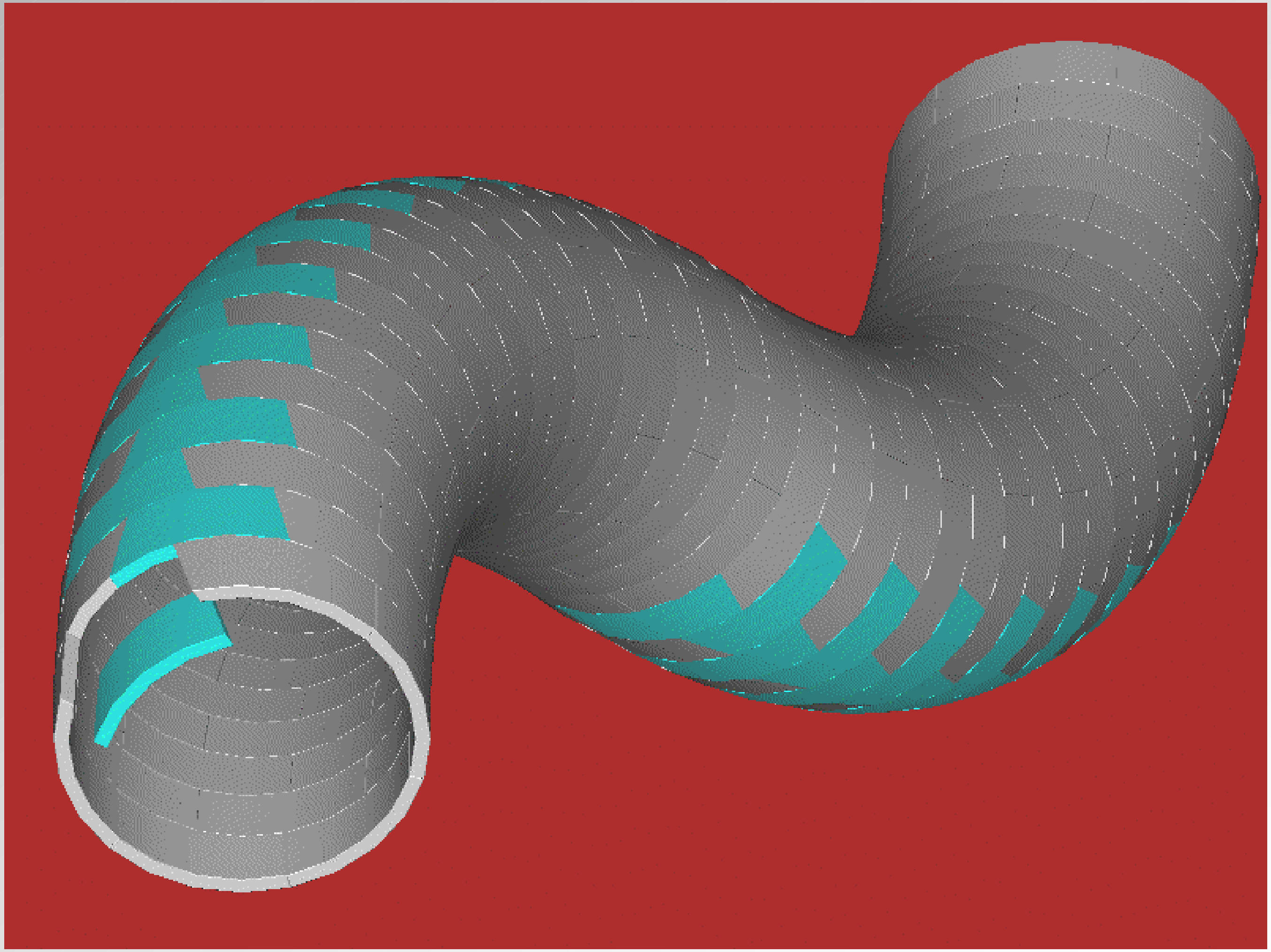
- Small faults during ring erection add over several rings to big steps
- If the longitudinal joints of adjacent rings do not fit exactly together, scaling and damages may not be avoided
- To egalize steps in the circumferential joints packers must be installed from time to time

