Keynote Lecture

Numerical Analysis in the Design of Urban Tunnels

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Lecture Outline

1. Characteristics of urban tunnels
   - Need to control ground deformations
   - Numerical analyses to predict ground deformations

2. Tunnelling methods in urban areas (to control settlements)
   - Emphasis on pre-convergence and face pre-treatment

3. Methods of numerical analysis
   - Continuum / discontinuum modelling
   - Continuum 3-D modelling:
     Analysis of pre-convergence & face pre-treatment (for design)
     Estimation of ground parameters (E) by monitoring extrusion
   - Continuum 2-D modelling:
     How to model the 3-D problem in 2-D (in a cross-section)
Main characteristics of urban (shallow) tunnels
Minimisation of ground surface displacements

Settlement depends on ground, depth, diameter and excavation method
Causes of ground surface displacements:
1. Ahead of tunnel face: Axial face extrusion (radial pre-convergence)
2. Behind tunnel face: radial convergence

Minimisation of ground surface displacements

Relative contribution of pre-convergence and convergence

In a properly supported non-TBM tunnel, 70-80% of total surface settlement is due to deformations ahead of tunnel face.

In TBM tunnels the fraction varies significantly (< 70%) depending on the method.

Conclusion:
In non-TBM tunnels, control of pre-convergence (face extrusion) is critical in urban tunnelling.
Control of pre-convergence is contrary to the basic NATM principle of mobilising rockmass strength by deformation.

This NATM principle is mainly applicable in mountain tunnels.

Mountain tunnels:
- Stability is critical
- Deformation not critical (usually desirable)

Urban tunnels:
- Deformation critical: to be minimised
- Stability is ensured by controlling deformation

Calculation of deformations requires numerical modelling (important in urban tunnels)

Urban tunnelling methods
Minimisation of pre-convergence & convergence

<table>
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<th>Tunnelling method</th>
<th>Minimisation of pre-convergence</th>
<th>Minimization of convergence</th>
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<tr>
<td>TBM</td>
<td>Adequate face support:</td>
<td>Control cutter-head overcut</td>
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<td>Pressure control (closed)</td>
<td>and tail-void grouting</td>
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<td>Cutter-head openings (open)</td>
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<td>NATM (North of Alps)</td>
<td>Multiple drifts ($u_R \propto D$)</td>
<td>Stiff support</td>
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<tr>
<td>SATM (South of Alps)</td>
<td>Face pre-treatment</td>
<td>Early closure of ring</td>
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Emphasis on pre-convergence, since it controls 70-80% of total settlement
Urban tunnelling methods: TBM tunnelling

Control of pre-convergence by face pressure and ground conditioning in closed-face machines

**Slurry shield**
- Bentonite (pressure p)

**EPB shield**
- Screw conveyor
- Excavated soil (pressure p)

Urban tunnelling methods: TBM tunnelling

Control of pre-convergence by the size of cutter-head openings in open face machines

Athens Metro – 9.5m dia. open TBM
Urban tunnelling methods: TBM tunnelling

Inadequate control of pre-convergence by ground raveling caused by too large cutterhead openings in open TBM

Athens Metro (1998)

Urban tunnelling methods: NATM tunnelling (North of Alps)

Control of pre-convergence by multi-drifting ($u_R \propto D$)

Excavation with side-drifting and central pillar

Athens Metro – Acropolis Station: excavation in “schist” (phyllite)
Urban tunnelling methods: NATM tunnelling (North of Alps)

- Control of pre-convergence by multi-drifting ($u_R \propto D$)
- Control of convergence by stiff support and early closure of ring

Urban tunnelling methods: SATM tunnelling (South of Alps)

Control of pre-convergence by face pre-treatment

1. Face protection methods: Reduction of $\sigma_1$ ahead of tunnel face

1.1 Pipe-roofing (forepoling umbrella)

Each forepole works independently along its length (in bending)
1. Face protection methods: Reduction of $\sigma_1$ ahead of tunnel face

Face protection using forepoling umbrella: How it works

Excavation reduces $\sigma_3$ to zero causing face instability.

