Compensation Grouting

Underground Grouting and Ground Improvement

September 12, 2018
Golden, Colorado
Phillip Gallet, P.E.
Presentation Outline

• What is Compensation Grouting
• Installation Methods/Monitoring
• Modeling of compensation grouting
• Finite element calculations for compensation grouting at Antwerp Central Station
• Case Histories
• Summary and conclusions
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Grouting Processes

- Slurry Grout (Intrusion)
- Chemical Grout (Permeation)
- Compaction Grout (Displacement)
- Jet Grout (Erosion)
- Fracture Grout (Compensation)
Compensation Grouting -or- Soilfrac® Grouting

• Originally developed in the oil industry for fracturing formations to aide in the production of the well.

• Keller/Hayward Baker developed the process to accommodate small scale installation process for the geotechnical construction industry

• Allows precise control of lifting structures and when coupled with computer monitoring, control within millimeters
Soilfrac® Process

**Construction site installation**

1. Water
2. Cement-Filler Stone dust
3. Accelerator and Additives
4. Mixer and pump
5. Measuring and control

Mixing- and grout station placed into a Soilfrac®-container allowing short installation period.
Uses for Soilfrac® Grouting
Typical Grouting Ranges

Application limits for the grouting processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
<th>Cobbles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soilfrac®</td>
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<td></td>
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</tr>
<tr>
<td>Soilcrete-Jet Grouting®</td>
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</tr>
<tr>
<td>Compaction Grouting</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Synthetic Solutions</td>
<td></td>
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<tr>
<td>Sodium Silicate Solutions (lv)</td>
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<tr>
<td>Silicate Gel (hv)</td>
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<tr>
<td>Ultratine Cement</td>
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<td></td>
<td></td>
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<tr>
<td>Cement suspension</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mortar</td>
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</tbody>
</table>

lv = low viscous
hv = high viscous
The injection pipes are made of multiple ported tubes that allow design placement of grout.

**Known as Tube-A-Manchette Pipes**
Exposed Soilfrac lenses following a single grout injection
Grouting Efficiency

- Ratio of ground volume change to grout volume injected
- Varies from site to site due to ground conditions

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Grouting Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands and Gravels</td>
<td>5% to 15%</td>
</tr>
<tr>
<td>Silts</td>
<td>15% to 25%</td>
</tr>
<tr>
<td>Soft Clays</td>
<td>0% to 10%</td>
</tr>
<tr>
<td>Firm Clays</td>
<td>15% to 25%</td>
</tr>
<tr>
<td>Stiff Clays</td>
<td>30% to 50%</td>
</tr>
</tbody>
</table>

RD Essler 2012
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Several methods of installing the grout pipes are available based upon site restrictions.
Compensation grouting from a shaft
Compensation grouting from nearby basement
Control of grouting parameters possible in real time

All grouting parameters under real time control

Use of computer controlled pumping units allow grout quantities to be individually controlled
Typical instrumentation types and locations considered for compensation grouting
Sophisticated and non sophisticated methods allow for movement monitoring

Systems allow monitoring within 0.005 in
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Grout Consumption Corresponds to the Settlement

\[ S_{\text{max}} \]

\[ V_{\text{Inj. max.}} \]

3 3 3 3 3 3 [m]
Problem Statement for modeling analysis

- Structure
- Surface
- Resulting settlements
- Settlements due to excavation
- Grouted zone
- Excavation
- Heave due to grouting
Comparison of grouting techniques and how they are modeled
Deformation modes of the grouted zones used in the modeling

\[ \varepsilon = \frac{\Delta a_0}{a} \quad \delta = \frac{\Delta a'}{a} \]

- Initial: $\varepsilon > 0$ contraction
- Deformed: $\varepsilon < 0$ expansion
- $\delta > 0$ vertical shortening
- $\delta < 0$ horizontal shortening
Analytical solution proposed by Sageseta (1987)

GROUND SURFACE

Vertical:

$$s_z = 2 \varepsilon a \left( \frac{a}{h} \right)^{2 \alpha - 1} \frac{1}{(1 + x^2)^\alpha} \left( 1 + \rho \frac{1 - x^2}{1 + x^2} \right)$$

