C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - TCR GS4

CRL Document No. **C300-BFK-C4-RGN-CRT00_ST005-51228**

Contract MDL reference: C13.016

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This document has been reviewed by the following individual for coordination, compliance, integration and acceptance and is acceptable for transmission to the above stakeholder for the above stated purpose.

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Stakeholder Organisation	Job Title	Name	Signature	Date	Acceptance
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3. Acceptance by *Crossrail:*

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1. PURPOSE OF THIS REPORT

A number of summary reports (or written submissions) are required by the Works Information within the Compensation Grouting (KC21) (C122-OVE-Z4-RSP-CR001-00010) and Instrumentation and Monitoring (KX10) Materials and Workmanship Specifications (C122-OVE-Z4-RSP-CR001-00007). The relevant Clauses are reproduced in Table 1.1.

The requirements that are addressed in this report are:

- Summary of pre-treatment, concurrent grouting and grout jacking records
- Summary of construction activities
- Comparison of measured movements with predicted movements
- Comparison of measured movements with Specification limits
- Proposal to de-commission Grout Shaft 4 at Tottenham Court Road Station (referred to as TCR within this document)

As required by the Compensation Grouting Specification KC21 Clause KC21.3220(c), a written submission is required to justify the de-commissioning of compensation grouting facilities a minimum of 3 months after the completion of construction. Comparisons are made to the Compensation Grouting Performance Requirements defined in Specification for the Control of Ground Movement (C122-OVE-C2-RSP-C125-00001) Clause 3.2.5.1 and 3.2.5.2.

All BFK excavation (tunnelling) works within the plan extent of the compensation grouting arrays from TCR Station Grout Shaft 4 were completed by August 2014. A grout jacking episode was implemented after the completion of tunnelling which was completed in September 2014. An abridged version of this report was issued in October 2014, about 3 months after the end of tunnelling, to justify de-commissioning of the grout shaft: this report was accepted by CRL and the grout shaft was subsequently de-commissioned (C300-CCM-09098 and C300-CCM-09389).

This report aims to summarise the relevant construction, compensation grouting and monitoring information for Grout Shaft 4 at TCR Station and includes manual monitoring up to September 2015 when the manual monitoring within the GS4 area was de-scoped under C300-PMI-01858. The purpose of this report is therefore to fully document the justification for the decommissioning of the shaft and also to provide a close-out report for all instrumentation, except the ATS network for which a separate report has been prepared (C300-BFK-C4-RGN-CRT00_ST005-53008).

The requirements of KC21.3228(e) & (f) not fulfilled by this report are:

- H&S file – submitted separately for construction and for de-commissioning.
- Grout shaft & array construction – submitted separately.

The requirements of KX10.2013 and KX10.2014 not fulfilled by this report are:

- Updated as-built record and status for all instrumentation which will be supplied as co-ordinates and digital data for incorporation into UCIMS.

The HLCs have been used for construction control during compensation grouting works and a separate “close-out” report is not required, since the 2mm/year criterion does not apply. Examples of data from the HLC in the GS4 area are included in Appendix B, together with crack meter data.

Table 1.1 Extracts from Works Information

KC21.3220 Compensation Grouting - General Requirements

c) The grouting facilities shall be maintained in place for a minimum of three months after the end of excavations or other construction activities which could produce settlement within the zone of compensation grouting. The grouting facilities shall be maintained for a further period until such time that the *Contractor* can demonstrate, by written submission, to the satisfaction of the *Project Manager*, that the specified criteria on movement specified in Volume 2C, *Specification* for the Control of Ground Movements will not be exceeded as a result of post-construction long term settlement. Automatic monitoring can be decommissioned at the same time as the grouting facilities whereas precise levelling points will be maintained in place and monitored until the *Contractor* can demonstrate compliance with the specified criteria for the cessation of monitoring to the satisfaction of the *Project Manager*.

KC21.3228 Reporting

e) Within one month of the completion of concurrent grouting the *Contractor* will supply a summary report of the grout shaft and array construction, pre-treatment and concurrent grouting, site H&S file, ground movement monitoring, construction activities and a comparison of observed behaviour with both predicted movements and the *Specification* limits on movement. This report is to be updated one month after the completion of any episodes of grout jacking.

f) A final version of the report will be prepared to incorporate the justification for de-commissioning, as required by Compensation Grouting - general requirements, and as-built records of the reinstatement of grout shafts and arrays including H&S closeout reporting.

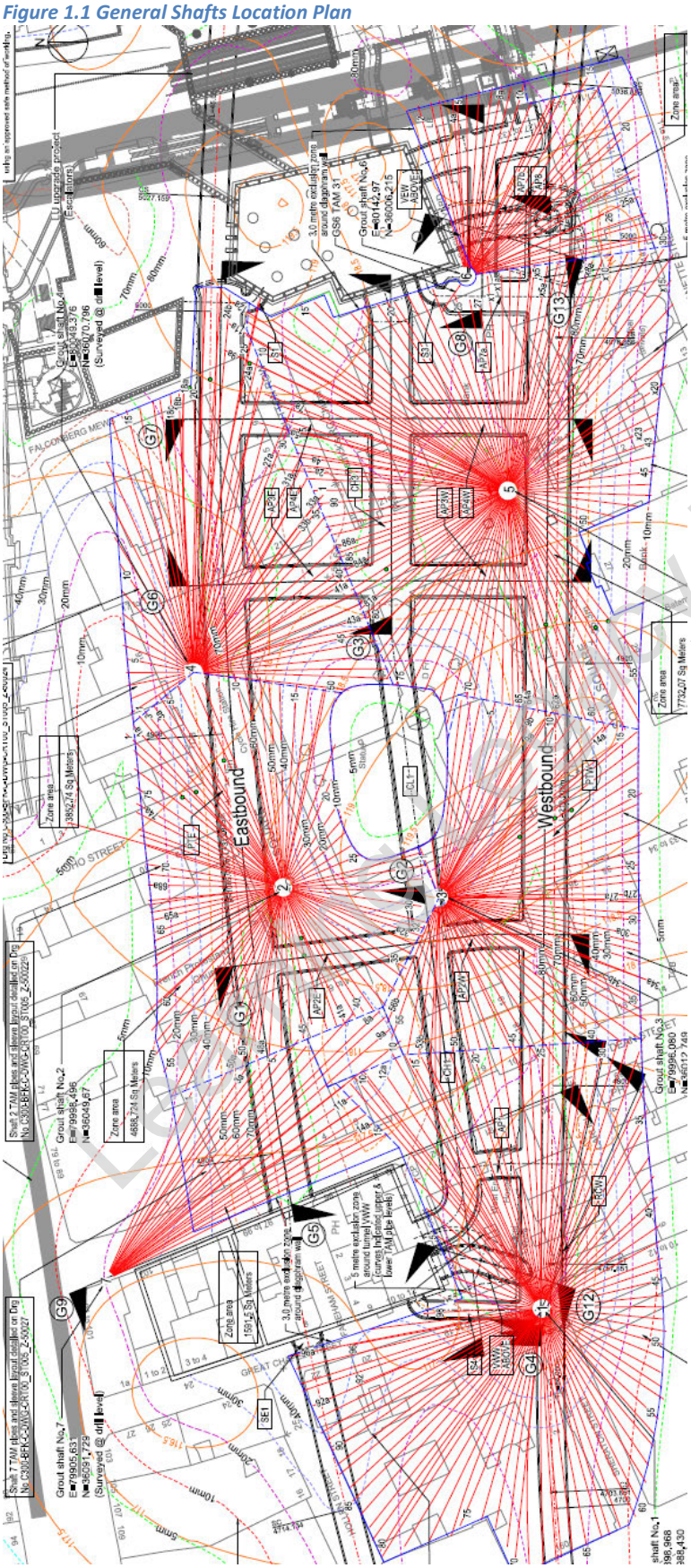
KX10.2113 Final Report

Within three months after completion of the Works the *Contractor* shall issue a final report providing an updated as-built record and status for all instrumentation. The report shall include a summary of the observed movements for each monitoring area (relative to the construction works) and appropriate *Drawings*. The report shall be submitted to the *Project Manager* in an approved format.

