Mechanized Tunnelling in Urban Areas General

TRAINING MATERIAL PREPARED BY

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<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td>Introduction (Markus Thewes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>TBM Types (Markus Thewes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Risks (Markus Thewes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4</strong></td>
<td>Execution of TBM Drives (Fritz Gruebl)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5</strong></td>
<td>Lining behind TBMs (Fritz Gruebl)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 $\theta$:

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

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

c) More exact: $\theta = 45^\circ + 0,5 \cdot \varphi$

$\varphi$ = 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)

- Groundwater lowering
- Influences at face
- Face pressure
- Settlemens by soil compacting caused by vibrations
- Grouting of ring gap
- Lowering of air pressure
- Sandy soil
- Slurry shield
- Open shield with de-watering by compressed air
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)

  \[ \Delta V = V_e - V_d \Rightarrow V_l = \frac{\Delta V}{V_e} \]

  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:

(Form of the settlement curve)

\[ S = S_{\text{max}} \times e^{\frac{-x^2}{2i^2}} \]

(Maximal settlement)

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

(Volume loss)

\[ \Delta V = \sqrt{2\pi \times i \times S_{\text{max}}} \]

\[ i \ldots \text{coefficient for settlement} \]
Coefficient i:

O’Reilly and New (1982):
- cohesive soil: $3m < z_0 < 34m$ \( i = 0.43 \, z_0 + 1.1m \)
- non cohesive soil: $6m < z_0 < 10m$ \( i = 0.28 \, z_0 - 0.1m \)

O’Reilly and New for 2 layers (1991):
- tunnel in cohesive soil, non cohesive layer over the tunnel \( i = 0.43 \, z_a + 0.28 \, z_b + 1.1m \)
- tunnel in non cohesive soil, cohesive layer over the tunnel \( i = 0.28 \, z_a + 0.43 \, z_b - 0.1m \)
Settlement curve after “Köster” (1988):

\[
S_1 = (X_1 \times D) \times e^{X_2 \times \log E_5} \times e^{X_3 \times \log E_5} \times e^{X_4 \times \log E_5} \times e^{X_5 \times \log E_5} \times e^{X_6 \times \log E_5} \times \left( \frac{\ln \left( \frac{H_u}{D} \right)}{3.5} \right)^{-0.1} - 0.02
\]
Settlement curve after “Scherle” (1977):

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

$$S_{z,\text{max}} = \frac{D_A}{\left(1 + \frac{H_A}{D_A}\right)} \times B_K$$
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

Sensitive machine foundations
Limit for damages in frameworks with infilling
Limit to avoid fissures in walls
Limit of fissures in supporting walls
Limit of optical visibility of inclined buildings
important fissures in supporting walls
safety limit of brick walls
limit for damages of buildings
leaning tower of Pisa
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 over 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
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- Compressed air
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- Slurry (bentonite mixture)
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- EPB
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- 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)

Parameters:
cal $\varphi$..........angle of inner friction (calculated) of the drained soil
cal $\gamma$.......... Spezific weight (calculated) of the soil
cal $c'$.......... cohesion (calculated) of the drained soil
z................. depth
$\Delta h$.......... 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)

   \[ k_{agh} \text{ from weight of soil} \quad k_{agh} = \tan^2\left(45^\circ - \frac{\text{cal } \phi^l}{2}\right) \]

   \[ k_{ach} \text{ from cohesion} \quad k_{ach} = 2 \cdot \tan\left(45^\circ - \frac{\text{cal } \phi^l}{2}\right) \]
Face pressure according to DIN 4085:

2. Form parameter for spheric calculation

\[ z \ldots \text{depth} \quad b \ldots \text{tunnel diameter} \]

<table>
<thead>
<tr>
<th>( \frac{z}{b} )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
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<tr>
<td>( \mu_{agh} = \mu_{aph} )</td>
<td>1</td>
<td>0,82</td>
<td>0,70</td>
<td>0,59</td>
<td>0,50</td>
<td>0,37</td>
<td>0,30</td>
<td>0,25</td>
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Face pressure according to DIN 4085:

3. Calculation of pressure coefficient

\[ \text{spa } e_{ah} = \text{cal } \gamma \cdot z \cdot \mu_{agh} \cdot k_{agh} + p \cdot \mu_{aph} \cdot k_{agh} - \text{cal } c^{l} \cdot \mu_{ach} \cdot k_{ach} \]
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)

\[ p_w = \gamma_w \cdot t_w \]

\( \gamma_w \)...... spezific weight of water \( (\gamma_w=10 \text{ [KN/m}^3\text{]}) \)

\( t_w \)...... 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
- \( \eta_W \) ...... security factor for waterpressure \( \eta_W = 1,05 \)
- \( \eta_E \) ...... security factor for earthpressure \( \eta_E = 1,5 \)

\[ (\eta = \frac{S}{(\eta_W \cdot W + \eta_E \cdot E) \geq 1,0}) \]
Face pressure according to DIN 4085:

b) Stability in top of tunnel

\[ S \geq 1,1 \cdot (W + E_{ah}) \]

\[ (\eta_{top} = \frac{S}{W + E} \geq 1,1) \]

