Crossrail

- £13 billion total value
- >200 buildings to protect by compensation grouting - many historic and/or important
- Across the project >£100 million of compensation grouting, >£60 million in instrumentation & monitoring

Crossrail C510 - £25+ million compensation grouting
Crossrail C315 - £2 million ground consolidation
Bond Street St. Upgrade - £6 million compensation grouting
Crossrail - Core Technical Challenges

- Settlement control for key structures and utilities
- Application of complex and detailed Crossrail specifications
- Structures with mixed foundations, diverse sensitivity, complex structural history
- Prestigious & historic structures, influential stakeholders
- Victorian era utilities and infrastructure 120-150 yrs
- Impact of compensation grouting on underground infrastructure and utilities
- Management of different specifications for buildings, LUL tunnels, utilities
- Assessment of potential settlement and damage
- Project scale and industry resource
Crossrail Project Geology

C510
Scope of Full Works - Crossrail C510 - Value > £300m
Scope of Settlement Mitigation Works - Value > £35m

- Liverpool Street Station Tunnels
  - Temporary access shaft
  - 750m Platform tunnels
  - 830m Cross passages and adits
  - 4 No. Grout Locations
  - Extensive monitoring
  - Depressurisation in most tunnels
  - Compensation, permeation grouting, pipe arch

  Excavation Vol.= 134,000 m³
  Concrete Vol.  = 57,000 m³

- Whitechapel Station Tunnels
  - Temporary access shaft
  - 640m Platform tunnels
  - 355m Cross passages and adits
  - 1 no Grout shaft
  - Depressurisation in most tunnels
  - Compensation grouting, Permeation grouting, pipe arch
  - Crossover tunnels

  Excavation Vol.= 130,000 m³
  Concrete Vol.  = 62,000 m³
Compensation Grouting
Design Considerations - Specified Performance Criteria
Current UK approach (Crossrail)
Crossrail - Settlement Control Criteria - Surface structures

No Displacement
No Issues

Even Settlement
No Issues for structure
But beware Utilities
Limits set in mm or defined by limits set for utilities

Differential Displacement
May be critical
Depends on condition of structure and type of construction
Limits have been set in range 1/500 to 1/3000. CRL limit is =1/1000 for settlement, 1/2000 and 5mm max. for heave

Deflection Ratio
Often much more critical
Requires more detailed information on structure
CRL limit is set at 1/2000 ie 0.5 x diff. settlement
Crossrail - Settlement Control Criteria - Infrastructure

Cross-Track Displacement

Limits set to avoid speed restriction and/or risk of derailment. Typical value in UK for full gauge railway, with running speeds < 45km/h = 5mm. Limits will vary for different track speeds, curvatures, and camber.

Longitudinal Chord Displacement

Limits set to avoid speed restriction, passenger discomfort, and/or risk of derailment. Typically the operator will set limiting values for the vertical displacement along a fixed chord length, and/or a radius of curvature. Limits will vary for different track speeds.

Compound Displacement

Set limits may be very onerous for compound displacements, particularly on high speed curves.
Displacement Limits may be defined in different ways eg:

- as a physical chord displacement
- as a deflection
- increasingly, as a value of limiting strain, verified by physical displacement monitoring, in situ strain gauges, or soil displacement monitoring, all to avoid physical damage of lining for brick or masonry structures
- to protect joints in the case of flanged cast iron pipes or jointed GRP conduits

For flanged / jointed structures, consideration of joint rotation can have a significant impact in reducing the degree of predicted strain.

New optic fibre strain monitoring systems may play an increasingly large role in future for asset monitoring and managing asset maintenance.

These are being considered for use by several infrastructure and utility companies on the basis of providing safe, remote access, and low maintenance.

Rod extensometers, crack-meters, LVDT’s, tilt-meters, electro-levels, inclinometers, etc.
Crossrail - Settlement Control Criteria - Structural Damage

Extract from Building Research Establishment report on Building Damage Classification, after Burland et al. (1977)

Burland (1995); Mair, Taylor and Burland (1996)
Compensation Grouting
Design Considerations - Geometry
Compensation Grouting - Premise

Where to grout for best effect and efficiency?

