Crossrail C510 - Overview
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
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 for structure
  - But beware Utilities
  - Limits set in mm or defined by limits set for utilities

- **Even Settlement**
  - No Issues

- **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.
Crossrail - Settlement Control Criteria - Structural Damage

Extract from Building Research Establishment report on Building Damage Classification, after Burland et al. (1977)
Compensation Grouting
Design Considerations - Geometry
Crossrail C510 - Protection of SCL Linings - Managing Exclusion Zones
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

Diagram showing various zones and components related to Crossrail Bond St. Station.
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 depression</td>
</tr>
<tr>
<td></td>
<td>CP3a / CP3b</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 Enlarge West</td>
<td>PTE Enlarge West</td>
<td>PTW pilot East incl depressurisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH1-2 pilot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH2 pilot and enlargement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP7 / CP8</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 Enlarge East</td>
<td>PTE Enlarge East</td>
<td>Ch1-2 enlargement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP 3 / 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP 1 / 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VD5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VD4</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/RCW pilot and enlarge incl depressurisation CP9 LCW pilot and enlarge VD5 box connection VD7</td>
<td>AP6 PMR lower lift AP10 PMR upper lift</td>
<td>PTE/RCE pilot and enlarge incl depressurisation CP10 CH5 pilot and enlarge AP9 CH6 ES3</td>
</tr>
</tbody>
</table>
C510 Liverpool Street Station Excavation Sequence
Base Bid not including TPO2

Team 1
AP1 pilot and enlarge
VD1
VD2
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

Crossrail - Application of COGNAC Compensation Grouting - example of basis of design
PROGRAMME CONSTRUCTS A MODEL WITH CELLS AND ASSIGNS SETTLEMENT VOLUMES FOR EACH CELL AND PHASE (FROM DATA PROVIDED BY CLIENT / MCR WHERE POSSIBLE)

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 $V_{max} = Vs \times \text{EFFICIENCY CO-EFFICIENT}$ (generally 3 - 5 for London Clay)
VOLUME Vs AND Vmax IS CALCULATED FOR EACH CELL AND COGNAC ALLOCATES 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. 20-25lts) AND A Vmax IS SET FOR EACH INJECTION, GENERALLY ≤ 50lts.

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

<table>
<thead>
<tr>
<th>SITE</th>
<th>Row</th>
<th>Column</th>
<th>Efficiency</th>
<th>ThVLoss</th>
<th>ThSettlement</th>
<th>ThGroutVolume</th>
<th>XCenter</th>
<th>YCenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATM</td>
<td>8</td>
<td>12</td>
<td>5</td>
<td>37.017</td>
<td>-5.923</td>
<td>185.087</td>
<td>-14.326</td>
<td>-275.505</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>1</td>
<td>5</td>
<td>48.3</td>
<td>-7.728</td>
<td>241.501</td>
<td>-24.116</td>
<td>-301.325</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>2</td>
<td>5</td>
<td>41.81</td>
<td>-6.69</td>
<td>209.049</td>
<td>-23.445</td>
<td>-298.917</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>3</td>
<td>5</td>
<td>35.961</td>
<td>-5.754</td>
<td>179.803</td>
<td>-22.774</td>
<td>-296.508</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>31.185</td>
<td>-4.99</td>
<td>155.925</td>
<td>-22.102</td>
<td>-294.1</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>27.842</td>
<td>-4.455</td>
<td>139.209</td>
<td>-21.431</td>
<td>-291.692</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>26.162</td>
<td>-4.186</td>
<td>130.81</td>
<td>-20.76</td>
<td>-289.284</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>7</td>
<td>5</td>
<td>26.209</td>
<td>-4.193</td>
<td>131.045</td>
<td>-20.089</td>
<td>-286.875</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>27.863</td>
<td>-4.458</td>
<td>139.315</td>
<td>-19.418</td>
<td>-284.467</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>10</td>
<td>5</td>
<td>34.676</td>
<td>-5.548</td>
<td>173.378</td>
<td>-18.076</td>
<td>-279.651</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<td>11</td>
<td>5</td>
<td>38.877</td>
<td>-6.22</td>
<td>194.385</td>
<td>-17.405</td>
<td>-277.242</td>
</tr>
<tr>
<td>NATM</td>
<td>9</td>
<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>
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 C510 - Liverpool Street 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
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