KX10.2114 Close-Out Reports

Prior to the de-commissioning of any instrumentation, the *Contractor* shall produce a "close-out" report which summarises the data from the instrumentation the *Contractor* wishes to remove and relates it to the construction activities which produced any observed changes. The report shall demonstrate that the rate of change in the data has reached an acceptably small rate either in accordance with specified rates or, where no rate is specified, in relation to trigger values and an evaluation of any potential residual risks.

Figure 1.1 General Shafts Location Plan



2. CONSTRUCTION WORKS PROGRESS

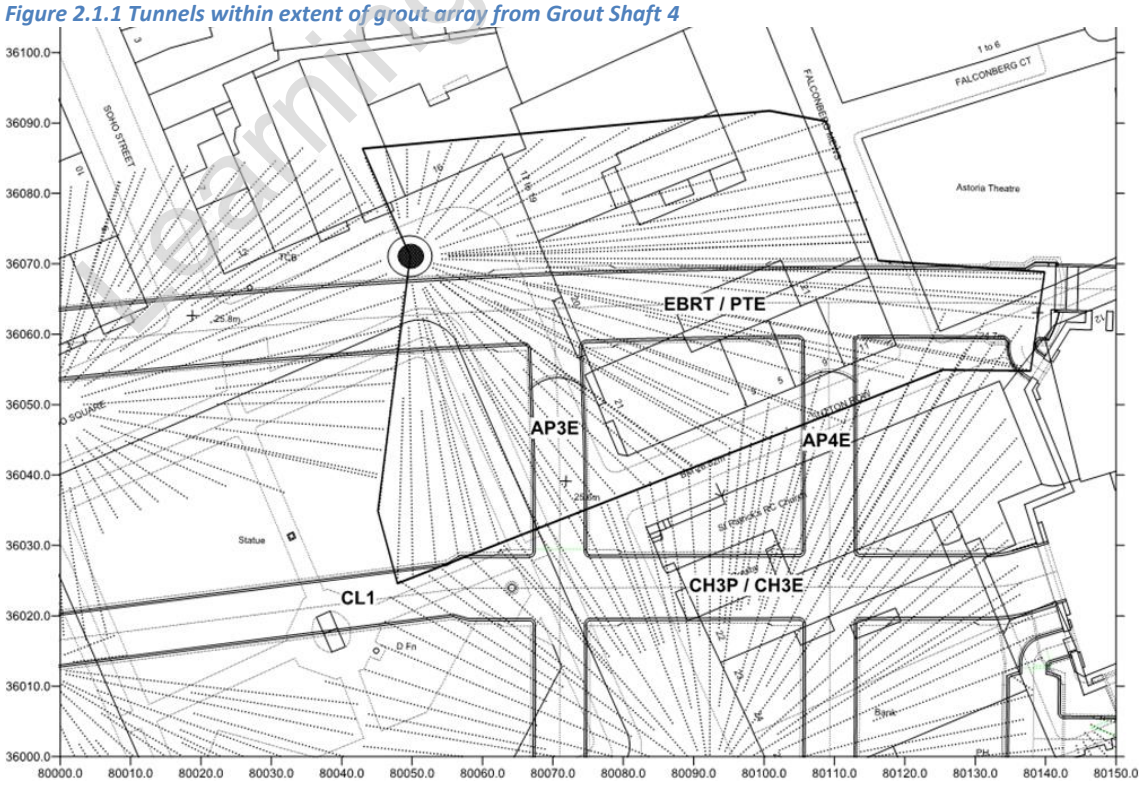
2.1. Tunnels

Table 2.1 and Figure 2.1.1 show the tunnel construction works undertaken within the footprint of the compensation grouting arrays installed from Grout Shaft 4 at TCR Station. Tunnel excavation commenced with CL1 in June 2013 and was completed with the junction between AP3E and PTE in August 2014. To facilitate comparison of monitoring data with construction activities 6 periods (A to F) have been assigned. Period F is the post-construction period up to September 2015. Tunnelling was completed in 4 of these periods (B, C, D & E) as shown in Table 2.1. The main construction activities in each period are summarised in Table 2.2.

Table 2.1 Progress of C300/C410 works at TCR GS4 area.

PERIOD	TUNNEL	START DATE	END DATE
A	Shaft Sinking	28/08/2012	18/10/2012
	TaM Drilling	19/11/2012	15/02/2013
A/B/C	TCRSU Goslett Yard Box below Level -3	05/09/2012	12/08/2013
B	Central Link 1 (CL1)	11/06/2013	21/06/2013
	Lower Concourse Tunnel 3 (CH3)	22/06/2013	24/07/2013
C	Eastbound Running Tunnel (EBRT)	07/08/2013	09/09/2013
D	Access Passage 3 East (AP3E) section 1 from CH3	29/09/2013	10/10/2013
	Access Passage 4 East (AP4E) section 1 from CH3	27/09/2013	08/10/2013
E	Platform Tunnel Eastbound (PTE)	13/06/2014	25/07/2014
	Access Passage 4 East (AP4E) junction with PTE	05/08/2014	08/08/2014
	Access Passage 3 East (AP3E) junction with PTE	10/08/2014	13/08/2014

Figure 2.1.1 Tunnels within extent of grout array from Grout Shaft 4



2.2. Other construction works

Works by BFK prior to the commencement of tunnelling included:

- Sinking of Grout Shaft 4
- Drilling for installation of TaMs
- Pre-treatment grouting

Works by Others prior to the start of tunnelling included:

- Basement extension to St. Patrick's Church
- TCRSU (Tottenham Court Road Station Upgrade) works – Goslett Yard Box (see Appendix C for details)

Works by Others during tunnelling comprised:

- TCRSU works – Goslett Yard Box (see Appendix C for details).

2.3. Compensation Grouting

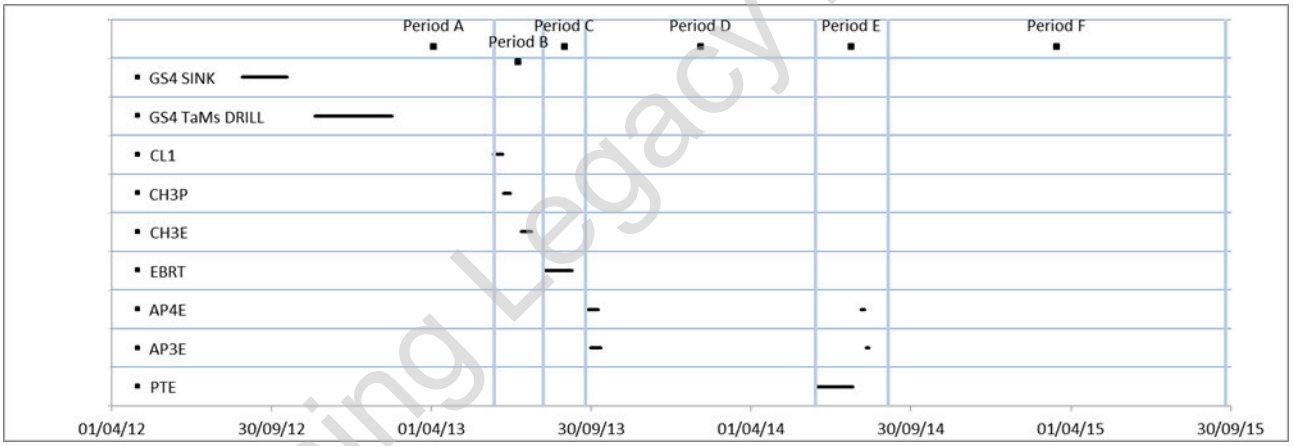
The volume of grout injected from TCR GS4 is plotted against time on Figure 2.3.1 together with a plot of when each of the tunnels was constructed. Figure 2.3.1 shows that pre-treatment comprised approximately 30m^3 injected prior to tunnelling, concurrent grouting just over 120m^3 and grout jacking under 20m^3. Concurrent grouting was undertaken with all tunnels except the EBRT, CL1 and the AP3E/ PTE AP4E / PTE junctions. A VE proposal was implemented to avoid any delays to the running tunnel drive which allowed grouting to be undertaken pre- and post- tunnelling (C300-PMI-00434) – the volume of grout associated with this is included under grout jacking. The AP / PTE junctions are a short length of tunnel and the extent of the exclusion zones over the tunnel face, as defined in the SCoGM, rendered concurrent grouting impractical. CL1 is a temporary tunnel below the centre of Soho Square and CRL deemed that concurrent compensation grouting was not mandatory. A 3m exclusion zone was also mandated around the TCRSU excavations at Faconberg Shaft and Goslett Yar Box (see Appendix C for locations).