Depends upon:
- structure foundations
- structure condition
- ground conditions
- predicted settlements
- damage risk
- tunnelling method
- access constraints
- time constraints

More observational

More predictive
Compensation - the importance of location and timing

Must catch the settlement as it migrates - if left too late the opportunity may be lost - this is a disadvantage of a deep array system, or slow engineering / management response
Compensation - selection of grouting zone

1. - Pilot Tunnel
2. - Enlargement
3. - Break Out
4. - Escalator
5. - Possible grout shaft
6. - Building requiring protection
The engineering decision is often easier than commercial decision when bidding competitively - the parties should try to bid a basic conforming design & address the coverage during the OCI period.

However, this issue of coverage is vital - it is too late to extend the arrays once settlements begin to develop - designers must fight to get this issue fully addressed at design and planning stage.

Clients should give due consideration to technical merit and sound concept / design. For compensation grouting, cheapest is rarely best.
Crossrail C510 - Excavation Methods
Excavation - Enlargement pilot to platform tunnel

- Safety - ca. 58% Declined Tunnel (3.5 m in 6 m)
Excavation - Enlargement pilot to platform tunnel

1) Top Heading with temp. invert
2) Enlargement of bench & invert
Liverpool Station Site - Up-slope Excavation of ES2 Escalator Tunnel
Up-slope Excavation of ES2 Escalator Tunnel

rail mounted excavation and support unit
Up-slope Excavation of ES2 Escalator Tunnel
Alternative Down-slope Excavation of Escalator Tunnel

Early Development of Broadgate Link
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

Team 1
SCL Shaft
CP5 / CP6
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

<table>
<thead>
<tr>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP7 West-1</td>
<td>AP7 East</td>
<td>PTE pilot West incl depressurisation</td>
</tr>
<tr>
<td>CH1-1 pilot</td>
<td>CH1-1 enlarge</td>
<td></td>
</tr>
<tr>
<td>PTW pilot West incl depressurisation</td>
<td>AP7 West-2</td>
<td></td>
</tr>
</tbody>
</table>
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

<table>
<thead>
<tr>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTW Transition</td>
<td>PTE Transition</td>
<td>PTE pilot East incl</td>
</tr>
<tr>
<td></td>
<td>CP3a / CP3b</td>
<td>depressurisation</td>
</tr>
</tbody>
</table>
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

Team 1: PTW Enlarge West
Team 2: PTE Enlarge West
Team 3: PTW pilot East incl depressurisation
       CH1-2 pilot
       CH2 pilot and enlargement
       CP7 / CP8
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

Team 1
- PTW/RCW pilot and enlarge incl depressurisation
- CP9
- LCW pilot and enlarge
- VD5 box connection
- VD7

Team 2
- AP6
- PMR lower lift
- AP10
- PMR upper lift

Team 3
- PTE/RCE pilot and enlarge incl depressurisation
- CP10
- CH5 pilot and enlarge
- AP9
- CH6
- ES3
Team 1

AP1 pilot and enlarge
VD1
VD2

C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

Team 1
AP2
CH3
ES2
Compensation Grouting
Design Considerations - An example of an approach for predictive grouting using COGNAC

Objective

Try to re-compact ground as close as possible in both time and space to the source of relaxation, to try to prevent the majority of this relaxation migrating to the foundation level of the structures above.
We must start with the same soil parameters and settlement trough monitoring as the tunnel designers.
Compensation Grouting - example of basis of design
The programme takes the tunnel geometry, predicted settlement profile, and as-built borehole layout, and overlays a reference grid as a basis for design of injection programmes.
The programme assigns given or calculated total volumes of grout to be injected within each individual cell, for each phase of tunnel excavation. Grout volumes derived from excavation volume, assumed face loss, GEC.
Compensation Grouting - example of basis of design
Creation of equivalent volume with common xyz location of centre of element

Application of same soil parameters, face loss assumptions, and settlement formulae as the client and the tunnelling designers

Automatic production of
• Surface volume loss for each 1m excavation element of each phase of tunnelling
• Application of GEC - the grouting efficiency co-eff., to calculate grout volume for each 1m element
• Grouting programme with grout distribution based upon surface settlement profile
IF THE CLIENT CAN NOT PROVIDE SETTLEMENT VOLUME, THE PROGRAMME WILL CALCULATE A THEORETICAL VOLUME BASED ON THE TOTAL SETTLEMENT.

