SETTLEMENTS INDUCED BY TUNNELING IN SOFT GROUND

Prepared by WG. 2 “Maintenance and Repair”

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Ground motion induced by tunneling and impact on existing structures

*Settlements Induced by Tunneling in Soft Ground*
Chapter 1

Tunneling Induced Ground Movements

Settlements Induced by Tunneling in Soft Ground
Displacements of the Excavation Profiles

Settlements Induced by Tunneling in Soft Ground
Yielding Zone Around the Opening

a. Limited extension  
b. Weaker grounds

Settlements Induced by Tunneling in Soft Ground
Tunnel Face Stability

a. Clayey Grounds

Settlements Induced by Tunneling in Soft Ground
Tunnel Face Stability

b. Frictional Grounds

Settlements Induced by Tunneling in Soft Ground
Tunnel Face Stability

- Clayey Grounds:
  - \( N = (\sigma_S + \gamma H - \sigma_T) / S_u \)
  - \( N < 5 - 6 \)
  - \( U \)- shear strength: \( S_u \)

- Frictional Grounds:
  - \( \sigma_S / \sigma_c, \gamma D / \sigma_c, \sigma_T / \sigma_c \)
  - \( \sigma_c = 2c' \cos \phi' / (1 - \sin \phi') \)
  - Cohesion: \( c' \)
  - Friction angle: \( \phi' \)
Propagation of Movements Towards the Surface

Settlements Induced by Tunneling in Soft Ground

a. Deeper Tunnel
Propagation of Movements Towards the Surface

b. Shallow Tunnel

Settlements Induced by Tunneling in Soft Ground
Influence of Support Conditions

- Support stiffness
- Installation timeframe

Settlements Induced by Tunneling in Soft Ground
Surface Settlement Trough

Settlements Induced by Tunneling in Soft Ground
Causes For Construction Induced Settlements

Settlements Induced by Tunneling in Soft Ground
Main Sources For Settlements (sequential construction)

• Face intake/instability
• Impact of characteristics and installation conditions of temporary support
• Staging of the excavation works (cross-section)
• Final liner installation and response
Settlements Along a Shield Driven Tunnel

Settlements Induced by Tunneling in Soft Ground

a: settlements caused by the face
b: settlements caused by the overcut
c: settlements induced by post shield/grout loss
d: settlements caused by the deflection of the lining and longterm settlements

Settlements Induced by Tunneling in Soft Ground
Typical Contributions to Shield Tunneling Induced Settlements

- Face intake: 10-20%
- Along the shield: 40-50%
- Tail skin: 30-40%
Sources For Additional Settlements

• Effect of groundwater
  – During construction
    • drawdown of ground water table
    • Seepage towards the tunnel face
  – In the long term (consolidation)

• Effect of worksite conditions
  – e.g. impact of vibrations of weaker grounds
Chapter 3

Evaluation of Ground Movements

Settlements Induced by Tunneling in Soft Ground
Settlement Evaluation Methods

- Empirical and Semi-empirical
  - Analytical
  - Observational

- Numerical
Settlement Trough Characterization

3D Distribution

Cross-section

Settlements Induced by Tunneling in Soft Ground

(Peck, Schmidt, 1969)
Settlement Trough Characterization

\[ s(x) = s_{\text{max}} \exp\left(-\frac{x^2}{2i^2}\right) \]

\[ V_s = (2\pi)^{1/2} i s_{\text{max}} \]

Key parameters: \( s_{\text{max}}, i \)

(Peck, Schmidt, 1969)
Dampening Effect

\[ V_l = \text{Volume loss at the opening} \]
\[ V_s = \text{Volume loss at ground level} \]

*Settlements Induced by Tunneling in Soft Ground*
Ground Movements at Depth

- \( S(x,z) = s_{\text{max}}(z) \cdot \exp(-x^2/2(Kz)^2) \)
- \( H(x,z) = S(x,z) \cdot \frac{x}{z} \)
- \( V_s(z) = (2\pi)^{1/2} \cdot Kz \cdot s_{\text{max}}(z) \)
- \( K = \) empirical coefficient
  - (varies typically from 0.5 for stiff clay and sandy clay to 0.25 to softer sands and gravels)

(after O’Reilly & New, 1982)
Incidence of Ground Displacements on Existing Structures

Settlements Induced by Tunneling in Soft Ground
Typical Idealized Building Response to Ground Motion

Settlements Induced by Tunneling in Soft Ground

(after Attewell et al, 1986)
Induced Vertical Movements

\[ \rho_{VA} \] = settlement at A
\[ \delta_{VAB} \] = differential settlement b/w A-B
\[ \omega \] = tilt
\[ \beta_{BC} \] = relative rotation b/w B-C
\[ \alpha_C \] = angular deformation at C
\[ \Delta_{AD} \] = relative deflection b/w A-D
\[ \Delta_{AD}/L_{AD} \] = deflection rate