1) Early Development of Broadgate Link: Phase 3
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

AS2 tunnel & enlargement

16mm of settlement across façade & interior junction

55mm of settlement across façade & interior junction

[Diagram of the area with annotations and measurements]
Crossrail C510 - Electra House
Electra House
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

1. All dimensions are in meters.
2. All levels are in m NAD83.
3. All angles are in degrees, 7/16ths up to 0.25 degrees decimal.
4. TML positions to be confirmed by site survey.
5. TML final alignment subject to minor changes, depending upon what is revealed by the excavation of all planned trial boring.
6. Boundaries illustrated in solid line are in section and those illustrated in dot line are in plan.
8. Access ramp not previously illustrated, but is to be considered to be the only practicable means of allowing access to such relief.
9. Soft radial coverage of ground treatment from tunnel profile deemed sufficient for tunnel stability, and therefore演奏 on 10027 ground treatment reduction meeting. BBMV however need 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

6mtr offset around new AP9 + CH6 + ES3 UMC

5mtr offset around new AP9 + CH6 + ES3 UMC

103.63  15.13  105.03

AP9

Sewer

HM&C Line Exclusion Zone
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>HMC Grout Curtain</td>
<td>284.6</td>
</tr>
<tr>
<td>HMC Curtain within 3m of Goswell Street Sewer</td>
<td>36.4</td>
</tr>
<tr>
<td>6m CRL Tunnel offset</td>
<td>1406.8</td>
</tr>
<tr>
<td>6m CRL Tunnel offset within 3m of Goswell Street Sewer</td>
<td>206.7</td>
</tr>
<tr>
<td>Total Vol:</td>
<td>1934.5</td>
</tr>
</tbody>
</table>
Electra House - 3D modelling of treatment from Moorgate box

Notes:
1. All dimensions are in millimeters

Key Plan

Front View
Left View
Right View
Electra House - HCL grouted cut-off wall - injection phase detail
Crossrail C510 - Whitechapel Station
Whitechapel Station Site
Whitechapel Station
Site
Whitechapel Station - Key Buildings
Whitechapel Station Settlement Mitigation
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

Logging PC's & Software (SMACS)
Motorised Total Station

Automatic survey of displacements in semi-real time

Process control - Settlement control for key structures

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
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
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

Be sure of what you are monitoring - significant elements only

- 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
• 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
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: 3,278 L
ACG-CPS 2,223 L
PRO-11-CJ44 10,664 L

Maximum heave: 2.8 mm
Maximum settlement: -0.5 mm

File Reference: 20121205-20121204-LW_DELTA_DAILY_WHOLESITE.dwg
Created By: BA - Checked By: MA
Printed: 2012/12/05
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 18:00HRS TO 05/12/12 07:00HRS minus
MEDIAN OF 10/10/12 19:00HRS TO 20/10/12 07:00HRS.

KRIEG METHOD USED TO ESTABLISH CONTOURS.

Grouted volume (cumul) : 148,261.43 L

Maximum heave: 4.7 mm
Maximum settlement: -7.5 mm

File Reference: 20121205-201210/19-3HISTO_5.png
Created By: IBA - Checked By: IBA
Printed: 2012-12-05
CROSSRAIL CS10 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS
LIVERPOOL STREET - Geotechnical Adits
CUMULATIVE REPORT
WHOLE SITE

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.

KRIGING METHOD USED TO ESTABLISH CONTOURS.

FILE REFERENCE: 20121205-20121127-LV_CUMUL [WORLD SITE PRG11] [r1]
CREATED BY: ISA - CHECKED BY: NFA
PRINTED: 2012-12-05

VOLUME:
CUT: 48545 L
FILL: 2611 L

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

KEY:
TUNNEL
Pilot
Smears
Invert
Active Advance
Proportional vol. @ 100 L
MEASUREMENTS
--- RP
--- SHR
--- LP, LC, LB
--- RL
- No reading
X Discarded data
CROSSRAIL C510 - Whitechapel and Liverpool Street Station Tunnels

LIVERPOOL STREET
ZONES: LIV1, LIV2

CUMULATIVE REPORT, from 08:33:32, 24/10/2012 to 18:49:43, 04/12/2012
total grouted volume: 148,261.43 (litres) 947 Sleeves

First Phase: AP7_P_E/0001-0006, Last Phase: CP6_P/0015-0019_075
CROSSRAIL C510 - Whitechapel and Liverpool Street Station Tunnels

