Finite element simulation of a tunnel excavation in an urban environment: case study of the CEVA project

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Outline

• Introduction of CEVA/Pinchat tunnel project

• Geological concept and parameters determination

• Tunnel construction phases

• FE simulations

• Conclusions
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CEVA – Pinchat tunnel

16 km railways in urban area between Geneva (CH) and Annemasse (FR)

Key element of the Geneva-France regional transport network

Creation of five new railway stations

Reduction of transport time between Geneva and Annemasse to 20 min (36 min today)
CEVA – Pinchat tunnel

7 sectors

Sector 1: Cornavin – Saint Jean
Sector 2: Saint Jean - La Praille
Sector 3: Carouge Bachet - Pinchat
Sector 4: Val d'Arve
Sector 5: Champel
Sector 6: Eaux Vives
Sector 7: Eaux Vives - frontière
CEVA – Pinchat tunnel

Sector 3

- Underground station of Carouge Bachet 234 m
- Pinchat Tunnel 2024 m
- Cut and covered trench of Carouge 100 m
CEVA – Pinchat tunnel

Clients

Designers of sector 3

Pilot: BG Ingénieurs Conseils SA
partners: SD Ingénierie Genève SA
Solfor SA à Satigny
Géotechnique Appliquée Dériaz SA à Lancy

SBB CFF FFS

REPUBLIQUE ET CANTON DE GENEVE

POST TRANSPORT LUX
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Geology

Geological longitudinal section of the tunnel

235 m- clay section
Cover layer
Clay
Moraine
Alluvions anciennes

Simulation section
In situ investigations boreholes: SPT, pressuremeter

Laboratory testing: classification, direct shear, oedometric and triaxial tests

<table>
<thead>
<tr>
<th></th>
<th>USCS classification</th>
<th>Geneva soil classification</th>
<th>$\gamma$ [kN/m$^3$]</th>
<th>$\phi'$ [°]</th>
<th>$\psi$ [°]</th>
<th>$c'$ [kPa]</th>
<th>$K_0$ [-]</th>
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</thead>
<tbody>
<tr>
<td>Cover layer</td>
<td>-</td>
<td>1-2</td>
<td>20</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
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<tr>
<td>Clay</td>
<td>CM</td>
<td>6e2-6e12</td>
<td>20</td>
<td>24</td>
<td>0-2</td>
<td>5</td>
<td>0.59</td>
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<tr>
<td>Alluvions Anciennes</td>
<td>GP-GM</td>
<td>9a</td>
<td>24</td>
<td>36</td>
<td>12</td>
<td>1</td>
<td>0.41</td>
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</tbody>
</table>

Alluvions anciennes: $E = 300$ MPa and $\nu = 0.25$

Elastic properties

Cover layer: $E = 30$ MPa and $\nu = 0.3$

Clay: back analyzed from the laboratory triaxial tests
Triaxial tests on clayey material

Sample is extracted from 9m depth
Back analyzing of the triaxial tests
Single element simulation

![Graphs showing experimental and FE simulation results for q and pore pressure with axial strain for σ_c=200 kPa]

<table>
<thead>
<tr>
<th>$E_{\text{ref}}$</th>
<th>$E_{\text{ref}}$</th>
<th>$E_{\text{ref}}$</th>
<th>$\nu_{\text{ur}}$</th>
<th>m</th>
<th>OCR</th>
<th>$\sigma_{\text{ref}}$</th>
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<tbody>
<tr>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[kPa]</td>
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<tr>
<td>16</td>
<td>6</td>
<td>10</td>
<td>0.2</td>
<td>0.76</td>
<td>1</td>
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Back analyzing of the triaxial tests

Single element simulation

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<tr>
<th>$E^{ref}_{\sigma}$</th>
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<th>$\nu^{\sigma}$</th>
<th>$m$</th>
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<td>0.76</td>
<td>100</td>
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</tbody>
</table>

\[ E_0 = \frac{140}{e} \sqrt{\frac{p'}{P_{\text{ref}}}} \]

Biarez and Hicher (1994) \[ E^{ref}_0 \approx 165 \text{ MPa} \quad \gamma_{a,7} = 0.0002 \]
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Cross section of the tunnel in the clayey formation
Side heading galleries excavation

HEB 120 each meter
Distance between HEB beams: welded wire mesh covered by shotcrete
Elastic shell/beam in 3D/2D models
Armed concrete mass inside side heading galleries

Elastic behavior for concrete in FE models

$$E_c = 20 \text{ GPa}, \ \nu = 0.2$$
Pre-supporting system: Umbrella arch

- Umbrella arch dimensions:
  - Height: 0.6 m
  - Width: 0.5 m

- Weight averaging:
  - $E_{\text{umbrella}} = 4.3$ GPa

- Material details:
  - 16 m petroleum tubes, $D=159$ mm, $t=10$ mm
  - Overlapping: 4 m
Crown excavation

HEB 180 each meter
Distance between HEB beams: welded wire mesh covered by shotcrete
Elastic shell/beam in 3D/2D models
Bench excavation-Invert construction

Ongoing project
Photos will come later!
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FE simulation

3D model

2m-Cover layer

24m-Clay

24m- Alluvions anciennes

50m

51m
Tunnel face stability

c'\text{face} = 40 \text{kPa}

Crown excavation
Tunnel face stability

Bench excavation
Surface settlement

Heading side galleries excavation
Surface settlement
Crown excavation

End of side heading gallery excavation
End of crown excavation
Stress reduction method: \( \lambda \) or \( \beta \) parameter is estimated by fitting the surface settlement between 3D and 2D models.
Back analysis of the surface settlement Monitoring program
In-situ surface settlement
Heading side galleries excavation

Distance to tunnel axis (m)

Normalized settlement (%)

-50 -40 -30 -20 -10 0 10 20 30 40 50

-300 -280 -260 -240 -220 -200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0

MS1
MS2
HSS model-E₀=165 MPa
HSS model-E₀=140 MPa
HS model

△ MS1
▲ MS2

△ HSS model-E₀=165 MPa
▲ HSS model-E₀=140 MPa

- ▲ HS model
In-situ surface settlement

Crown excavation

Distance to tunnel axis (m)

Normalized settlement (%)
Conclusions

- Hardening soil parameters are successfully estimated from the laboratory tests

- Tunnel face stability is verified by using the 3D FE model

- For heading side galleries the HSS model predict well the measured surface settlement however HS model predicts almost 3 times the settlement

- Umbrella arch Young modulus has significant effect on the predicted surface settlement
  - The Young modulus by weight averaging predicts 50% error in settlement prediction
  - An ten time smaller Young modulus is needed to predict correctly the in-situ settlement