Vs = PREDICTED SETTLEMENT VOLUME PER CELL

d = AN ARBITRARY VALUE FOR THE ‘CELL’ DIMENSIONS APPROPRIATE TO THE WORKS

THE GROUT INJECTION VOLUME Vmax = Vs x EFFICIENCY CO-EFFICIENT (generally 3 - 5 for London Clay)
VOLUME Vs AND Vmax IS CALCULATED FOR EACH CELL AND COGNAC ALLOWS A % OF THE CELLS FOR INJECTION, AND DISTRIBUTES THE GROUT VOLUME BETWEEN THOSE SLEEVES.

A PRACTICAL MINIMUM FIGURE Vmin IS SET FOR EACH INJECTION (e.g. 20-25 lts) AND A Vmax IS SET FOR EACH INJECTION, GENERALLY ≤ 50 lts.

INJECTION RANGE WOULD THEREFORE BE 25-50 lts, AND THE PROGRAMME SELECTS A NUMBER OF BOREHOLES NECESSARY FOR VOLUME TO BE INJECTED.
Compensation Grouting - example of basis of design

Able to calculate in advance of the tunnel excavation the volume of grout anticipated, and the distribution of these injections, whilst respecting the exclusion zone.

- Reference grid
- Sleeves to be injected
- Injection ports
- Elements of tunnel advance
### Compensation Grouting - example of basis of design

<table>
<thead>
<tr>
<th>SITE</th>
<th>Row</th>
<th>Column</th>
<th>Efficiency</th>
<th>ThV Loss</th>
<th>ThSettlement</th>
<th>ThGroutVolume</th>
<th>XCenter</th>
<th>YCenter</th>
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<tbody>
<tr>
<td>NATM</td>
<td>8</td>
<td>12</td>
<td>5</td>
<td>37.017</td>
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<td>185.087</td>
<td>-14.326</td>
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<td>5</td>
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<td>5</td>
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<td>-21.431</td>
<td>-291.692</td>
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<td>5</td>
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<td>5</td>
<td>26.209</td>
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<td>131.045</td>
<td>-20.089</td>
<td>-286.875</td>
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<td>8</td>
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<td>27.863</td>
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<td>10</td>
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<td>34.676</td>
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<td>173.378</td>
<td>-18.076</td>
<td>-279.651</td>
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<td>NATM</td>
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<td>11</td>
<td>5</td>
<td>38.877</td>
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<td>194.385</td>
<td>-17.405</td>
<td>-277.242</td>
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<td>NATM</td>
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<td>12</td>
<td>5</td>
<td>42.885</td>
<td>-6.862</td>
<td>214.424</td>
<td>-16.734</td>
<td>-274.834</td>
</tr>
</tbody>
</table>
Crossrail - Application of COGNAC

Compensation Grouting - example of basis of design
Compensation Grouting - example of basis of design

Excavation volume = 39.868m³
Est’d face loss = 1.4%
39.868m³ x 1.4% = 0.558m³
Efficiency Factor = 2.5
Theo. Volume of grout = 1329.446 lts
Actual Volume available
Outside exclusion zone = 440 lts
Retained volume = 1889 lts

As the settlement develops, the programme prepares Injection programmes in phases according to the volume of settlement predicted for each phase, and the rate of progress. The model is refined daily on the basis of settlement and injection data.
Crossrail Liverpool St Station

Huge monitoring programme
- 80 Cyclops at surface, 15 underground
- 25 instrumented boreholes
- 12 horizontal IPI arrays
- >300 of PL monitoring studs
Crossrail Liverpool St Station

Very large listed structures, mixed foundations, high loads, limited access, influential owners - example: Finsbury Circus
Crossrail Liverpool St Station