Settlements Induced by Tunneling in Soft Ground
Induced Horizontal Movements

\[ \varepsilon_{hAB} = \frac{(\rho_{hA} - \rho_{hB})}{L_{AB}} \]

Settlements Induced by Tunneling in Soft Ground
Induced Horizontal Deformations
## Damage Classification

<table>
<thead>
<tr>
<th>Damage Type</th>
<th>Damage Degree</th>
<th>Damage Description</th>
<th>Crack width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Negligible</td>
<td>Micro-cracks</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>1</td>
<td>Very slight</td>
<td>Architectural</td>
<td>&lt;1</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>Archit. - to treat</td>
<td>&lt;5</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Functional</td>
<td>5-15 or sev.&gt;3</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Structural</td>
<td>15-25 (number)</td>
</tr>
<tr>
<td>5</td>
<td>Very severe</td>
<td>Structural</td>
<td>&gt;25 (number)</td>
</tr>
</tbody>
</table>

*(after Burland et al, 1977; Burland, 1995; Mair et al, 1996)*

### Settlements Induced by Tunneling in Soft Ground
### Relationship Between Critical Extension and Cracking

<table>
<thead>
<tr>
<th>Damage Type</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4&amp;5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{crit}}$ (%)</td>
<td>$\leq 0.050$</td>
<td>$0.050 &lt; \leq 0.075$</td>
<td>$0.075 &lt; \leq 0.150$</td>
<td>$0.150 &lt; \leq 0.300$</td>
<td>$0.300&lt;$</td>
</tr>
</tbody>
</table>

*(after Boscardin & Cording, 1989)*

*Settlements Induced by Tunneling in Soft Ground*
## Range of Serviceability Limit State For Standard Structures

<table>
<thead>
<tr>
<th>Damage Type</th>
<th>Average Slope of Settlement Trough Under Structure (%)</th>
<th>Maximum Settlement of the Structure (mm)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>&lt; 2</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>2</td>
<td>2 &lt; &lt; 4</td>
<td>10 &lt; &lt; 20</td>
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*Settlements Induced by Tunneling in Soft Ground*
Design Methodology

• Phase 1: Investigation of Existing Buildings
• Phase 2: Information Summary
• Phase 3: Selection of Damage Criteria
• Phase 4: Modeling (after Burland, 1995; Mair et al, 1996)
  – Preliminary Assessment
  – Second Stage Assessment
  – Detailed Evaluation
• Phase 5: Determination of Allowable Thresholds
• Phase 6: Back-analysis & Calibration of Models

Settlements Induced by Tunneling in Soft Ground
Settlement Control
Preventive & Remedial Approaches

1. Improvement of Overall Project Conditions
   - Aim at larger depth of cover
   - Look for ground layers of good mechanical properties
   - Minimize excavated cross-section
   - Aim at straight alignments

2. Improvement of Ground Characteristics

3. Structural Improvement of Building

4. Improvement During Construction
   a. Sequential/Conventional
   b. Shield Tunneling

Settlements Induced by Tunneling in Soft Ground
Pre-support

Face Bolting

Settlements Induced by Tunneling in Soft Ground
Pre-support

Fore-poling

Settlements Induced by Tunneling in Soft Ground
Pre-support

Umbrella Vault

Settlements Induced by Tunneling in Soft Ground
Pre-support

Settlements Induced by Tunneling in Soft Ground
Crown Support

Expanded Concrete Segment Vault

Settlements Induced by Tunneling in Soft Ground
Underpinning

Settlements Induced by Tunneling in Soft Ground
Chapter 6

Observation and Monitoring of Ground Response

Settlements Induced by Tunneling in Soft Ground
Observation & Monitoring

• Inspection
• Instrumentation
  – Monitoring of existing structures
  – Ground measurements
• Monitoring Program
Chapter 7

Contractual Aspects

Settlements Induced by Tunneling in Soft Ground
Contractual Aspects

• Usual contractual clauses
• Position of the different players
  – The Owner
  – The Engineer
  – The Contractor
Further Developments and References
Recommendations and Possible Ways of Improvement

• At Owner – and Engineer - Level
  – Organize preliminary inspections & studies
  – Commission a comprehensive program of studies
  – Set appropriate settlement limits
  – Provide available information at tender stage

• At Contractor’s Level
  – Provide assistance required during construction
  – Set accountabilities

• Possible contribution of Insurance Companies
  – Obtain greater technical clarity when defending cases
  – Require risk analyses prior to finalizing binding agreements
  – Exercise greater diligence when reviewing litigious situations

Settlements Induced by Tunneling in Soft Ground
References

- Additional references quoted in WG2 document (TUST, 22)
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