Segmental ring design

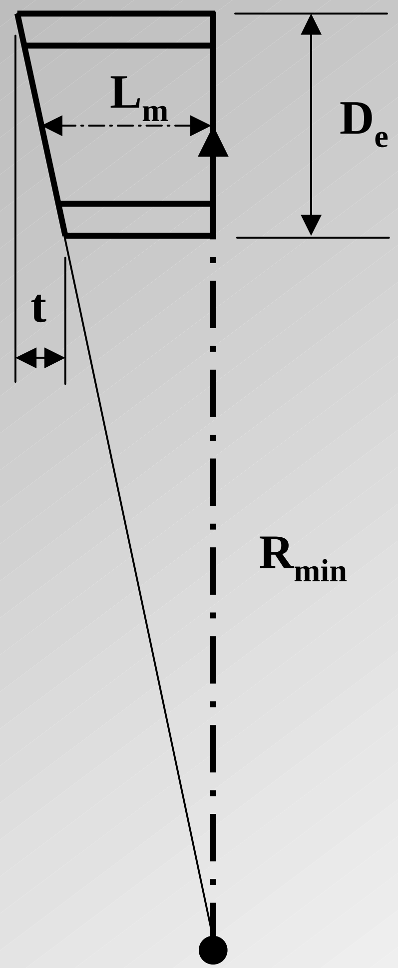
Continuous longitudinal joints

Staggered longitudinal joints

Tapered Rings



Tapered Rings



$$t = \frac{D_e \times L_m}{R_{min}}$$

Example: Calculation of taper

l_m = 2,0 m
D_e = 8,2 m
R_{DTA} = 300 m
30° staggered longitudinal joints

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correction curve radius: R_{min} = 240m (R_{DTA} - ~20%)

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→ $t'' = l \times D_a / R_{min} = 2{,}0 * 8{,}2 / 240 = 0{,}068$ m = 68 mm

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→ t‘‘ = l x D_a / R_{min} = 2,0 * 8,2 / 240 = 0,068 m = 68 mm

→ t‘ = t‘‘ / [(1 + cos 30°) * 0,5] = 73 mm

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$\rightarrow$ t = t' + 5 mm = 78 mm