Original design
Crossrail Liverpool St Station

- Arrays truncated @10mm contour
- Grout adit replaces shafts
- Holes re-aligned, shortened, more efficient spacing
- Targeting of settlement source, not just structures
Liverpool St Station

Hammersmith & City Line @ 2m depth

Major Thames Water Utilities
Crossrail Liverpool St Station
Finsbury Circus Site
Layout

Hammersmith & City Line @ 2m depth

Compensation Grouting Adit
Crossrail C510 - 1 to 5 Broad St. Place
1-5 Broad St Place

Access passage AP2

LU tunnel

600mm diameter friction piles

Crossrail receiving chamber eastbound

Access passage AP1
1-5 Broad St Place
1-5 Broad St Place

- Additional passive arrays for early intervention
- Minimised grout jacking
- Targeting of settlement origin
- IPI arrays for early warning
1-5 Broad St Place

16mm of settlement across façade & interior junction

Tunnel & enlargement
Crossrail C510 - Electra House
Electra House - revised design of borehole layout
Electra House - revised design of ground treatment

Section G:G

Section H:H

Section I:I

Section J:J

Section K:K

Revised ground treatment zone

Notes:
1. All dimensions are in millimeters.
2. All levels are in WCD. Set out to ±25mm.
3. All angles are in degrees. Tolerances up to ±2.5 degrees accepted.
4. TMM positions to be confirmed by as built survey.
5. TML final alignment to be subject to minor changes, depending upon what is revealed by the excavation of all preliminary level dig.
6. Snag holes illustrated in solid line are in section and those illustrated in dotted line are out of section.
7. Closing based on CRS: 135254928296088 +0000000000000004 and plan of HDT shop floor (revised 23-11-12).
8. Access ramp not previously illustrated, but is to be considered to be the only practicable means of allowing access to south end pit.
9. Semi-radial coverage of ground zone from tunnel profile deemed sufficient for tunnel stability. See structure on 12/01/11 provisional external reduction meeting. BBMV however insist this radial coverage in order to ensure performance requirements are fully met within this zone.
Electra House - Transverse section detail at Moorgate headwall

Basement Concrete Floor

Grout Target Zone

5mtr offset around new AP9 + CH6 + ES3 UMC

5mtr offset around new AP9 + CH6 + ES3 UMC
Electra House - 3D modelling of treatment from Electra basement

<table>
<thead>
<tr>
<th>Name/Area</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 HMC Grout Curtain</td>
<td>284.6</td>
</tr>
<tr>
<td>2 HMC Curtain within 3m of Goswell Street Sewer</td>
<td>36.4</td>
</tr>
<tr>
<td>3 6m CRL Tunnel offset</td>
<td>1406.8</td>
</tr>
<tr>
<td>4 6m CRL Tunnel offset within 3m of Goswell Street Sewer</td>
<td>206.7</td>
</tr>
<tr>
<td><strong>Total Vol.</strong></td>
<td><strong>1934.5</strong></td>
</tr>
</tbody>
</table>
Electra House - 3D modelling of treatment from Moorgate box

<table>
<thead>
<tr>
<th>Name/Area</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMC Curtain with Stage 1</td>
<td>443.4</td>
</tr>
<tr>
<td>Grouting</td>
<td></td>
</tr>
<tr>
<td>Stage 2 Grouting</td>
<td>211.3</td>
</tr>
<tr>
<td>New deeper Clay interface level extra volume to grout</td>
<td>157.0</td>
</tr>
<tr>
<td><strong>Total Vol.</strong></td>
<td><strong>811.7</strong></td>
</tr>
</tbody>
</table>

Goswell Street Sewer
Crossrail C510 - Whitechapel Station
Whitechapel Station Site
Whitechapel Station
Site
Whitechapel Station - Key Buildings
Whitechapel Station - Compensation Grouting Array
Whitechapel Station - Break-out chamber
Process control

Settlement monitoring for key structures

Challenges
• Provide adequate frequency of monitoring to allow for active compensation grouting
• Integrate data from several sources, including grouting
• Display data in a format compliant with specified criteria - differential settlement, deflection
• Display/analyse historic project-wide data
• Provide remote and multi-user access to data
Compensation Grouting - settlement control for key structures & utilities
Compensation Grouting - settlement control for key structures & utilities
Process control - Settlement control for key structures