Figures 2.3.2 to 2.3.4 show contours of the total grout intensity for each of the three types of grouting (pretreatment, concurrent and jacking respectively) and a cumulative total of all grout injected from TCR GS4 is shown in Figure 2.3.5 The grout intensity is the equivalent thickness of grout injected into the ground in millimetres. The methodology used to generate these contours is described in Appendix A. Comparison of the contour plots of grout intensity with observed settlements is discussed in Section 3.

Table 2.2 Construction Periods for works in TCR GS4 area.

PERIOD	START DATE	END DATE	MAIN WORKS
A	28/08/2012	11/06/2013	Shaft Sinking, TAM Drilling, Pre-treatment, TCRSU_GYB
B	11/06/2013	07/08/2013	Central Link 1 (CL1), Lower Concourse Tunnel 3 (CH3), concurrent grouting, TCRSU_GYB
C	07/08/2013	24/09/2013	Eastbound Running Tunnel (EBRT), TCRSU_GYB
D	24/09/2013	13/06/2014	Access Passage 3 East (AP3E), Access Passage 4 East (AP4E), concurrent grouting
E	13/06/2014	04/09/2014	Platform Tunnel Eastbound (PTE), Access Passage 3 East (AP3E) & Access Passage 4 East (AP4E) junctions, concurrent grouting and jack grouting
F	04/09/2014	25/09/2015	Post Construction

Figure 2.3.1 Volume of grout injected from TCR GS4 by grouting type.



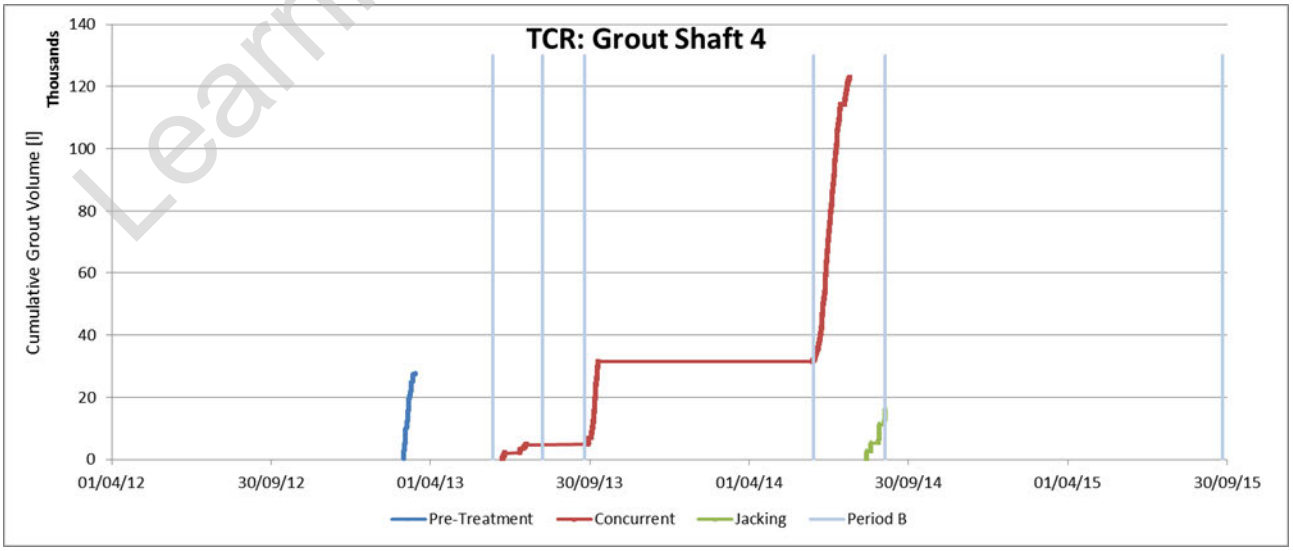


Figure 2.3.2 Distribution of grout injected from TCR GS4: Pretreatment grouting. Grout Intensity (mm).

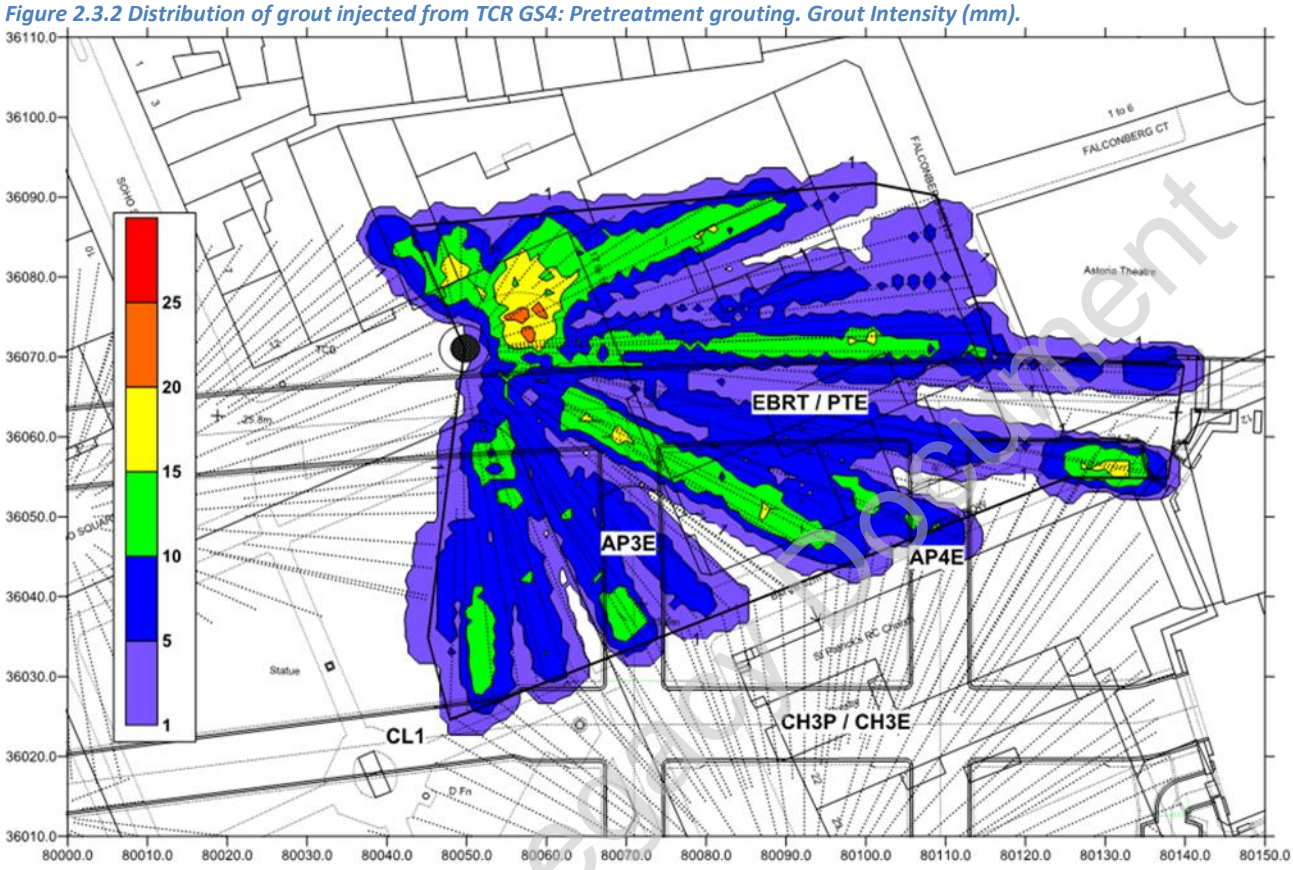


Figure 2.3.3 Distribution of grout injected from TCR GS4: Concurrent grouting. Grout Intensity (mm).