LIVERPOOL STREET
ZONES: LIV1, LIV4

CUMULATIVE REPORT, from 09:12:29, 28/11/2012 to 05:49:48, 05/12/2012
total grouted volume: 23,142.17 (litres)  467 Sleeves

# 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  
**Page:** 1 / 30  
**Printed on:** 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>4.6</td>
<td>98</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>5.3</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**
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, GJ26, GJ27, GJ28

Programme 06 to start 08/11/2012 Night Shift

KEY:
- # RP
- # CH-IR
- ## LP LC LB
- ### RL
- X No reading
- V Discarded data

SURFACE MONITORING INFORMATION:

DATA 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.

Printed: 2012-11-06

File Reference: 20121106-LV_ABSOLUTE_WHOLE_SITE.pdf

Created By: NRA - Checked By: ALE
CROSRAIL C510 - Whitechapel and Liverpool Street Station Tunnels

LIVERPOOL STREET
ZONES: LIV1, LIV4
05/12/2012
Instruction Phase(s): GJ25 PRG06 [GJ25 to GJ28], GJ26 PRG06 [GJ25 to GJ28], GJ27 PRG06 [GJ25 to GJ28], GJ28 PRG06 [GJ25 to GJ28]
Max. Volume: 50.00 L  Max Pressure: 8.00 bar  302 Sleeves.
CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS
LIVERPOOL STREET - Geotechnical Adits

CUMUL REPORT
WHOLE SITE

CORRECTIVE GROUTING
G125 - G127

SURFACE & BASEMENT MONITORING INSTRUMENTATION.

Grouted Volume for Cumul: 6521.43 L

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

KINGING METHOD USED TO ESTABLISH CONTOURS.
Maximum heave: 1.8mm

KEY:
- Cumul Grout Injected
- RP
- SHR
- LP LC LB
- RL
- No reading
- Discarded data

File Reference: 20121109-20121107-LV_CUMUL_WHOLE_SITE G127

Created By: DMA - Checked By: NRA

Printed: 2012-11-09
LIVERPOOL STREET - Geotechnical Adits

CROSSRAIL C510 - WHITECHAPEL & LIVERPOOL STREET STATION TUNNELS

CUMUL REPORT
WHOLE SITE
CORRECTIVE GROUTING PRG6
GJ26 - GJ27

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.

SURFACE & BASEMENT MONITORING INSTRUMENTATION.
Grouted Volume for Cumul: 8972 L

VOLUME:
CUT: 8877 L
FILL: 24245 L

Maximum heave: 3.4 mm

FILE REFERENCE: 20121112-20121107-LV_CUMUL_WHOLE_SITE_GJ27.png

KEY:
- CUMUL: GROUT INJECTED
- RP
- SHR
- LP, LC, LB
- RL
- No reading
- Discarded data

POSITIVE INDICATES INCREASE IN SETTLEMENT (mm)
NEGATIVE INDICATES INCREASE IN SETTLEMENT (mm)
### Contract C510 Drilling Task

#### Liverpool St

<table>
<thead>
<tr>
<th>Location</th>
<th>No of holes</th>
<th>Drill m</th>
<th>Avg</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</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pipe roofing</td>
<td>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>
<td></td>
<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>Avg</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>
</tbody>
</table>

**Total @ 15Sep14**

<table>
<thead>
<tr>
<th></th>
<th>1214</th>
<th>22303</th>
<th>18.4</th>
</tr>
</thead>
</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
Crossrail Bond St Station

Notes:
1. All Dimensions in Meters (m).
2. Dimensions are not to be scaled from drawings.
3. For Ground Treatment target zone refer to drawing: Col.CAD440007939REV2 dated 6th June 2019.
5. All Levels are in mLLD.
6. W. Clay is carried out within 5m of a Ground Shelf, the shall be done on an observational basis.
7. If Table is to be operated within 5m of any foundation a risk assessment is required in accordance with the Compensation Grouting Performance Specification.

Key:
- TAM: TAM Tolerance Envelope
- TDR: TDR No Drilling Zone
- NGZ: No Grouting Zone
- LGZ: Low Grade Clay Zone
- LGZ: Low Grade Clay Zone
- RCZ: Rectangular Concession Zone
- C: Existing 40/92
Crossrail Bond St Station