THE CENTRAL ROLE OF REAL TIME DATA ACQUISITION & PRESENTATION
FOR STRUCTURAL / GEOTECHNICAL MONITORING

CYCLOPS

Radio Transceiver

Radio Transceiver

Radio Transceiver

Radio Transceiver

DATA LOGGER

Radio Transceiver

Radio Transceiver

Radio Transceiver

Dispacement Transducers

ELECTRO LEVEL

STRAIN GAUGES

Pager Alarms

Beacon Alarms

Auxiliary Output

E-Mail Alarms

Siren Alarms

Alarms

Logging PC’s & Software (SMACS)
Process control - Settlement control for key structures

Automatic survey of displacements in semi-real time

Motorised Total Station  Settlement Contours

[Image of motorised total station]

[Diagram of settlement contours]
Process control - Settlement control for key structures

GEOSCOPE WEB - Example of remote monitoring via Internet
Process control - Settlement control for key structures

GEOSCOPE WEB - Settlement contours

THE CENTRAL ROLE OF REAL TIME DATA ACQUISITION & PRESENTATION FOR STRUCTURAL / GEOTECHNICAL MONITORING
Process control - Settlement control for key structures
Process control - Settlement control for key structures
GEOSCOPE WEB - Example of remote monitoring via Internet

Process control - Settlement control for key structures
Process control - Settlement control for key structures

GEOSCOPE WEB - Settlement contours

THE CENTRAL ROLE OF REAL TIME DATA ACQUISITION & PRESENTATION FOR STRUCTURAL / GEOTECHNICAL MONITORING
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Process control - Settlement control for key structures
Specification requires monitoring of differential settlement between any 2 adjacent points, & deflection across any 3
If taken literally this is too much information, and can be misleading, The specification must be applied sensibly
We must select and agree key structural elements to be monitored
We must advise the client what we need in order to manage the works, and ensure provision is made for this
To achieve all this properly requires
a) a measured survey, b) a structural survey, c) a settlement prediction, and d) a building damage assessment

Be sure of what you are monitoring- significant elements only
• We must pare back the instrumentation, eliminating unnecessary detail
  It is necessary
• to identify the key structural elements,
• to install appropriate survey points and instruments
• to define whether data needs to be real-time, semi real-time, or periodic,
• to decide how to present and distribute the data
Daily Report Pack for all-party SRG Meeting
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

ABSOLUTE REPORT: SURFACE & BASEMENT MONITORING INSTRUMENTATION.

BASIS OF CONTOURS:
For Automatic monitoring: NIGHTSHIFT OF 04/12/12 (19:00 to 07:00 HRS ending next day)
For Manual monitoring: DAYSHIFT OF 04/12/12 ending at 19:00 HRS

KRIGING METHOD USED TO ESTABLISH CONTOURS.
CTC Pack

C510 LIVERPOOL STREET
FINSBURY CIRCUS GROUTING ZONES

06/12/2012
Proposed programme for next day and night shift if approved in SRG meeting.
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

SHIFT REPORT
SURFACE & BASEMENT MONITORING INSTRUMENTATION.

WHOLE SITE
BASIS OF CONTOURS:
NIGHTSHIFT OF 04/12/12 MINUS NIGHTSHIFT OF 03/12/12
I.E. MEDIAN OF 04/12/12 19:00HRS TO 05/12/12 07:00HRS minus
MEDIAN OF 03/12/12 19:00HRS TO 04/12/12 07:00HRS.

KRIGING METHOD USED TO ESTABLISH CONTOURS.