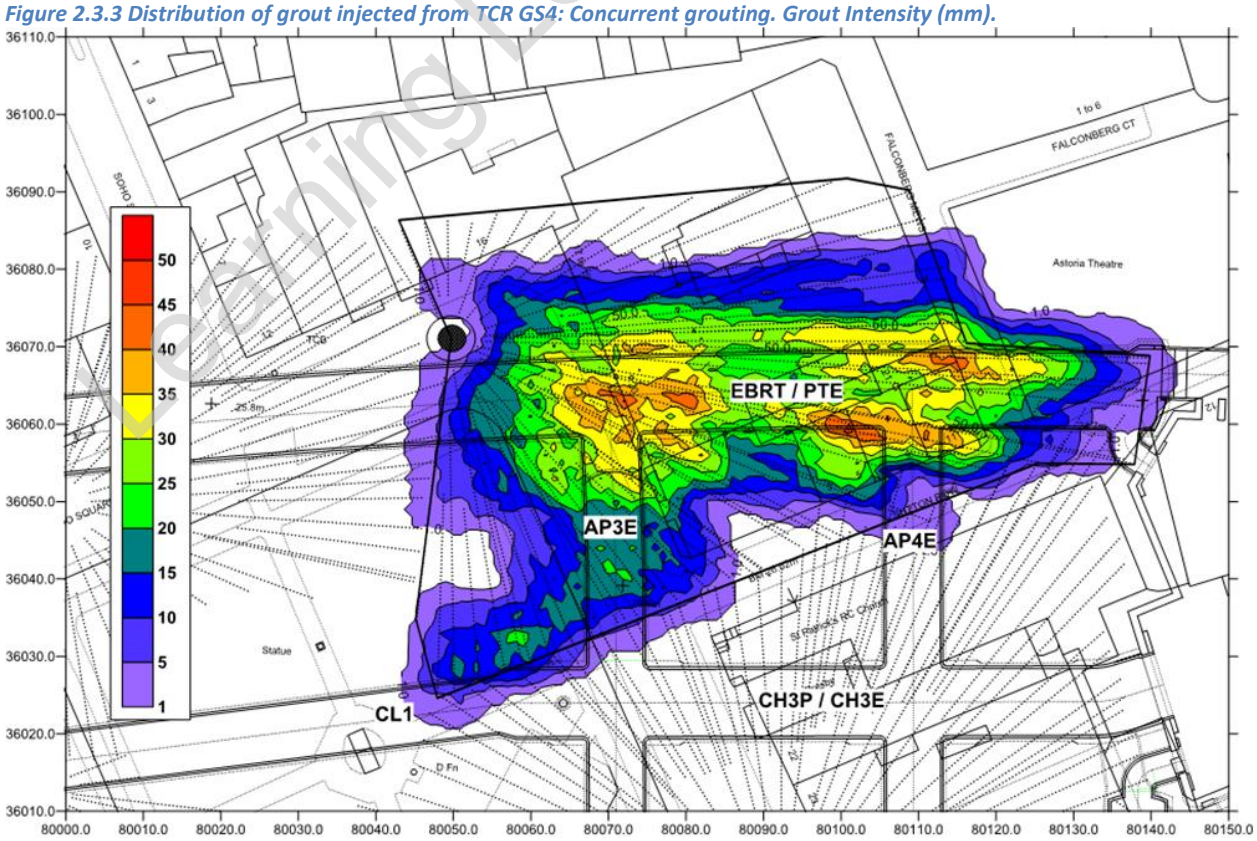


Figure 2.3.4 Distribution of grout injected from TCR GS4: Jack grouting. Grout Intensity (mm).

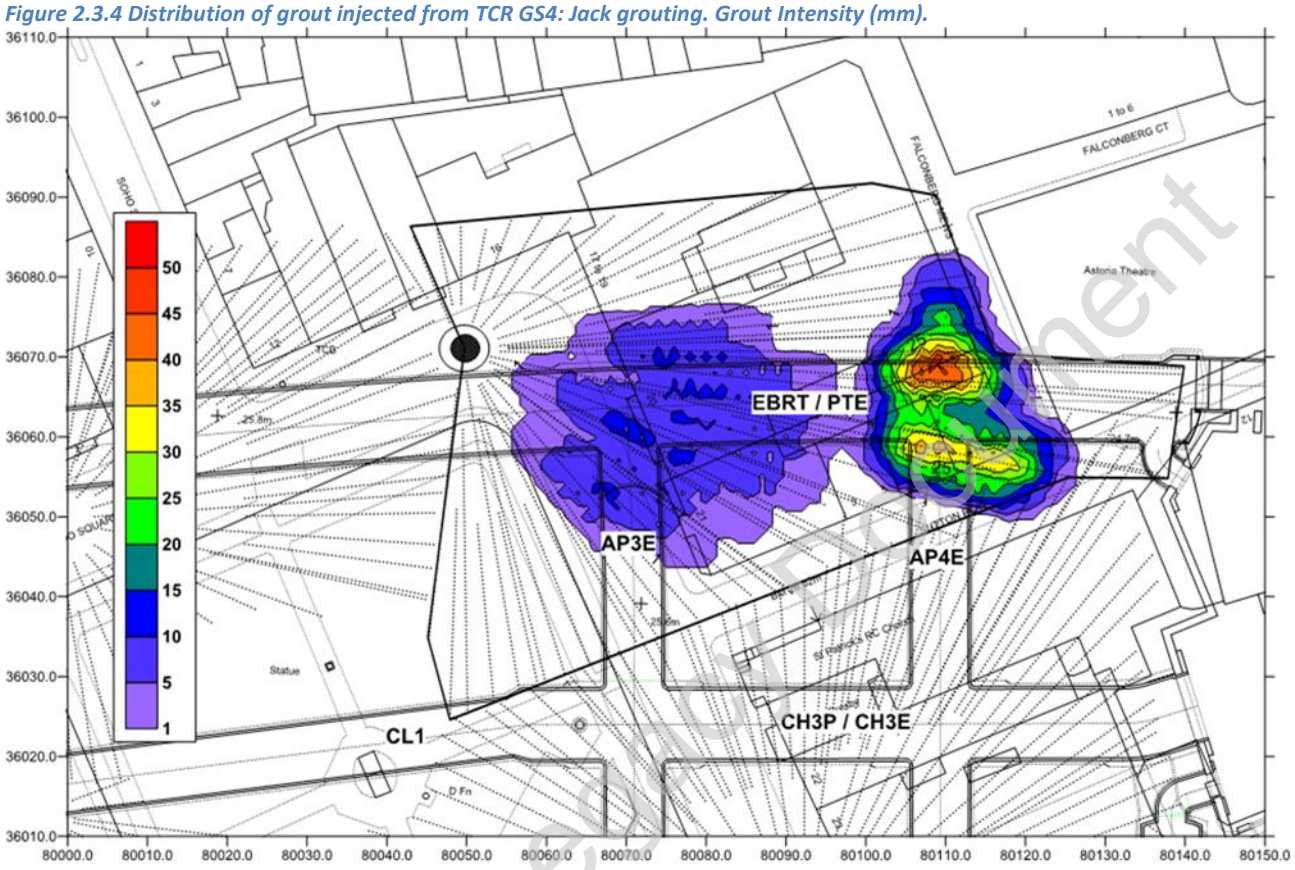
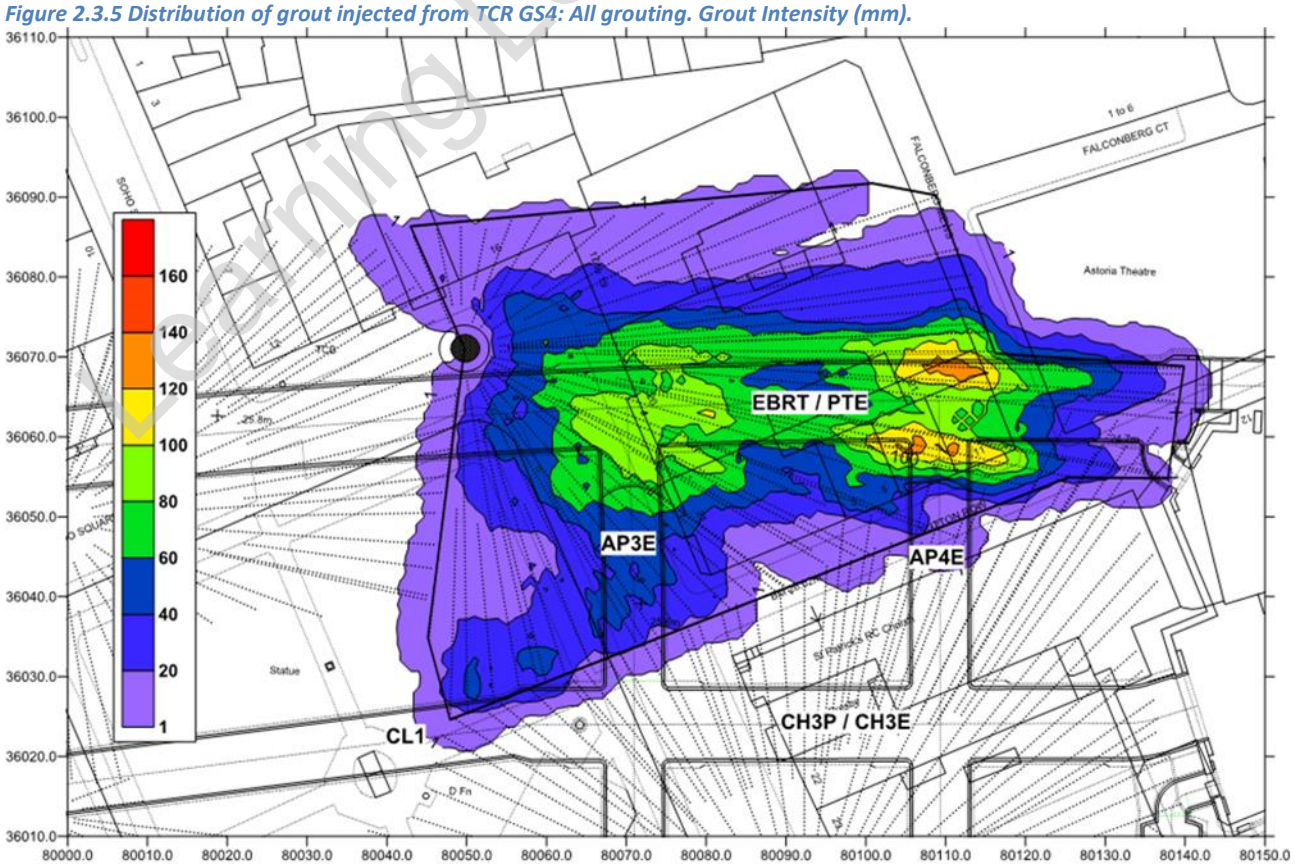


