Settlements Induced by Tunnelling in Soft Ground

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Tunneling Induced Settlements

1. Specific features of tunneling in urban areas
2. Ground motion induced by Tunneling
3. Evaluation, monitoring, and mitigation
4. Risk management approach
5. Case history
6. Conclusions
1. Specific features of tunneling in urban areas

- Recent geological formations
- Frequently changing conditions
- Presence of groundwater
- Existing underground structures
- Potential damage on buildings
2. Ground Motion induced by Tunneling

Face Stability

Model Test Results
For Tunnel Face
Displacements and
Stability in Sands
Ground Motion induced by Tunneling

In the field, at ground surface
Ground Motion induced by Tunneling

Studies completed

Cambridge University (Mair, 1979; Schofield, 1980; Davis et al., 1980)

re: tunnel face stability in clays
Ground Motion induced by Tunneling

In the field, at ground surface
Ground Motion induced by Tunneling
Ground Motion induced by Tunneling

Two-dimensional response

Development of arching effects

Cambridge physical modelling
Ground Motion Induced by Tunneling

Tunneling induced ground motion in elastic conditions

- Inward deformation of tunnel face
- Direction of tunnel advance
- Radial displacement reaches its final value at about one and one half tunnel diameters behind the face
- Radial displacement reaches about one third of its final value at the tunnel face
- Radial displacement starts about one half a tunnel diameter ahead of the advancing face
Ground Motion Induced by Tunneling

Conventional tunneling operation scheme

in rock

in soil
Ground Motion Induced by Tunneling

Mechanized Tunneling
Closed Face TBMs

Slurry shield

Earth Pressure Balance (EPB) Shield
The sum of the 2 radial displacements is termed ‘radial’ ground loss.
Face loss. + radial loss = overall volume loss, VL, for the construction of the tunnel [ m3 / metre of advance of the tunnel drive]
Settlements observed during the construction of the Washington DC Metro (F3 and F4 contracts) observed at Instrumented section SSI-4. The graph shows the settlements vs. distance to the tunnel face, with different records (A, B, C) plotted. The settlements are due to face intake and tail void closure, as indicated in the diagram. The data is from Clough & Leca (1993).
Settlements observed during the construction of the Washington DC Metro (F3 and F4 contracts)

Soil Profile on F4 section after Clough & Leca (1993)
Settlements observed during the construction of the Washington DC Metro (F3 and F4 contracts)

Settlements vs. distance to tunnel face observed at Instrumented section SSI-3

after Clough & Leca (1993)
3. Evaluation of Tunneling Induced Settlements

Evaluation of tunnelling induced settlements
Evaluation of Tunneling Induced Settlement

Based on settlement data from over 20 case histories, Peck (1969) determined that the short-term transverse settlement trough in the "greenfield" could be approximated by a Gaussian curve

\[ S(y) = S_{\text{max}} \exp \left( -\frac{y^2}{2i^2} \right) \]

- \( S(y) \) = surface settlement at distance \( y \) from centerline
- \( S_{\text{max}} \) = maximum surface settlement at centerline
- \( i \) = trough width parameter

\[ V_s = \sqrt{2\pi i S_{\text{max}}} \]
The expression for the total surface settlement, $S(y)$, may be rewritten as:

$$S(y) = S_{\max} \exp\left(\frac{-y^2}{2i^2}\right) = \frac{V_s}{i\sqrt{2\pi}} \exp\left(\frac{-y^2}{2i^2}\right)$$

and may be related to the source volume loss, $V_L$, which is normally expressed as a percentage $V_L\%$ of the gross area of the finished tunnel. Assuming a circular tunnel of outside diameter $D$,

$$V_L\% = \frac{V_L \times 100\%}{V_{\text{tunnel}}} = \frac{V_L \times 100\%}{\pi D^2/4}$$

$V_s$ equals $V_L$ if there is no volume change (typically clays under undrained conditions)

$V_s$ is usually less than $V_L$ with dense sands because of dilation. It may exceptionally exceed $V_L$ with loose material.
Evaluation of Tunneling Induced Settlement

More specific approaches may be required in some conditions:

- Very shallow tunnels
- Specific topographic conditions
- Refined integration of construction process
- Strong interaction with existing structures
- ...