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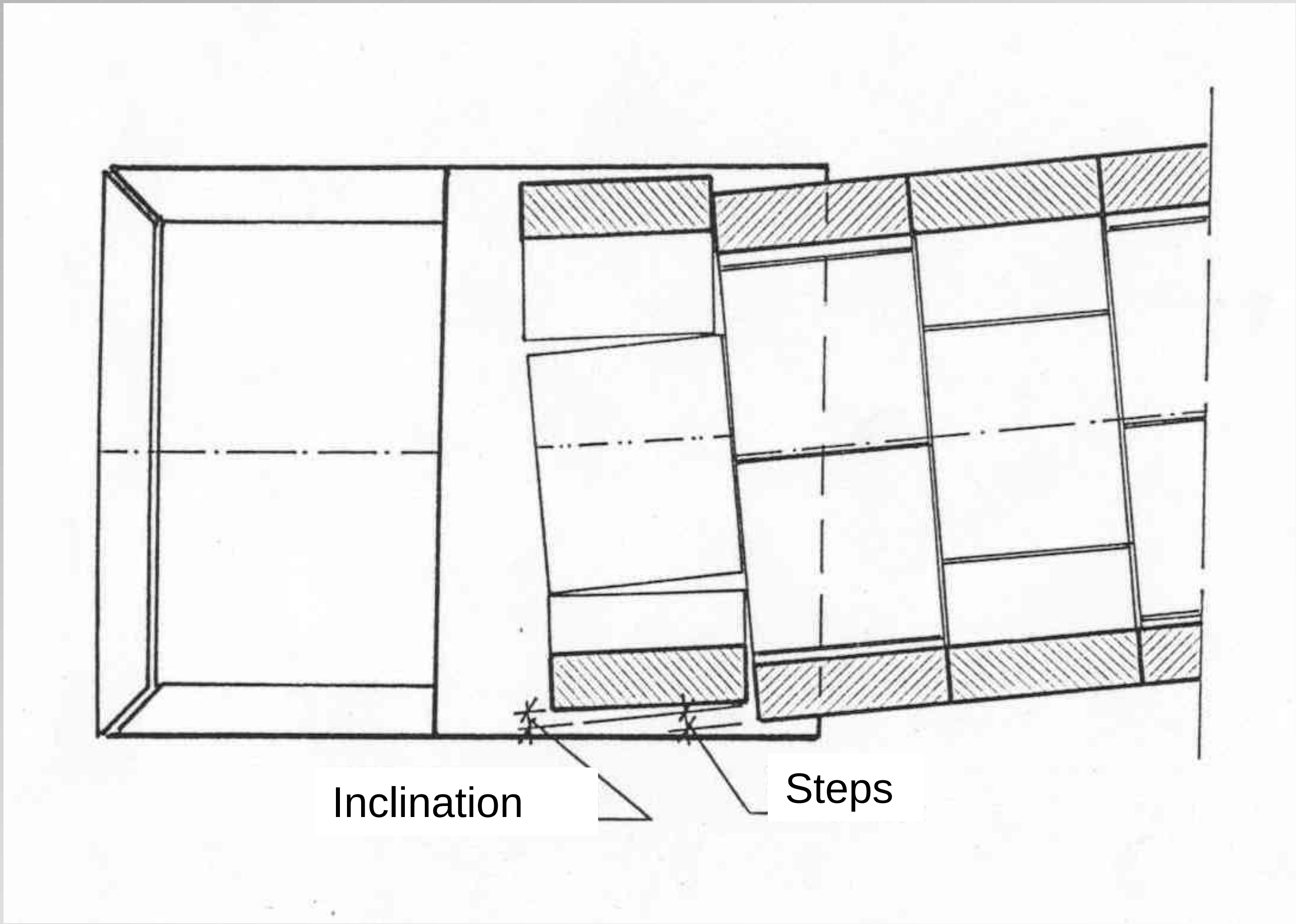
→ t = t‘ + 5 mm = 78 mm