Figure 2.3.5 Distribution of grout injected from TCR GS4: All grouting. Grout Intensity (mm).



3. COMPARISON OF OBSERVED AND PREDICTED GREENFIELD SETTLEMENT

3.1. Settlement Overview

Contours of total predicted short term greenfield settlement (supplied by C122) are shown in Figure 3.1.1. The measured settlement at the end of construction (Period E) in September 2014, including consolidation settlement during the period of construction is shown in Figure 3.1.2.

The following points are noted:

- The effects of the TCRSU works (see Appendix C) are included in the volume loss contour. The BFK monitoring data has been adjusted to take into account movements generated by the TCRSU works (see Section 3.2);
- Settlements are generally less than 50% of the predicted values, notwithstanding that the observed movements include a significant proportion of consolidation settlement over the 2½ year construction period.
- The most obvious differences between the predictions and the observations are:
    - the maximum observed settlement contour is 30mm (close to the shaft) compared to the predicted greenfield settlement of 100mm over the east end of PTE;
    - the spacing of the contours implies that actual slopes are much less than the volume loss prediction;
    - the extent of the zone of settlement cannot be determined due to the adjacent TCRSU works.

Figure 3.1.1 Predicted greenfield settlement contour (supplied by C122)

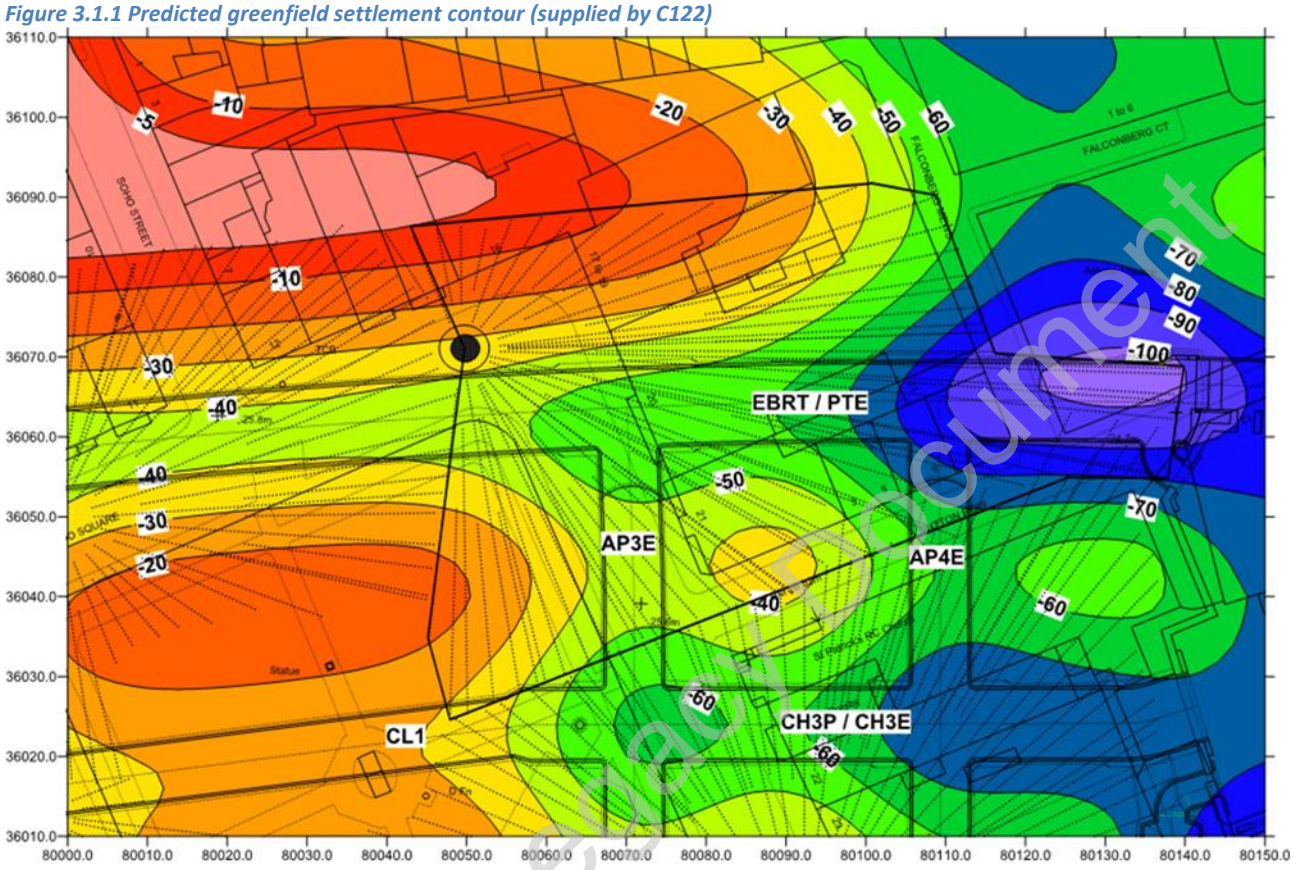
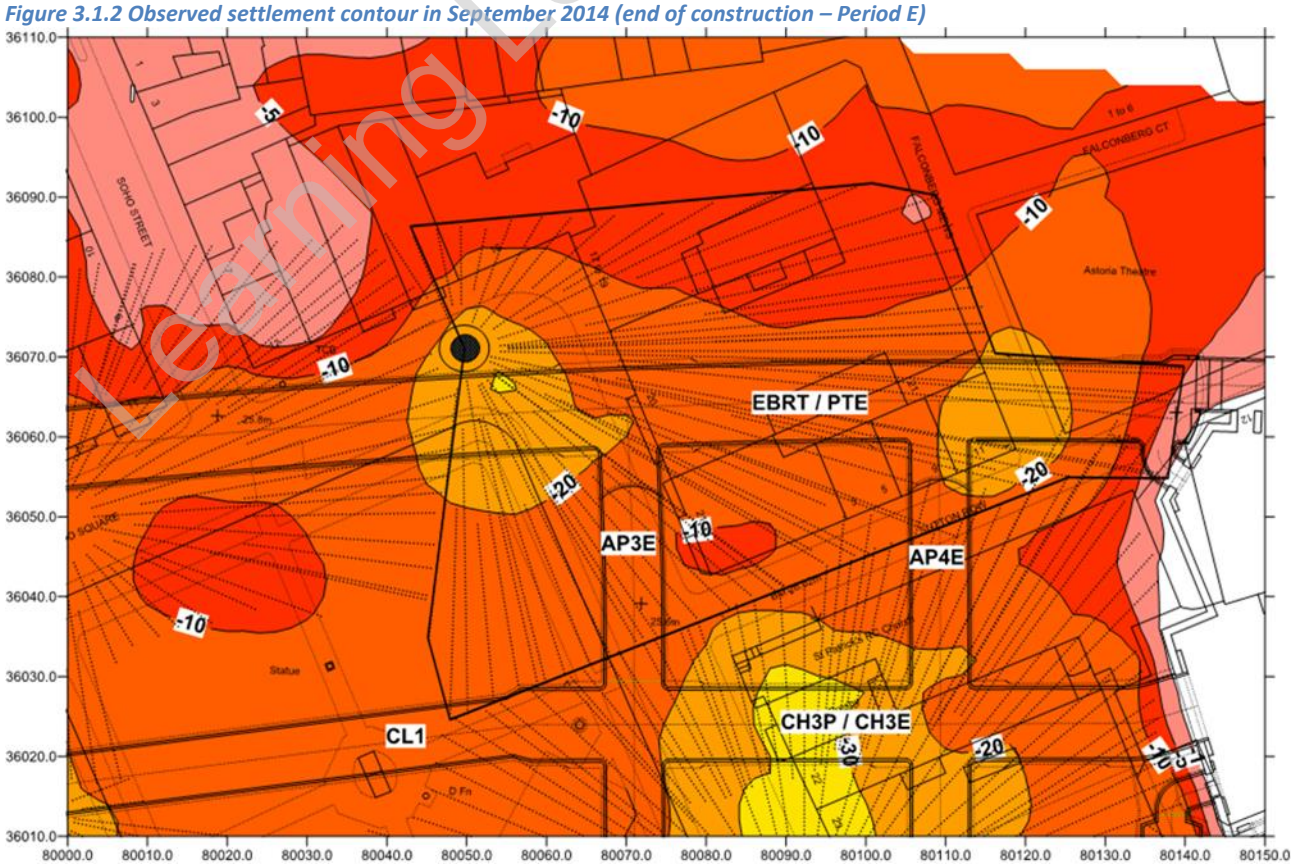


Figure 3.1.2 Observed settlement contour in September 2014 (end of construction – Period E)



In order to compare the predicted and actual movements at various stages of construction, the overall monitoring period from April 2012 to the cessation of monitoring (under PMI C300-PMI-01858) in September 2015 has been divided into a number of periods, based largely on tunnel excavation progress. TCRSU works were carried out throughout all periods (see Appendix C). The construction activities completed in each period are summarised in Table 2.2.

The following plots are presented, as appropriate, for each period:

1. Volume loss settlement for tunnels constructed in the Period at the specified volume loss values;
2. Observed change in settlement within the Period;
3. Total settlement at the end of the Period;
4. Contour of grout intensity for concurrent grouting within the Period;
5. Contour of grout intensity for grout jacking within the Period

3.2. Period A: 01/04/12 – 11/06/13: Shaft sinking, TaMs drilling, Pre-treatment

Period A includes all of the BFK preparatory work prior to the commencement of tunnelling, including shaft sinking, TaMs drilling and pre-treatment from TCR GS4. Extensive works had been undertaken for the LU TCRSU project prior to the start of BFK monitoring and adjustments have been applied based on the contour shown in Figure 3.2.1: the effects are significant within and to the north of the GS4 area where up to 15mm settlement is indicated. The contour is based on monitoring data from TCRSU provided by CRL and on the results of joint surveys undertaken by BFK and the TCRSU contractor in April and May 2013. The contour represents the best estimate of movements at 24/04/13 after the completion of BFK shaft sinking, TaM drilling and Pretreatment grouting.

No calculated short term movements associated with the TCRSU works completed in Period A is available.

The observed settlements at the end of Period A (adjusted to allow for movements prior to the start of BFK monitoring) are shown on Figure 3.2.2. . A maximum settlement of 15mm is indicated to the north of the GS4 arrays. Within the GS area, the maximum settlement is about 10mm local to the shaft as a result of shaft sinking and TaM drilling. Figure 3.2.3 shows the contours of grout intensity from pre-treatment. In general, a grout intensity up to 15mm was injected, but additional injections were made in the area of greatest settlement, giving a grout intensity of up to 25mm.

Figure 3.2.1 Contours of observed settlement based on TCRSU data.