![Diagram of tunneling induced settlement](image)
Evaluation of Tunneling Induced Settlement

Yield density curve
(Celestino & Ruiz, 1998)

\[ s(x) = \frac{s_{max}}{1 + \left(\frac{|x|}{a}\right)^b} \]

Figure 3. Adjustments of Gaussian and yield density curves to field settlement data: Polish Tunnel – Profile 1, 1958 (data from Schmidt 1969).

Figure 2. Influence of parameter \( b \) on the shape of the settlement trough.

after Celestino et al. (2000)
Evaluation of Tunneling Induced Settlement

Numerical modelling

- must include a credible representation of the tunnelling process
- must use an appropriate constitutive model for the ground
- can account for complexe conditions
- can be used for parametric studies once calibrated

after Chiriotti (2012)
Achievable results in terms of settlement control

Experience from CRTL in UK

- C220 Stratford to St Pancras
- C240 Stratford o Barrington Road
- C250 Dagenham to Barrington Road
Potential impact of ground motion induced by Tunneling

Collapses observed in the field

Collapsed subway tunnel in Munich, Germany (1994)

Subsidence caused by a collapsed tunnel in Taegu, South Korea

Sinkhole observed during the construction of metro L2 in Lille, France
Evaluation of Tunneling Induced Settlement

Idealisation of building as an elastic beam and definition of relative deflection
(Burland and Wroth, 1975)
4. Risk management approach

- Planning/policy
- System definition
- Hazard identification
- Frequency analysis
- Consequence analysis
- Risk analysis
- Risk
- Risk evaluation
- Risk acceptance criteria
- Risk reduction measures
- Unacceptable
- Acceptable
Typical Risk Management Plan for urban tunnelling

- Evaluation of tunneling induced ground motion and potential impact
  - Components of volume loss
  - Settlements prediction and calculation

- Mitigation measures depending on the results of settlement predictions at design stage

- Continuous monitoring and observation of both ground surface, buildings and TBM parameters during construction

- Countermeasures to reduce settlements based on analysis of monitoring data obtained during construction
Key success factors

➢ Reduction of uncertainties during the design stage so as to ensure sufficient reliability of input data

➢ Robust design with respect to remaining uncertainties

➢ Methods and equipment to be validated or adapted by the contractor

➢ Contractor takes ownership of risk management documents and additions when relevant

➢ Introducing a Risk Committee can help resolve incidents related to non-identified risks

after Robert (2017)
Typical support documentation for risk management

- Risk Management Plan, providing details on methodology, residual risk characteristics, specific technical requirements for mitigation measures
- Risk Register, listing all residual risks per category and decreasing criticality, as well as preventive measures (and contractual detection criteria), and mitigation measures (and contractual allocation)
- Residual risk follow up files and incident record files
- Risk mitigation associated unit costs

after Robert (2017)
<table>
<thead>
<tr>
<th>Libellé du risque</th>
<th>Quelle est son origine (éventuellement individuel)</th>
<th>Contexte / description (contextes)</th>
<th>Évaluation du MNP avant traitement</th>
<th>Action de traitement du risque indiqué au PNP1a</th>
<th>Conséquences de l'événement redressé en cas de non-résolution de l'événement redressé (toutes les conséquences en cas de non-résolution)</th>
<th>Caractéristiques de la solution adoptée pour résoudre le risque (PNP)</th>
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<td>Non-observance des normes de l'unité</td>
<td>Réduction de la température de l'unité de l'unité</td>
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<td>Non-observance des normes de la pièce</td>
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after Robert (2017)
5. Case history: Sofia Metro Line 2