Forepoling:
The presence of a stiff beam reduces the major (vertical) stress ($\sigma_1$) on the face
Urban tunnelling methods: SATM tunnelling (South of Alps)

Control of pre-convergence by face pre-treatment

1. Face protection methods: Reduction of $\sigma_1$ ahead of tunnel face

1.2 Improved arch above tunnel crest

Grouted umbrella arch method

Control of pre-convergence by face pre-treatment

1. Face protection methods: Reduction of $\sigma_1$ ahead of tunnel face

1.2 Improved arch above tunnel crest

Athens Metro: Monastiraki Station (18m wide span)

micro-tunnel pipe arch (bicycle chain)
1. Face protection methods: Reduction of $\sigma_1$ ahead of tunnel face
   1.3 Vertical nails (or piles) from ground surface

   ![Diagram showing vertical nails and tension elements reducing $\sigma_1$.]

   Tension elements reduce $\sigma_1$

2. Face reinforcement methods: Increase of $\sigma_3$ ahead of tunnel face

   Urban tunnelling methods: SATM tunnelling (South of Alps)

   Control of pre-convergence by face pre-treatment
2. Face reinforcement methods: Increase of $\sigma_3$ ahead of tunnel face

Face reinforcement with fibre-glass nails

Lateral confinement ($\sigma_3$):

$$\sigma_3 = \frac{P}{A} = \frac{n F_y}{(FS_F) A}$$

Factor of safety before nailing:

$$FS_o = \frac{2}{(1-\lambda)N_s}$$

$$N_s = \frac{2 p_o}{\sigma_{cm}}$$

$$\sigma_1 = (1-\lambda) p_o$$

$p_o$ = geostatic stress

Factor of safety with FG-nails:

$$FS = FS_o + \frac{1}{(1-\lambda)} \left( \frac{\sigma_3}{p_o} \right) \tan^2 \left( 45 + \frac{\phi}{2} \right)$$

Urban tunnelling methods: SATM tunnelling (South of Alps)

Control of pre-convergence by face pre-treatment

3. Face improvement methods: Increase of cohesion ahead of tunnel face

Face improvement using grouting

Grouting: increases cohesion ($\Delta c$)

Factor of safety before grouting:

$$FS_o = \frac{2}{(1-\lambda)N_s}$$

$$N_s = \frac{2 p_o}{\sigma_{cm}}$$

$$\sigma_1 = (1-\lambda) p_o$$

Factor of safety after grouting:

$$FS = FS_o + \frac{2}{(1-\lambda)} \left( \frac{\Delta c}{p_o} \right) \tan \left( 45 + \frac{\phi}{2} \right)$$
Control of pre-convergence by face pre-treatment

3. Face improvement methods: Increase of cohesion ahead of tunnel face
   Face improvement using grouting

Numerical Analysis in the Design of Urban Tunnels

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3. Methods of numerical analysis
   - Continuum vs. discontinuum modelling
   - Continuum 3-D modelling:
     Analysis of pre-convergence & face pre-treatment (for design)
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     How to model the 3-D problem in 2-D (in a cross-section)
Urban tunnel design using numerical analysis

*Tunnel excavation and support is traditionally an empirical art*

Numerical analyses are useful in the following cases:

- Calculation of ground surface settlements
- Design of face pre-treatment in difficult ground conditions (selection among alternative methods)
- Sensitivity analyses:
  - Effect of locally inferior ground on the support system
  - Comparison of alternative support methods
- Selection of most appropriate corrective action in case of contingency
- Assessment of ground properties ahead of the excavation face using monitoring data (mainly face extrusion)
- “Legal” support of design decisions (decisions based on “engineering judgment” rarely stand in courts)