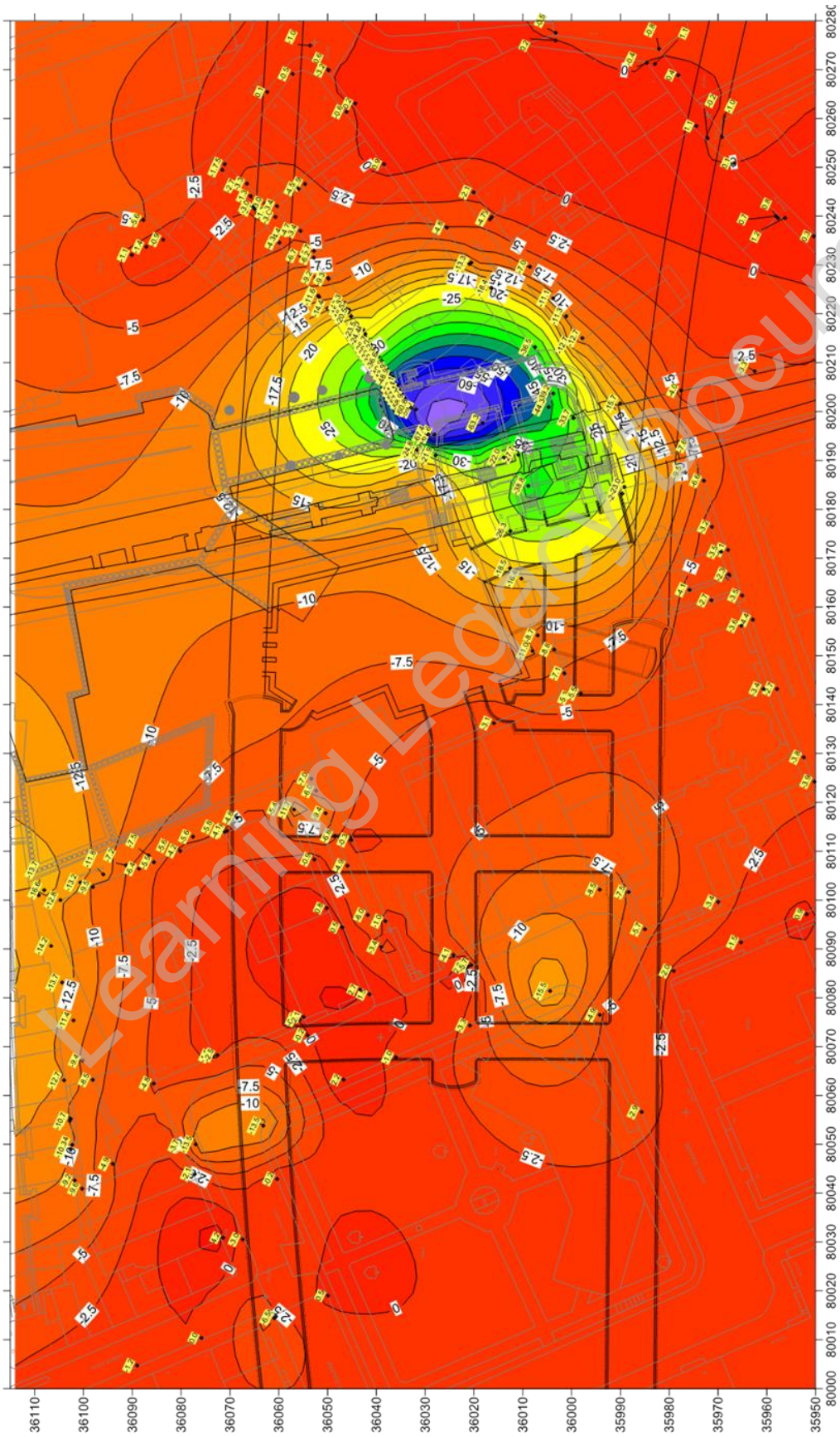


Figure 3.2.2 Period A: Total measured settlement (including adjustments for movements prior to BFK monitoring)