Chosen: 80 mm

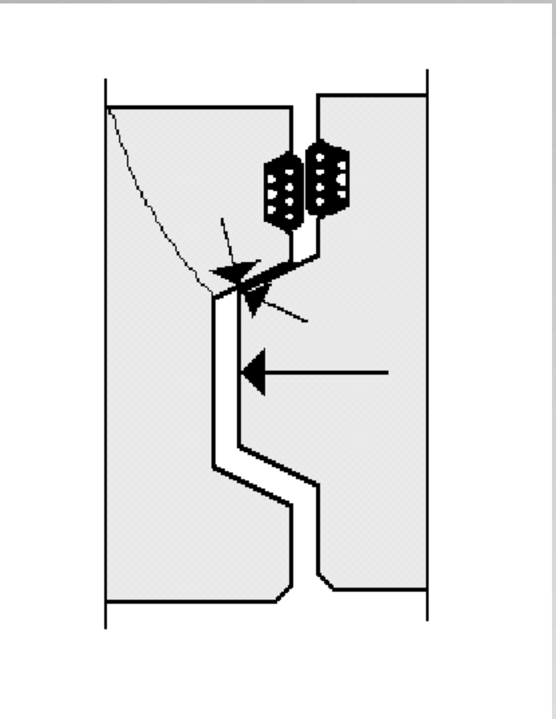
Constraints during ring erection



Design of joints

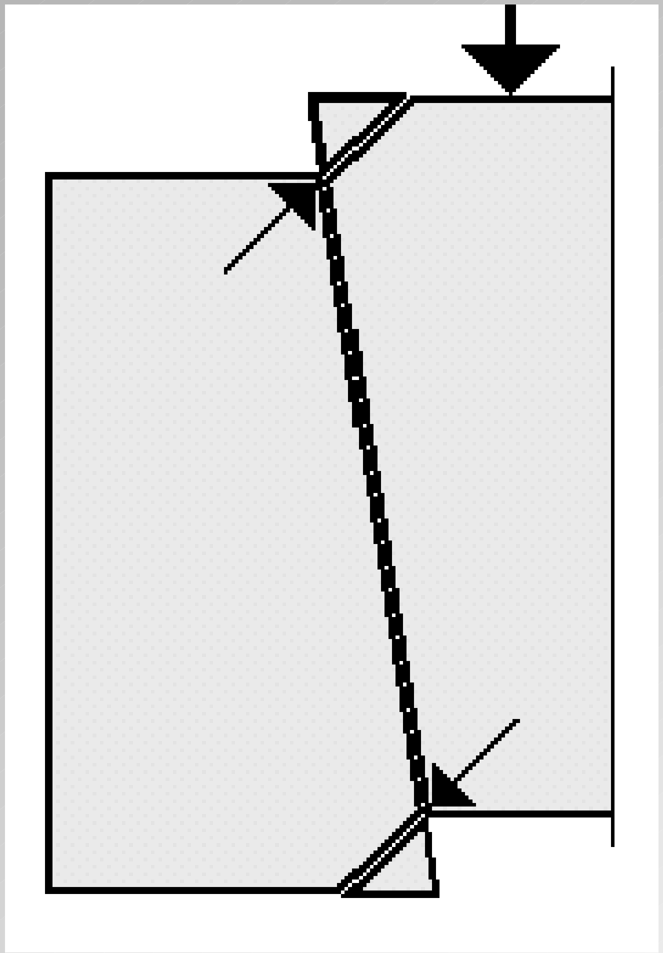
Cams in circumferential joints

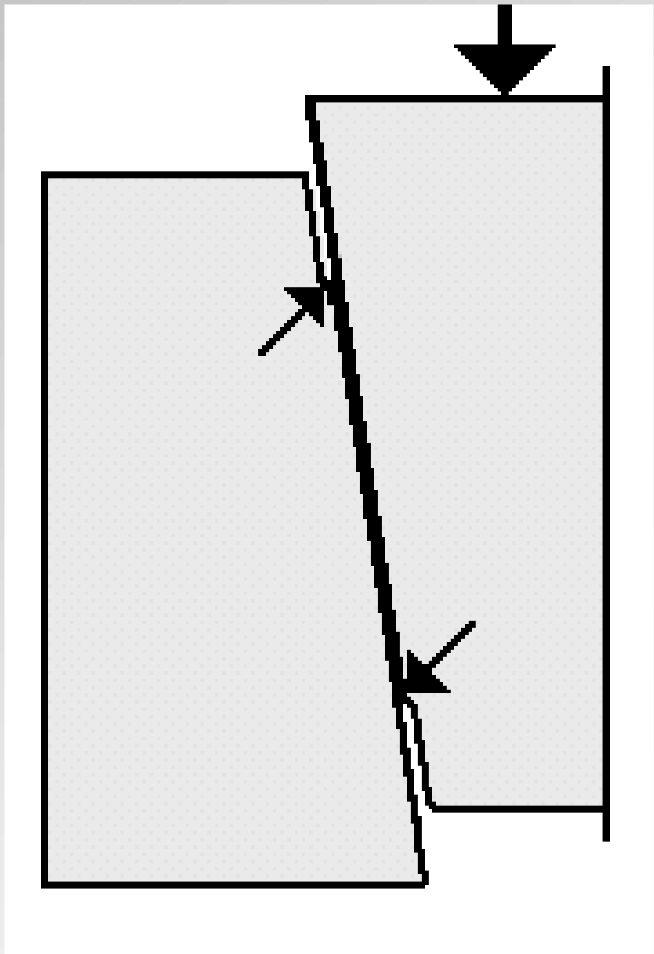
Design of joints