VOLUME
CUT: 24086 L
FILL: 2711 L

Grouted Volumes for the 04/12/2012 (DS-NS): 16,188 L
ACG-AP7 P E 150: 3,272 L
ACG-AP8: 2,226 L
PG011-GJ46-4B: 10,684 L

Maximum heave: 2.8 mm
Maximum settlement: -0.5 mm
CROSSRAIL C510 - Whitechapel and Liverpool Street Station Tunnels

LIVERPOOL STREET
ZONES: LIV1, LIV2, LIV4

DAILY REPORT,

from 08:21:24, 04/12/2012 to 05:49:48, 05/12/2012

total grouted volume: 16,187.45 (litres)  398 Sleeves

First Phase: AP7_P_E/0019-0024_150,  Last Phase: GJ48 PRG11 [GJ45 to GJ48]
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

CUMULATIVE REPORT

WHOLE SITE

Historic
Active Compensation Grouting
from 19/10/2012

SURFACE & BASEMENT MONITORING INSTRUMENTATION.

BASIS OF CONTOURS:
NIGHTSHIFT OF 04/12/12 MINUS NIGHTSHIFT OF 19/10/12
I.E. MEDIAN OF 04/12/12 16:00HRS TO 05/12/12 07:00HRS minus
MEDIAN OF 10/10/12 19:00HRS TO 20/10/12 07:00HRS.

KRIGING METHOD USED TO ESTABLISH CONTOURS.

VOLUME:
CUT: 59364 L
FILL: 18876 L

Grouted volume (cumul) : 148,261.43 L

Maximum heave: 4.7 mm
Maximum settlement: -7.5mm

KEY:

TUNNEL
• Pilot
• Enlargement
• Invert
• Active Advance
• Proportional vol. @ 1,000 L

MEASUREPOINTS
### RP
### SHR
### LP; LC; LB
### RL

X No reading
• Discarded data

File Reference: 20121205-20121019-LT_V_CUMUL_WHOLE_SITE_Tunnel_HISTO.wbst
Created By: JBA - Checked By: HRA
Printed: 2012-12-05
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

CUMULATIVE REPORT

WHOLE SITE

SURFACE & BASEMENT MONITORING INSTRUMENTATION.

VOLUME:
CUT: 48545 L
FILL: 2611 L

BASIS OF CONTOURS:
NIGHTSHIFT OF 04/12/12 MINUS NIGHTSHIFT OF 26/11/12
I.E. MEDIAN OF 04/12/12 19:00HRS TO 05/12/12 07:00HRS minus
MEDIAN OF 26/11/12 19:00HRS TO 27/11/12 07:00HRS.

PRG 11 - Cumul Grouted Vol : 23,142.17 L
Maximum heave: 3 mm
Maximum settlement: -3 mm

KRYING METHOD USED TO ESTABLISH CONTOURS.

FILE REFERENCE: 20121205-20121127-LIV_CUMUL_WHOLE_SITE_PRG11.png
CREATED BY: IDA - CHECKED BY: NRA
PRINTED: 2012-12-05
**Grouting Report**

**Site:** LIVERPOOL STREET  
**Zones:** LIV1_H2, LIV2_B1, LIV4_E  
**From:** 08:21:24, 04/12/2012  
**To:** 05:47:49, 05/12/2012

**Zone:** LIV1  
**Area:** G1

<table>
<thead>
<tr>
<th>Area</th>
<th>Hole</th>
<th>Sleeve</th>
<th>Phase</th>
<th>Start Time</th>
<th>End Time</th>
<th>Grouted Volume (litre)</th>
<th>Final Pres. (bar)</th>
<th>Av. Final Pres. (bar)</th>
<th>Av. Flow (l/h)</th>
<th>Stop Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1S01</td>
<td>14</td>
<td>AP7_P_E/0019-0024_150</td>
<td>04/12/2012 08:21</td>
<td>08:24</td>
<td>25.0</td>
<td>4.0</td>
<td>4.5</td>
<td>96</td>
<td>Maximum Volume</td>
</tr>
<tr>
<td>G1</td>
<td>1S01</td>
<td>16</td>
<td>AP7_P_E/0025-0030_150</td>
<td>04/12/2012 08:32</td>
<td>08:37</td>
<td>25.0</td>
<td>6.9</td>
<td>7.0</td>
<td>102</td>
<td>Maximum Volume</td>
</tr>
<tr>
<td>G1</td>
<td>1S02</td>
<td>6</td>
<td>AP7_P_E/0019-0024_150</td>
<td>04/12/2012 08:54</td>
<td>09:11</td>
<td>25.0</td>
<td>4.4</td>
<td>6.3</td>
<td>48</td>
<td>Maximum Volume</td>
</tr>
<tr>
<td>G1</td>
<td>1S02</td>
<td>12</td>
<td>AP7_P_E/0019-0024_150</td>
<td>04/12/2012 09:29</td>
<td>09:31</td>
<td>25.0</td>
<td>2.8</td>
<td>2.9</td>
<td>72</td>
<td>Maximum Volume</td>
</tr>
<tr>
<td>G1</td>
<td>1S02</td>
<td>20</td>
<td>AP7_P_E/0019-0024_150</td>
<td>04/12/2012 09:43</td>
<td>09:45</td>
<td>25.0</td>
<td>5.4</td>
<td>5.6</td>
<td>101</td>
<td>Maximum Volume</td>
</tr>
</tbody>
</table>