**Design using numerical analysis: Continuum / Discontinuum models**

*Influence of rockmass discontinuities*

**Continuum models**
- Intact rock strength controls response

**Discrete models**
- Structural features control response

**Continuum models**
- Rockmass strength controls response

**Heavily jointed rock mass**

**Many joints**

**Two joint sets**

**One joint set**

**Intact rock**
Design using numerical analysis: Discontinuum models

Applicable: mainly in rock where structural features control response

1. Analysis of wedge stability (at roof and sidewalls):

Typical numerical analysis using computer programs:
- UNWEDGE (for tunnels)
- SWEDGE (for slopes)

Design using numerical analysis: Discontinuum models

2. Analysis of tunnel excavation and support using discontinuum models:

Discrete Element Method: Calculation scheme e.g. programs UDEC (2-D), 3-DEC (3-D)

2-D analysis of tunnel face stability:
UDEC Results
Kamata & Mashimo (2003)
Design using numerical analysis: Continuum models
3-D models: Check face stability / design face pre-treatment

Modelling stages are direct:
1. Geostatic (initial conditions)
2. Installation of face support
3. Advancement of the excavation (one step)
4. Installation of side support
5. REPEAT steps 3–4 until new face support
6. Install face support.....

However:
- Input preparation and output presentation is often complicated
- Analysis is time consuming
- Improved accuracy may be incompatible with the level of knowledge of ground conditions

Use of 3-D FE/FD models for face pre-treatment:
- Modelling face treatment
- Constitutive model (E-sensitive analyses)
- Knowledge of input ground parameters (E)
Use of numerical analyses in assessing ground parameters

Ground parameters for tunnelling can be obtained by:

- Boreholes & lab tests: not very relevant
- Field tests (inside the tunnel): expensive, slow and not very relevant
- Exploitation of excavation data (monitoring)
  - Wall convergence (not sensitive)
  - Face extrusion (very useful)

Measurement of face extrusion by sliding micrometers ahead of the tunnel face

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Lunardi & Bindi (2004)
Use of numerical analyses in assessing ground parameters

3-D numerical analyses (using FLAC-3D) were performed to assess the magnitude of face extrusion in terms of critical ground parameters (modulus $E$).

Maximum extrusion $u_{y,max}$ (at tunnel face) as a function of the controlling ground parameter $M_s$. Extrusion is not influenced by the installation of shotcrete lining (thickness $t$) behind the face (distance $L$) $\Rightarrow$ correlation $u_{y,max}$ & $M_s$ is useful $\Rightarrow E$

Purely elastic response for $M_s > 4$

$u_{y,max} = \text{maximum extrusion (at tunnel face)}$

$\frac{u_{y,max}}{D} = 0.0004 \ M_s^{-2.25}$

$M_s = \frac{E}{1000 \gamma H^{0.90} D^{0.10}}$

 Spyropoulos, 2005

Crown settlement $u_{z,max}$ (at tunnel face) as a function of the controlling ground parameter $M_s$. Crown settlement is strongly influenced by the installation of shotcrete lining (thickness $t$) behind the face (distance $L$).

Crown settlement cannot be used to assess the value of $M_s$ ahead of the tunnel face.

Purely elastic response for $M_s > 4$

$u_{z,max} = \text{crown settlement (at tunnel face)}$

$\frac{u_{z,max}}{D} = 0.001 \ M_s^{-1.80}$

$M_s = \frac{E}{1000 \gamma H^{0.90} D^{0.10}}$

 Spyropoulos, 2005
Use of numerical analyses in assessing ground parameters

Extrusion $u_y$ as a function of the distance from tunnel face. Since the value of $u_{y,max}$ is related to $M_s \Rightarrow$ correlation $u_y$ & $M_s$ (for any $x/R$) is useful $\Rightarrow E$

Reduction of face extrusion ($u_{y,max}$) by using FG-nails

Face extrusion can be reduced up 30 - 50% by installing FG-nails
Reduction of crest settlement ($u_z$ at $x=0$) by using FG-nails

Crest settlement is only slightly reduced by installing FG-nails (and any reduction is masked by the shotcrete liner)

Reduction of face extrusion ($u_{y,max}$) by using forepoles

Practical forepoling applications correspond to $f_{F1} < 20$
Reduction of crest settlement ($u_z$ at $x=0$) by using forepoles