Damages when using cams in circumferential joints

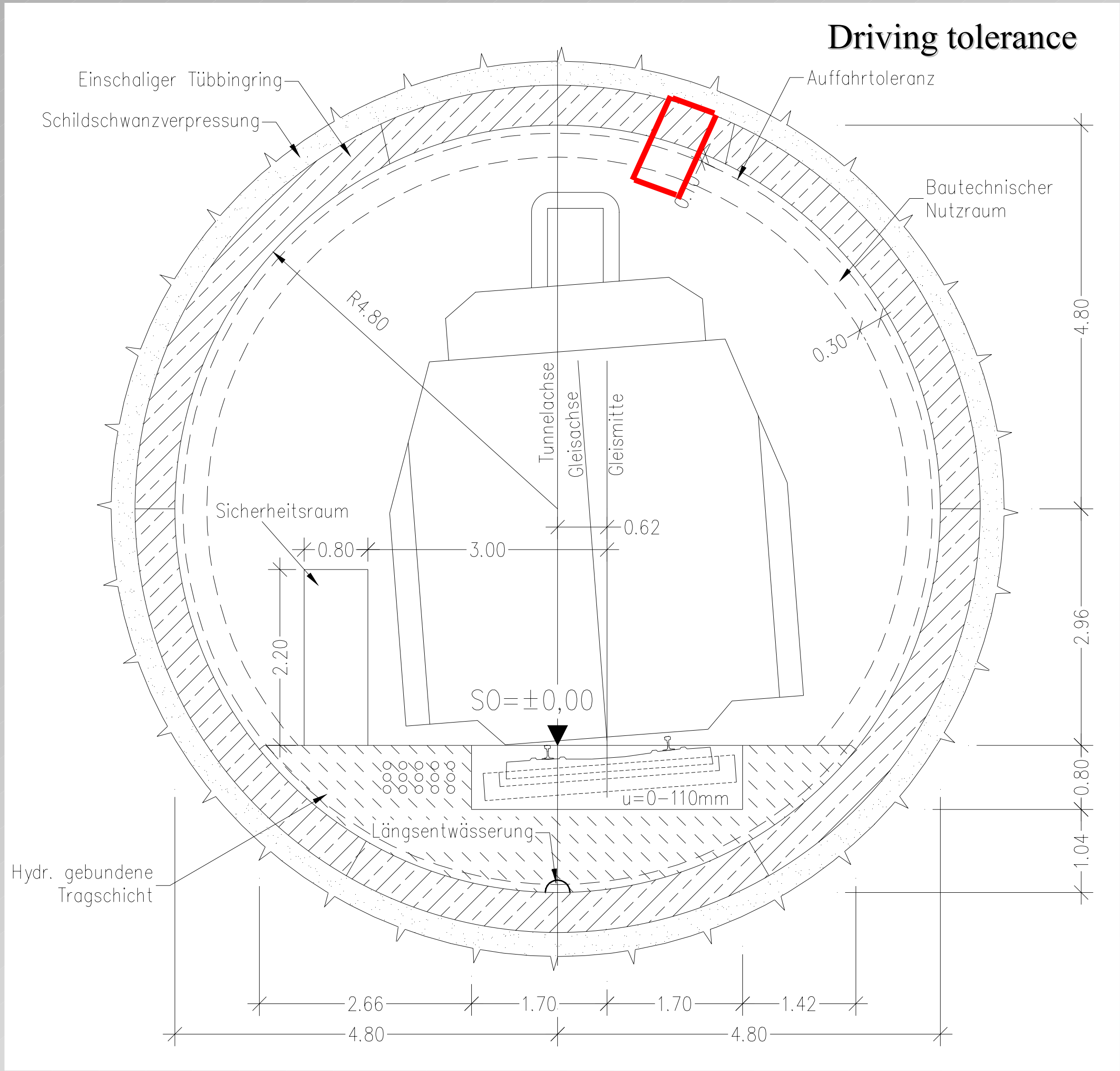
Recesses in the segment corners





Recesses in the longitudinal joints – no touch of segments in the corner areas during ring erection