Horizontal:

$$s_x = -2 \varepsilon a \left( \frac{a}{h} \right)^{2 \alpha - 1} \frac{x'}{(1 + x'^2)^\alpha} \left( 1 + \rho \frac{1 - x'^2}{1 + x'^2} \right)$$

$s_z$ ... vertical displacement
$s_x$ ... horizontal displacement
$h$ ... depth of injection/excavation
$a$ ... radius of grouted zone/excavation
$x'$ ... normalized horizontal distance ($x/h$)
$\varepsilon$ ... uniform radial deformation
$\delta$ ... ovalization
$\rho$ ... relative ovalization ($\delta/\varepsilon$)
$\alpha$ ... exponent for drained cases
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ANTWERP CENTRAL STATION

Historical Landmark

High Loads considered

Minimal movement
ANTWERP CENTRAL STATION

- 84 TAMs
- 3500 m borings
- 45 m max. length

picture: Eurostation, Brussels
ANTWERP CENTRAL STATION

picture: Eurostation, Brussels
Compensation Grouting efficiency at Antwerp Station

\[
\text{efficiency } E (%) = 100 \frac{\text{average heave } s \text{ (mm)}}{\text{average grout volume } l \text{ (l/m}^2\text{)}}
\]

<table>
<thead>
<tr>
<th>phase</th>
<th>grout volume (litres)</th>
<th>average vol. per injection (litres)</th>
<th>efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-treatment</td>
<td>330,000</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>pipe jacking and part of tunnel walls</td>
<td>200,000</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>rest of tunnel walls and preparatory work for the tunnel excavation</td>
<td>50,000</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>tunnel excavation and deflection of the roof slab</td>
<td>170,000</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>total</td>
<td>750,000</td>
<td>33</td>
<td>20</td>
</tr>
</tbody>
</table>
FE-CALCULATIONS ANTWERP PROJECT

FINITE ELEMENT MODEL

foundations
conditioned zone
pipes A-B-C-D
tunnel

Antwerp Sand
Boomse Clay
COMPARISON MEASUREMENT – FE-MODEL

VERTICAL DISPLACEMENTS AT WATER LEVEL POINT P455

- Pipe B
- Comp. B*
- Pipe D
- Comp. D*
- Pipe A
- Comp. A
- Pipe C*
- Comp. C
- Tunnel excavation

Displacement [mm]

- Measurement P455
- Calculation P455
COMPARISON MEASUREMENT FE-MODEL

VERTICAL DISPLACEMENTS AT WATER LEVEL POINT P470


- Black line: measurement P470
- Red line: calculation P470
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Soilfrac® - City-Tunnel Leipzig
Central Station
Soilfrac® - City-Tunnel Leipzig

Drilling
Soilfrac® - City-Tunnel Leipzig

Control of drilling deviation
Soilfrac® - City-Tunnel Leipzig

Grout control

Vertical displacement

Grout volume

TAM
Project “San Ruffillo”, Bologna, Italy

Tunnel excavation
- twin tunnels with 15m distance
- length 6,112m
- diameter 9.4m
- excavated area 69.81m²
- cover 15 – 21m
- EPB-shield

Compensation grouting
Problem statement

- expected volume loss of the TBM-excavation: 1%
- maximum advancement of the TBM: 10m/day

Compensation of differential settlements of piers

- Allowable differential settlement: $\Delta u_{ij} \leq l/3000$
Compensation grouting “San Ruffillo”
TYPICAL CROSS SECTION

Original design with SHAFT

- Railway bridge
- Shaft
- Grouting pipes (2 layers)
- Tunnel (9.1m diameter)
Compensation grouting “San Ruffillo”

railway bridge

grouting pipes
2 layers
maximum length 68m
HDD-drilling

tunnel
9.1m diameter

fill sand, gravel, sandy, silty
Compensation grouting “Via Emilia”

existing railway bridge
length 112m
1 central arch (l=16.0m)
8 lateral arches (l=8.1m)

Milano
Florence
Via Emilia Levante
Compensation grouting “Via Rimesse”

existing railway bridge
length 41m
1 central arch (l=14.4m)
2 lateral arches (l=7.2m)