**Total Grouted Volume for Area:** G1 0.125 m³
LIVERPOOL STREET
ZONES: LIV1
04/12/2012
Instruction Phase(s): CP5_P/0001-0006_150, CP5_P/0007-0012_150, CP5_P/0013-0018_150, CP5_P/0024-0027_125
Max. Volume: 25.00 L   Max Pressure: 8.00 bar   361 Sleeves.

START DATE:

SIGNATURE DATE

AZ_LIV_Inst_Print.xc3  Phase(s) 0048, 0050, 0052, 0055 Instruction sent to the Plant (folder: C:\BDD2\LIV\Central\1\Cajige)
Design – selection of zones for Corrective Grouting
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

Proposed Programme for Corrective Grouting

LIVERPOOL STREET
LONDON WALL

Programme 06 to give absolute settlement an incremental heave of +5mm in highlighted region

PHASES GJ26, GJ36, GJ27, GJ28

Programme 06 to start 08/11/2012 Night Shift

KEY:
- RP
- CH-R
- LP LC LB
- RL
- No reading
- Discarded data

SURFACE MONITORING INFORMATION:

DAG OF CONTOURS:
For Automatic monitoring: NIGHTSHIFT OF 07/11/12 (19:00 to 07:00 HRS ending next day)
For Manual monitoring: DAYSHIFT OF 07/11/12 ending at 19:00 HRS

KRIGING METHOD USED TO ESTABLISH CONTOURS.

File Reference: 20121108-LIV.Absolute[Whole Site].pdf
Created By: NRA - Checked By: ALE
Printed: 2012-11-08
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

CUMUL REPORT

WHOLE SITE

CORRECTIVE GROUTING
G125 - G127

SURFACE & BASEMENT MONITORING INSTRUMENTATION.

BASIS OF CONTOURS:
NIGHTSHIFT OF 08/11/12 MINUS NIGHTSHIFT OF 07/11/12
I.E. MEDIAN OF 08/11/12 19:00HRS TO 09/11/12 07:00HRS minus
MEDIAN OF 07/11/12 19:00HRS TO 08/11/12 07:00HRS.

VOLUME:
CUT: 6929 L
FILL: 14035 L

Grouted Volume for Cumul: 6521.43 L

Maximum heave: 1.8 mm

KEY:
- VOLUM 4 GROUT INJECTED
- RPR
- SRR
- LP LC LB
- RL
- No reading
- Discarded data

POSITIVE INDICATES HEAVE, NEGATIVE INDICATES SETTLEMENT (mm)
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

LIVERPOOL STREET - Geotechnical Adits

CUMUL REPORT

WHOLE SITE

CORRECTIVE GROUTING PRG6

GJ26 - GJ27

SURFACE & BASEMENT MONITORING INSTRUMENTATION.

Grouted Volume for Cumul: 8972 L

VOLUME:

CUT: 8877 L
FILL: 24245 L

BASIS OF CONTOURS:
NIGHTSHIFT OF 11/11/12 MINUS NIGHTSHIFT OF 07/11/12
I.E. MEDIAN OF 11/11/12 19:00HRS TO 12/11/12 07:00HRS minus
MEDIAN OF 07/11/12 19:00HRS TO 08/11/12 07:00HRS.