Driving tolerance

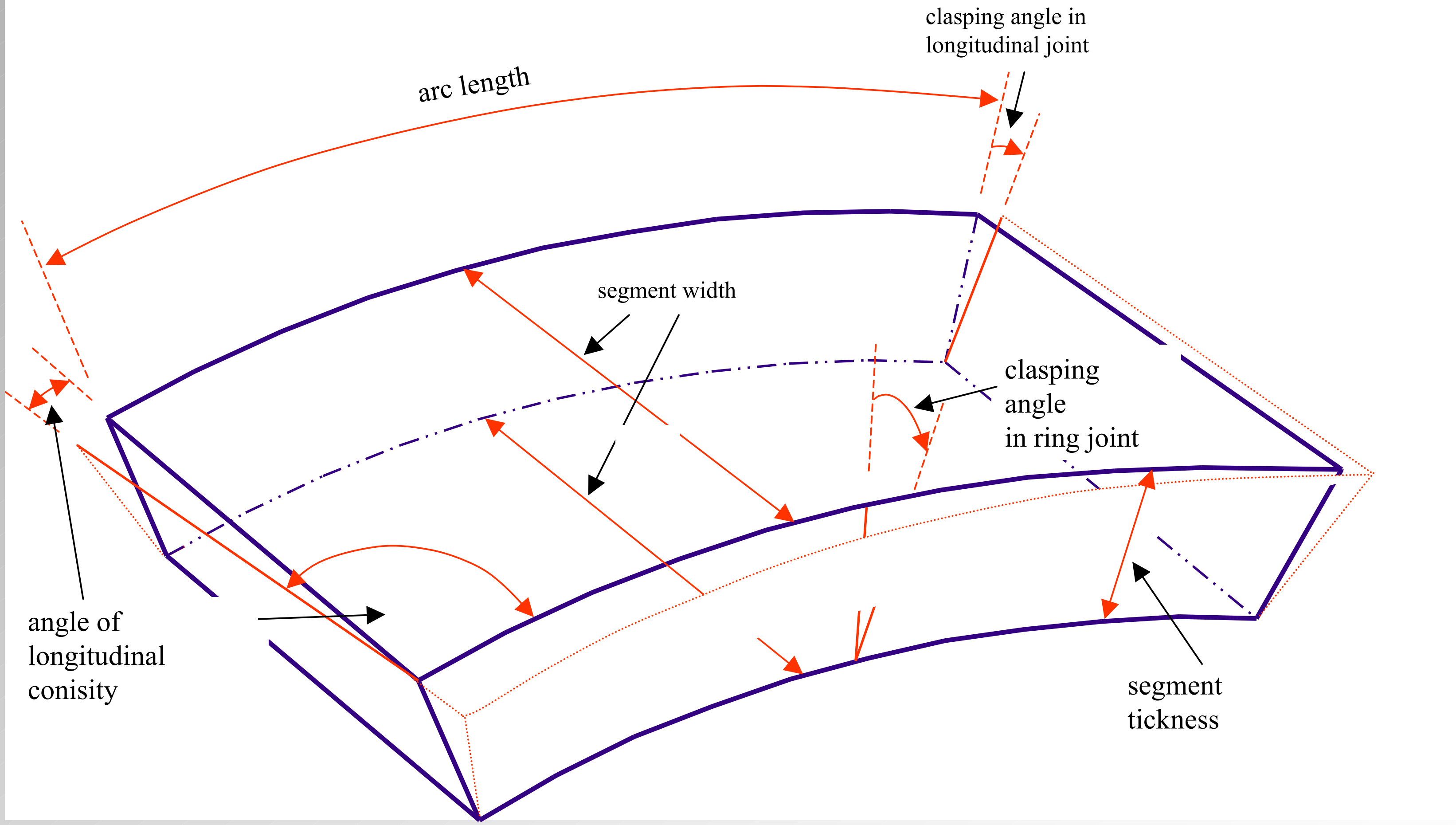


Tolerances

Tolerances according DB AG RiL 853:

1.	Angles:	
1.1	Clasping angle in longitudinal joint	± 0,04°
1.2	Angle of longitudinal joint conicity	± 0,01°
2.	Linear Values:	
2.1	Width of segment	± 0,5 mm
2.2	Thickness of segment	± 2,0 mm
2.3	Arc length of segment	± 0,6 mm
2.4	Inner radius (one segment)	± 1,5 mm
2.5	Width of gasket groove	± 0,2 mm
3.	Plane and parallelness of contact zones:	
3.1	Longitudinal joint	± 0,3 mm
3.2	Circumferential joint	± 0,3 mm
4.	Details:	
4.1	Axis of gasket	± 1,0 mm
4.2	Axis of contact zone	± 1,0 mm
4.3	Plane of bolts	± 1,0 mm
5.	Tolerances of an erected ring:	
5.1	Outer diameter	± 10 mm
5.2	Inner diameter	± 10 mm
5.3	Outer circumference (measured in 3 levels)	± 30 mm