Metro line („Suburbana“)
Compensation grouting “Via Rimesse”

Upper circuit > vertical displacements

Lower circuit > monitoring of vertical displacements (and rotations)

transition point
Compensation grouting “Via Rimesse”

Displacements resulting after TBM 2

> Maximum differential settlement 1.9mm
Compensation grouting “Via Rimesse”

3D graph of total grout volume
San Francisco 3rd Street Light Rail - Central Subway Drilling and Grouting Programs

➢ Chinatown Station (CTS)
  ➢ Issue: Adjacent Building Settlement along Station Excavation
  ➢ Solution: Compensation Grouting

➢ Union Market Square Station (UMS)
  ➢ Issue: Adjacent Building Settlement along Station Excavation
  ➢ Solution: Compensation Grouting
3rd Street Light Rail - Central Subway Project Alignment

Chinatown Station (CTS)

Union Market Square Station (UMS)

Moscone Station (YBM)
Pre-conditioning Statistics

- Total Installed Grout Holes = 94
- Drilling Rigs = 2 on 2 Shifts
- TAM Installed = 13,320 LFT
- TAM Installation Rate = 73 LFT / Rig Shift
- Grout Injected = 86,000 Gal
- Grout Injection Rate = 1385 Gal / Shift
- Treatment = 10 Buildings – 41,150 Sq. Ft.
CTS Compensation Grouting
TAM Pipe Array
CTS Compensation Grouting

Drilling and TAM Installation
CTS Compensation Grouting

Pre-conditioning Grouting
Union Market Compensation Grouting
Pre-conditioning Statistics

- Total Grout Holes = 209
- Drilling Rigs = 1 on 2 Shifts
- TAM Installed = 19,605 LFT
- TAM Installation Rate = 94 LFT / Rig Shift
- Whips = 4
- Grout Injected = 204,000 Gal
- Grout Injection Rate = 1416 Gal / Shift
- Treatment = 15 Buildings – 126,815 Sq. Ft.
- Completed 2017
TAM Pipe Array
Drilling and TAM Installation
Pre-conditioning Grouting
Case History
Annunciation Church
Layout of Soilfrac® Pipes and Jet Grout Columns
Amount of Movement Required

What this set of data indicates is that there is a differential between the left side of the church and the middle of nearly 6 inches and from North to South of 4.5 inches.
Frac Grouting
Results of Survey

5/28/2010

Avg Movement to the North = 0.3225 deg
0.44 - 0.32 = 0.12 deg remaining

Avg Movement to the East = 0.215 deg
0.34 - 0.22 = 0.12 deg remaining
Grouting Recap

- Installed 93 full and half triple system jet grout columns to depths exceeding 25 feet.
- Installed 86 Soilfrac® pipes and pumped 4,178 cft of grout
- Achieved plumbness within 0.12° of perfectly plumb from 0.44° and 0.34°, 65 to 75% correction.
Compensation Grouting Program at Jack II

- Access Shaft
  - 34 Secant Piles
- Monitoring Instrumentation
  - Getec UK
  - Hydrostatic Leveling Cells (HLC)
  - Tiltmeters
  - Extensometers
- Preconditioning of TAM pipes
  - 3500+ ports
  - 5200 CFT grout
- Compensation Grouting
  - 9000 CFT grout
Compensation Grouting

Isometric View Looking Southwest
Compensation Grouting

- Grouting Efficiency Factor
  - 12 Quadrants
  - GEF = (Grout Tributary Area * Avg. Heave) / Grout Volume

AVERAGE Grouting Efficiency Factor = 32.3%

Maximum Heave = 4.5 Inches
Compensation Grouting

Project: Jack II STG Remediation
Grout Volume Distribution Elevation View from the South
SUMMARY and CONCLUSIONS

• Finite element model proposed to simulate the effects of compensation grouting
• Numerical model compares well with analytical solution for elastic, undrained behaviour
• Compensation grouting allows for quicker tunnelling applications
• Precise levelling of sensitive structures is more efficient with compensation grouting
• HDD installation procedures extend the treatment possible on project sites
This is the Last Slide
Thank You!! Questions?

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