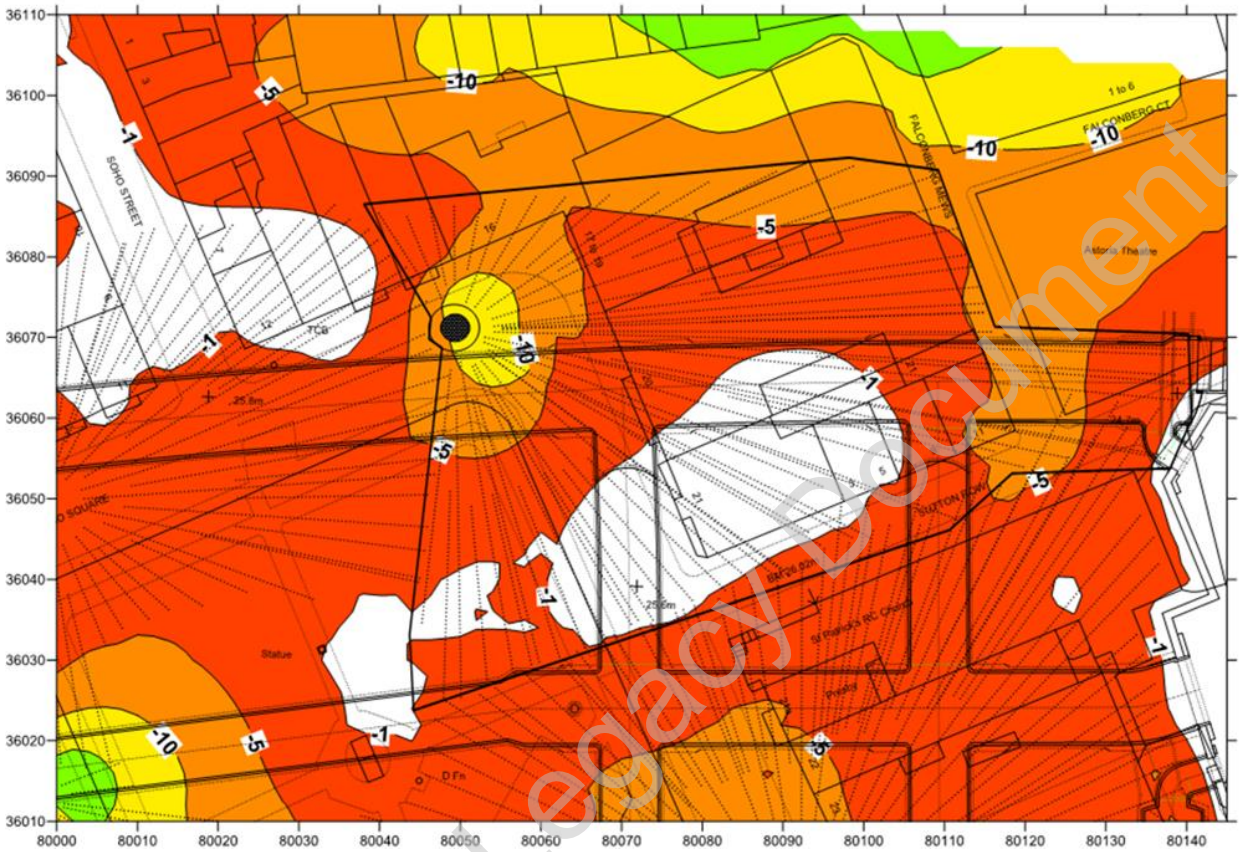
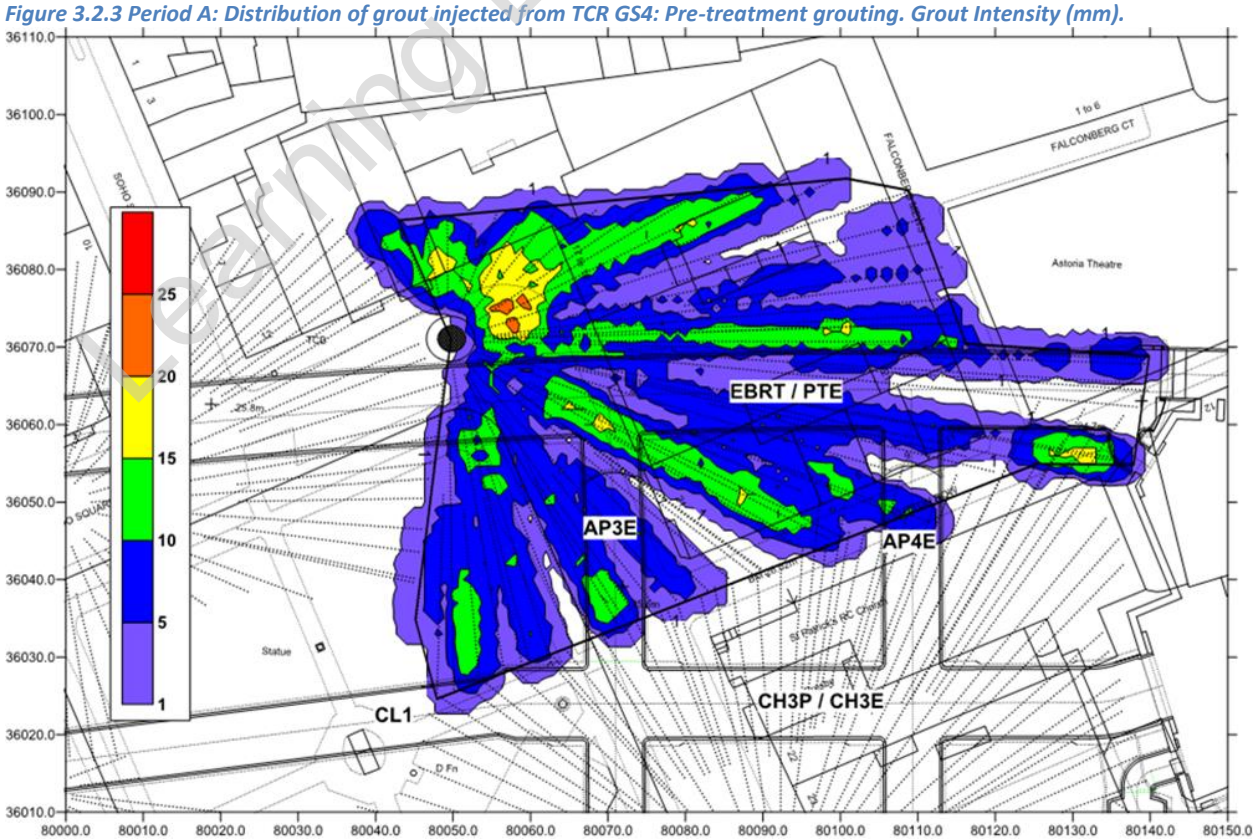
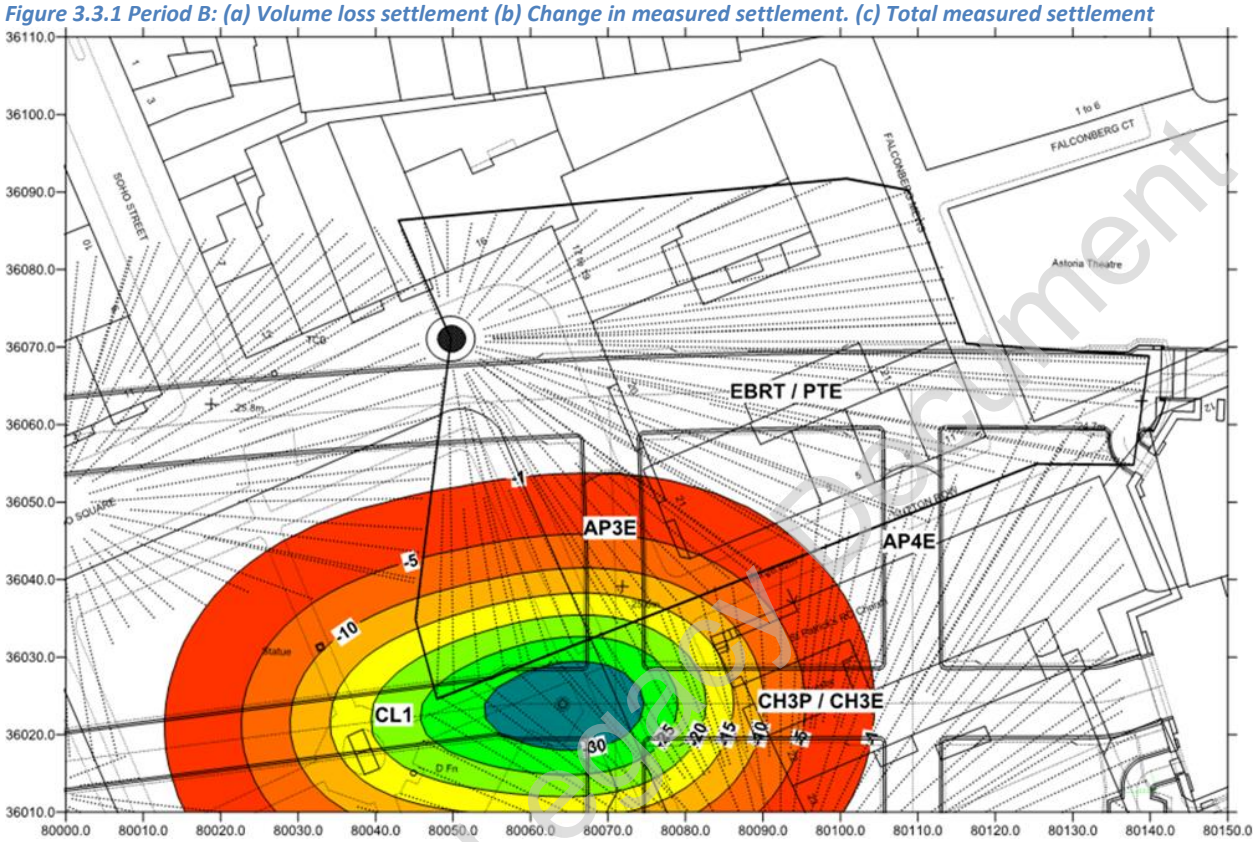