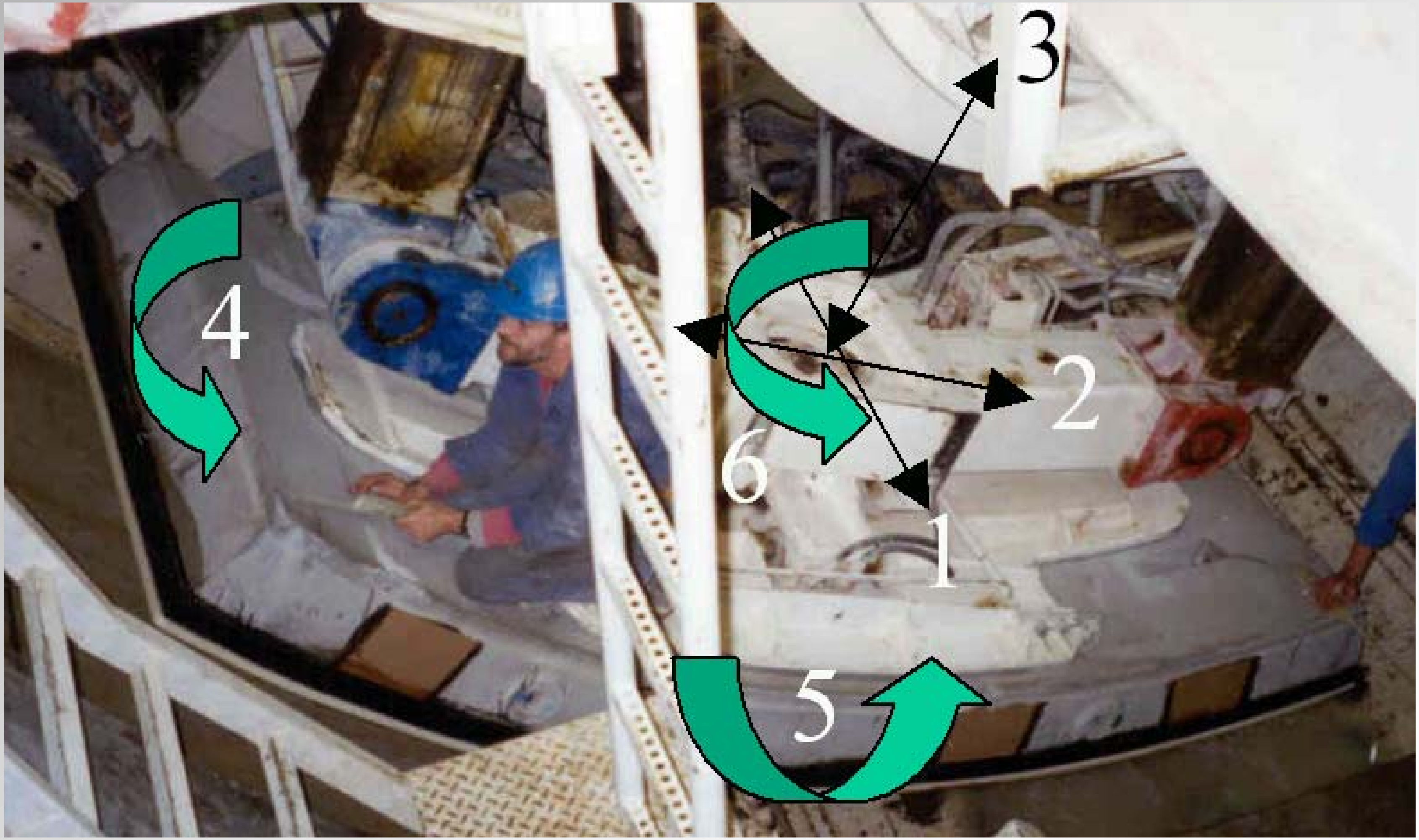
Fabricatio n



Fabrication tolerances

Ring erection with mobile erector control panel

Necessary active movements for ring assembly



Thank you for your attention