S …… pressure for face stability
W …… waterpressure
\( E_{ah} \)…… sum of active earthpressure
Face pressure according to DIN 4085:

c) Stability in bottom

\[ S - (W + E_{ah}) \geq 10\ldots20 \text{ KN/m}^2 \]

- \( S \) ...... pressure for face stability
- \( W \) ...... waterpressure
- \( E_{ah} \) ...... sum of active earthpressure
Face pressure according to DIN 4085:

d) Stability against blow outs

\[ \eta = \frac{\left( \sigma_z + p_{W_0} \right)}{p_0} \geq 1,1 \ldots 1,2 \]

\[ \eta = \frac{\gamma \cdot t_1 + \gamma' \cdot t_2 + \gamma_w \cdot (t_w - D)}{S_{LF, LH, LV}} \geq 1,1 \ldots 1,2 \]

1.1 …… Security factor for normal advance

1.2 …… Security factor during air pressure at face
Blow outs
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.
**Guidance system - components**

1. **Laser (-theodolite):**
   - provides an exposed guiding beam in the tunnel
   - is equipped with an electronic distance measuring device: \( \Rightarrow \) 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

- Prism
- Laser Station
- Tunnel
- Target unit
- Tunnelling Machine
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)
Correction curve with tangential approach to the DTA
Correction curve with tangential approach to the DTA

Real TBM-position

Deviation of TBM

Correction curve

DTA
Screen – longitudinal section
TBM position
Problems concerning advance control

- 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
Lining behind TBMs

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

- Gap for steering
- Bentonite slurry
- Shield tail
- Wirebrush sealing
- grease
- Segment
- t = 8 to 20 cm

Grouting
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

\[ t = \frac{D_e \times L_m}{R_{\text{min}}} \]
Example: Calculation of taper

\[ l_m = 2.0 \text{ m} \]
\[ D_e = 8.2 \text{ m} \]
\[ R_{DTA} = 300 \text{ m} \]

30° staggered longitudinal joints
Example: Calculation of taper

\[ l_m = 2,0 \text{ m} \]
\[ D_e = 8,2 \text{ m} \]
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30° staggered longitudinal joints

correction curve radius: \( R_{\text{min}} = 240 \text{ m} \) (\( R_{DTA} \) - \(~20\%\)
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30° staggered longitudinal joints

Correction curve radius: \[ R_{\text{min}} = 240 \text{ m} \ (R_{DTA} - \sim 20\%) \]

\[ t^{\prime\prime} = \frac{l \times D_e}{R_{\text{min}}} = \frac{2.0 \times 8.2}{240} = 0.068 \text{ m} = 68 \text{ mm} \]
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\[ t''' = \frac{l \times D_e}{R_{min}} = \frac{2,0 \times 8,2}{240} = 0,068 \text{ m} = 68 \text{ mm} \]

\[ t' = \frac{t''}{(1 + \cos 30°) \times 0,5} = 73 \text{ mm} \]
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\[ t^\prime = \frac{t^{\prime\prime}}{\left(1 + \cos 30^\circ\right) \times 0.5} = 73 \text{ mm} \]

\[ t = t^\prime + 5 \text{ mm} = 78 \text{ mm} \]
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Chosen: 80 mm
Constraints during ring erection

Inclination

Steps
Cams in circumferential joints

Design of 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 according DB AG RiL 853:

1. Angles:
   1.1 Clasping angle in longitudinal joint \( \pm 0,04^\circ \)
   1.2 Angle of longitudinal joint conicity \( \pm 0,01^\circ \)

2. Linear Values:
   2.1 Width of segment \( \pm 0,5 \text{ mm} \)
   2.2 Thickness of segment \( \pm 2,0 \text{ mm} \)
   2.3 Arc length of segment \( \pm 0,6 \text{ mm} \)
   2.4 Inner radius (one segment) \( \pm 1,5 \text{ mm} \)
   2.5 Width of gasket groove \( \pm 0,2 \text{ mm} \)

3. Plane and parallelness of contact zones:
   3.1 Longitudinal joint \( \pm 0,3 \text{ mm} \)
   3.2 Circumferential joint \( \pm 0,3 \text{ mm} \)

4. Details:
   4.1 Axis of gasket \( \pm 1,0 \text{ mm} \)
   4.2 Axis of contact zone \( \pm 1,0 \text{ mm} \)
   4.3 Plane of bolts \( \pm 1,0 \text{ mm} \)

5. Tolerances of an erected ring:
   5.1 Outer diameter \( \pm 10 \text{ mm} \)
   5.2 Inner diameter \( \pm 10 \text{ mm} \)
   5.3 Outer circumference (measured in 3 levels) \( \pm 30 \text{ mm} \)
Fabrication tolerances

- Angle of longitudinal conisity
- Clasping angle in longitudinal joint
- Arc length
- Segment width
- Clasping angle in ring joint
- Segment thickness
Ring erection with mobile erector control panel
Necessary active movements for ring assembly
Thank you for your attention