Maximum heave: 3.4 mm

KRIGING METHOD USED TO ESTABLISH CONTOURS.

KEY:

- Cumul Grount Injected
- RP
- SHR
- LP LIC LB
- RL
  - No reading
  - Discarded data

POSITIVE INDICATES INCREASED ALTITUDE

NEGATIVE INDICATES NEGATIVE SETTLEMENT (mm)
### Contract C510 Drilling Task
#### Liverpool St

<table>
<thead>
<tr>
<th>Location</th>
<th>No of holes</th>
<th>Drill m</th>
<th>Avge</th>
<th>Grouting Type</th>
<th>Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liv St Adit E</td>
<td>121</td>
<td>5632</td>
<td>46.5</td>
<td>Compensation</td>
<td>88.9mm dia steel TaM x 4mm wall</td>
</tr>
<tr>
<td>Liv St Adit W</td>
<td>118</td>
<td>6210</td>
<td>52.6</td>
<td>Compensation</td>
<td>88.9mm dia steel TaM x 4mm wall</td>
</tr>
<tr>
<td>Moorgate box</td>
<td>168</td>
<td>1559</td>
<td>9.3</td>
<td>Permeation</td>
<td>50mm PVC TaM for permeation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pipe roofing</td>
<td>114mm, 7mm wall Heavy Duty TaM</td>
</tr>
<tr>
<td>Blomfield box</td>
<td>48</td>
<td>1823</td>
<td>38.0</td>
<td>Compensation</td>
<td>88.9mm dia steel TaM x 4mm wall, 114mm, 7mm wall Heavy Duty TaM below Metro</td>
</tr>
<tr>
<td>Electra House</td>
<td>695</td>
<td>4930</td>
<td>7.1</td>
<td>Permeation</td>
<td>50mm PVC TaM</td>
</tr>
<tr>
<td><strong>Sub total Liv St</strong></td>
<td><strong>1150</strong></td>
<td><strong>20154</strong></td>
<td><strong>17.5</strong></td>
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<td></td>
</tr>
</tbody>
</table>

### Contract C510 Drilling Task
#### Whitechapel

<table>
<thead>
<tr>
<th>Location</th>
<th>No of holes</th>
<th>Drill m</th>
<th>Avge</th>
<th>Grouting Type</th>
<th>Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>W'chapel shaft</td>
<td>64</td>
<td>2149</td>
<td>33.6</td>
<td>Compensation</td>
<td>88.9mm dia steel TaM x 4mm wall</td>
</tr>
<tr>
<td><strong>Total @ 15Sep14</strong></td>
<td><strong>1214</strong></td>
<td><strong>22303</strong></td>
<td><strong>18.4</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C510 Injection Quantities

A. Compensation grouting

<table>
<thead>
<tr>
<th>GROUT QUANTITIES (m3)</th>
<th>PRE-CON</th>
<th>ACG</th>
<th>CORRECTIVE</th>
<th>GRAND TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIV</td>
<td>286</td>
<td>2322</td>
<td>3380</td>
<td>5988</td>
</tr>
<tr>
<td>WHI</td>
<td>66</td>
<td>162</td>
<td>225</td>
<td>452</td>
</tr>
</tbody>
</table>

Quantity still to inject - Approx 1000m3 for escalators
- Approx 2000m3 for long-term settlement

B. Permeation Grouting

Volume injected to date - Approx. 1000m3 Microsol
Quantity still to inject - Approx 400m3 for escalators
Crossrail C510 - Liverpool St. - Photos
Steel TAMs
Bond Street Station - Overview
Another site, like Kings Cross, where heavy duty passive arrays may be required - a combined pipe roof / compensation grouting solution?
Crossrail Bond St Station

- Made Ground
- River Terrace Deposits
- London Clay
- Lambeth Group
- Westminster sewer
- Existing UUL
- Escalator Barrel 6/7/8
- Central Line Eastbound
- New Tunnel
- Access Shaft 1 (AS1)
- 3m Exclusion Zone on New Tunnel
- Location beyond end of TBM
- Existing Tunnel Excavation Zone
- Questions Mark

DRAFT FOR COMMENT
Crossrail Bond St Station