2\textsuperscript{nd} metro line in Sofia 2\textsuperscript{nd} section - Package 1

- 3.8km of bored-tunnel
- 3 stations (MC-5, MC-6, MC-7)
- EPB TBM 9.39m-diameter
- Internal diameter of lining: 8.43m
- Tunnel lining thickness: 0.32m

MOST SENSITIVE TUNNELLING SECTION: Excavation under the Lavov Most (Lions Bridge)

after Semeraro et al. (2012)
Case history: Sofia Metro Line 2
Tunneling underneath the Lions Bridge (Lavov Most)

Masonry bridge of the 19th century over the Vladaiska River

- **Structure:** granite blocks forming 2 arches of 11m span each
- **Length:** 22m
- **Width:** 20.5m
- **Foundations:** wooden piles caissons filled with stone blocks

*after Semeraro et al. (2012)*
Case history: Sofia Metro Line 2
Tunneling underneath the Lions Bridge (Lavov Most)

Top of the tunnel at the interface between the silty clay and gravel

- **Backfill** (5m)
- **Quaternary deposits** (4m)
  - fine to medium gravel
  - \( k = 8 \times 10^{-5} \) m/s
- **Pliocene deposits**
  - highly plastic silty clay
  - \( k = 2 \times 10^{-6} - 10^{-9} \) m/s
- **Water level**: -6m beneath ground level

after Semeraro et al. (2012)
Sofia Metro - Line 2
Numerical analysis of construction impact

Finite element models with PLAXIS 3D

- Real Excavation of the first 40 rings after station MC-7
  - Stroke 1.5m-long
  - EPB pressure applied to the excavation face
  - Conical shape of shield and lining at the rear of TBM considered
  - Injection of tail void
- Limit of model: tunnel alignment parallel to the bridge axis

**MODEL A**: “Do-nothing” solution

**MODEL B**: Quaternary deposits treated, with increased c’ and E values

after Semeraro et al. (2012)
## Case history: Sofia Metro Line 2

### Tunneling underneath the Lions Bridge (Lavov Most)

#### Simplified risk register (extract)

<table>
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<tr>
<th>AREA</th>
<th>HAZARD</th>
<th>CAUSES</th>
<th>CONSEQUENCES</th>
<th>INITIAL RISK</th>
<th>MITIGATION MEASURES</th>
<th>RESIDUAL RISK</th>
<th>CONTINGENCY MEASURES</th>
</tr>
</thead>
</table>
| CROSSING THE RIVER | Loss of pressure with foam leakage to surface | - Face pressure above the designed value, heave and soil cracks  
- Sleeve pipes left open and in contact with the tunnel crown  
- Defect of the soil treatment or of the concrete slab | - Stoppage of TBM  
- Excessive settlement at river level potentially leading to damages on the bridge | H | - Concrete slab  
- Confine the grouting area when treating the gravels.  
- Fill in the injection holes.  
- Monitoring system checking continuously the settlement/heave and strictly interpreted with TBM data | L | - Maintain an active drilling rig on site to be able to do interventions from the surface in case of anomalies. |
| | Differential settlement of Lions Bridge | - Defect of the soil treatment beneath the foundations or the bridge arches.  
- Face Pressure different than the designed value  
- Over-excavation or instabilities due to wooden piles pulled into the TBM chamber. | Cracks on the bridge | H | - Monitoring design + thresholds definition  
- Real-time Monitoring  
- Reinjectable upper level of TAMs under the foundations  
- Continuous and systematic control of excavated quantities and face pressure.  
- Installation of a supporting steel frame under the bridge to protect the structure. | L | - Re-injection of TAMs beneath the bridge piers) |
| | Possible sticky behaviour of the clay | - Presence of plastic clay (layer 7) | - Slow TBM advancing  
- Interventions in the chamber  
- Potentially increases of settlements at the surface due to slow advance | M | - Injection of polymers or water in the excavation chamber to condition properly the excavated material  
- Control the trend of the TBM torque and of the total thrust | VL | - Review the use of additives  
- Wash the cutterhead (with high pressure) |