Purely elastic response for $M_s > 4$

$$M_s = \frac{E}{1000 \gamma H^{0.90} D^{0.10}}$$

L / D = 0.40

Spyropoulos, 2005

Practical forepoling applications correspond to $f_{F1} < 20$

Design using numerical analysis: Continuum models

3-D models: Most suitable for face pre-convergence / face pre-treatment
2-D models: Analysis of tunnel cross-section (from 3-D to 2-D)

3-D model using FLAC
Disadvantage: sophisticated

2-D model using PHASE2
Disadvantage: cannot model face
Design using numerical analysis: Continuum models / 2-D

The analysis is performed by gradually reducing the internal pressure “p”

\[ p = \text{tunnel “internal pressure”} \]

\[ \lambda = \text{deconfinement ratio} \]

\[ \lambda = 1 - \frac{p}{p_o} \Rightarrow p = p_o (1 - \lambda) \]

Need to know \( \lambda = \lambda(x) \)

The use of deconfinement ratio \( \lambda \)

Deconfinement using internal pressure reduction:

\[ p = (1 - \lambda) p_o \]

\( p_o = \text{geostatic stress (isotropic)} \)

Example:

\[ \lambda = 0.70 \Rightarrow p = 30\% \, p_o \]

Deconfinement using section modulus reduction:

\[ E = \left[ \frac{(1 - 2 \nu) (1 - \lambda)}{(1 - 2 \nu) + \lambda} \right] E_o \]

\( E_o = \text{ground E-modulus} \)

Example:

\[ \lambda = 0.70 \Rightarrow E = 10\% \, E_o \]

Advantage: Good in anisotropic fields
Use of deconfinement ratio ($\lambda$) and equivalent “reduced modulus” $E$

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<tr>
<th>$\lambda$</th>
<th>$p/p_0$</th>
<th>$\nu = 0.25$</th>
<th>$\nu = 0.30$</th>
<th>$\nu = 0.35$</th>
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<td>0.90</td>
<td>0.10</td>
<td>0.036</td>
<td>0.031</td>
<td>0.025</td>
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$E = \frac{(1-2\nu)(1-\lambda)}{1-2\nu+\lambda}$

Determination of the deconfinement ratio ($\lambda$) along the tunnel axis

Tunnel wall displacement ($u_R$) varies along the tunnel axis

Calculation method:

3-D model: $u_R = u_R(x)$
2-D model: $u_R = u_R(p)$

Thus: $\lambda = \lambda(x)$

Standard diagrams are available.
Determination of the deconfinement ratio ($\lambda$) along the tunnel axis

$$\lambda = f\left(\frac{x}{R}; M_s\right)$$

FLAC-3D : Spyropoulos, 2005

Purely elastic response for $M_s > 4$

$$\lambda = 1 - \frac{2}{(k-1)N_s} \left( \frac{u_R}{u_{R\infty}} \right)^{\frac{k-1}{K+1}} - 1$$

Chern, 2000

Unlu, 2003

Panet, 1995

$$\frac{u_R}{u_{R\infty}} = \left(1 + \exp\left[2.2 M_s^{0.37} \left(\frac{x}{R}\right)\right]\right)^{-1.2}$$

$$M_s = \frac{E}{1000 \gamma H^{0.90} D^{0.10}}$$

curves plotted for $M_s = 0.20$

Excavation with side-drifting and central pillar

40 mm surface settlement

Athens Metro : Acropolis Station excavation in “schist” (phyllite)
Conclusions

1. Ground deformations are critical
2. Estimates of ground deformations require 3-D numerical analyses ( + ground model + ground properties)
3. Relevant ground properties (mainly E) can be obtained by measurement of face extrusion & numerical back-analyses (or use of the normalised graphs)
4. For many tunnel designers, 3-D analyses may seem too sophisticated :
   • Methods exist to analyse the problem in 2-D using the “deconfinement method ($\lambda$)”
   • Normalised graphs are available to estimate ($\lambda$) in tunnels without / with face pre-treatment