_after Semeraro et al. (2012)_
Sofia Metro - Line 2
Mitigation measures from risk analysis

➢ Water diversion into pipes
➢ 0.5m-thick concrete slab on the river bed
➢ Interruption of traffic
➢ Temporary scaffolding beneath the bridge arches
➢ Accurate monitoring system and interpretation of the TBM parameters

after Semeraro et al. (2012)
Case history: Sofia Metro Line 2
Tunneling underneath the Lions Bridge (Lavov Most)

Monitoring plan at the surface, bridge’s deck and foundations

➢ Levelling points above the tunnel every 10m
➢ 3 transversal sections with 5 benchmarks each
➢ 6 levelling points at the bridge foundations
➢ 2 theodolites outside the TBM influence area

Results:
➢ Maximum settlement : 7mm
➢ Average settlement : 1-4mm

after Semeraro et al. (2012)
Case history: Sofia Metro Line 2
Tunneling underneath the Lions Bridge (Lavov Most)

- Parameters calibrated through back analysis of the section built before reaching the bridge
- EPB pressure and injection parameters slightly lower than planned
- Adjustment of TBM parameters to minimize volume loss beneath the bridge
- Monitored grout pressure in line with prescribed
- Injection volumes 15% lower than theoretical
- Maximum volume loss: 0.18%
- Massive soil treatment & bridge underpinning could be avoided thanks to confidence in TBM performance and procedures adjusted in previous sections

after Semeraro et al. (2012)
Case history: Sofia Metro Line 2
Results obtained, without massive ground treatment

EPB tunnelling successfully completed under the bridge in difficult soil conditions and reduced overburden using the following approach:

➢ Numerical models to justify and quantify the need for soil treatment

➢ Risk management approach to identify the risks and propose adequate mitigation and contingency measures

➢ Follow-up and back-analysis of TBM in previous stretches used to adapt TBM launching procedure and set up EPB parameters for successful tunnelling

➢ Thorough monitoring of TBM performance, ground and structural displacements throughout the whole tunnelling section

after Semeraro et al. (2012)
6. Conclusions

- Soft ground tunneling generates ground motion which may propagate into surface settlements.
- The magnitude and distribution of surface settlements is dependent upon a number of parameters, including ground conditions and tunneling technique.
- Analytical and numerical approaches have been developed to evaluate potential settlements and impact on structures.
- Modern technology allows to address challenging tunneling conditions.
- Special measures and monitoring, combined with a robust risk management approach, usually required to control settlements in difficult conditions.
ITAP2G Report on Settlements induced by Tunneling in Soft Ground

References
Guidelines for tunnelling risk management

Scope and purpose

➢ To present a guideline for designers to prepare comprehensive tunnelling risk assessment

➢ To indicate to owners what is accepted industry practice for construction risk analysis

➢ By risk management should be understood as risk identification, risk assessment, risk analysis, risk elimination, risk mitigation and risk control
Other Guidelines for Risk Management

THE JOINT CODE OF PRACTICE FOR RISK MANAGEMENT OF TUNNEL WORKS IN THE UK

A CODE OF PRACTICE FOR RISK MANAGEMENT OF TUNNEL WORKS

www.britishtunnelling.org

www.imia.com
References (1/2)

References (2/2)

Celestino, T.B, Ruiz, A.P.T (1998), Shape of settlement trough due to tunneling through different types of soft ground. Felsbau 16:2, 118-121


Grasso, P. (2014) Risk and Safety Management in Tunnelling, ITACET Session on Mechanized Tunnelling, ITA - AMITOS, Mexico City, 26-27 June


Semerano, M., Chiriotti, E., Mercier, B., Della Vale, N. (2012). «EPB tunnelling with shallow cover under the historical Lavov Most (Lions bridge) in Sofia», 1° Earstern European Conference, Budapest, 19-21 September