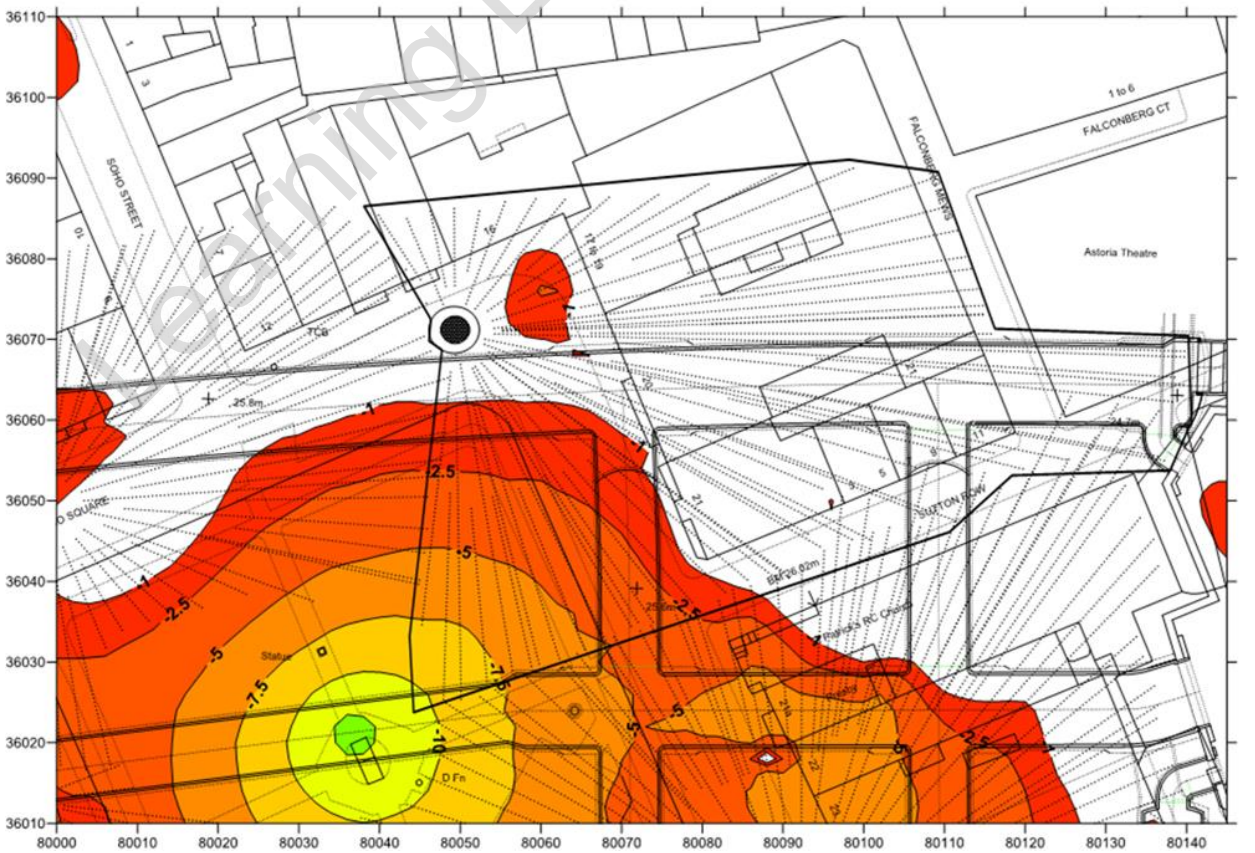
Figure 3.2.3 Period A: Distribution of grout injected from TCR GS4: Pre-treatment grouting. Grout Intensity (mm).



3.3. Period B: 11/06/13 - 07/08/13 CL1, CH3P, CH3E, concurrent grouting

Figure 3.3.1 Period B: (a) Volume loss settlement (b) Change in measured settlement. (c) Total measured settlement





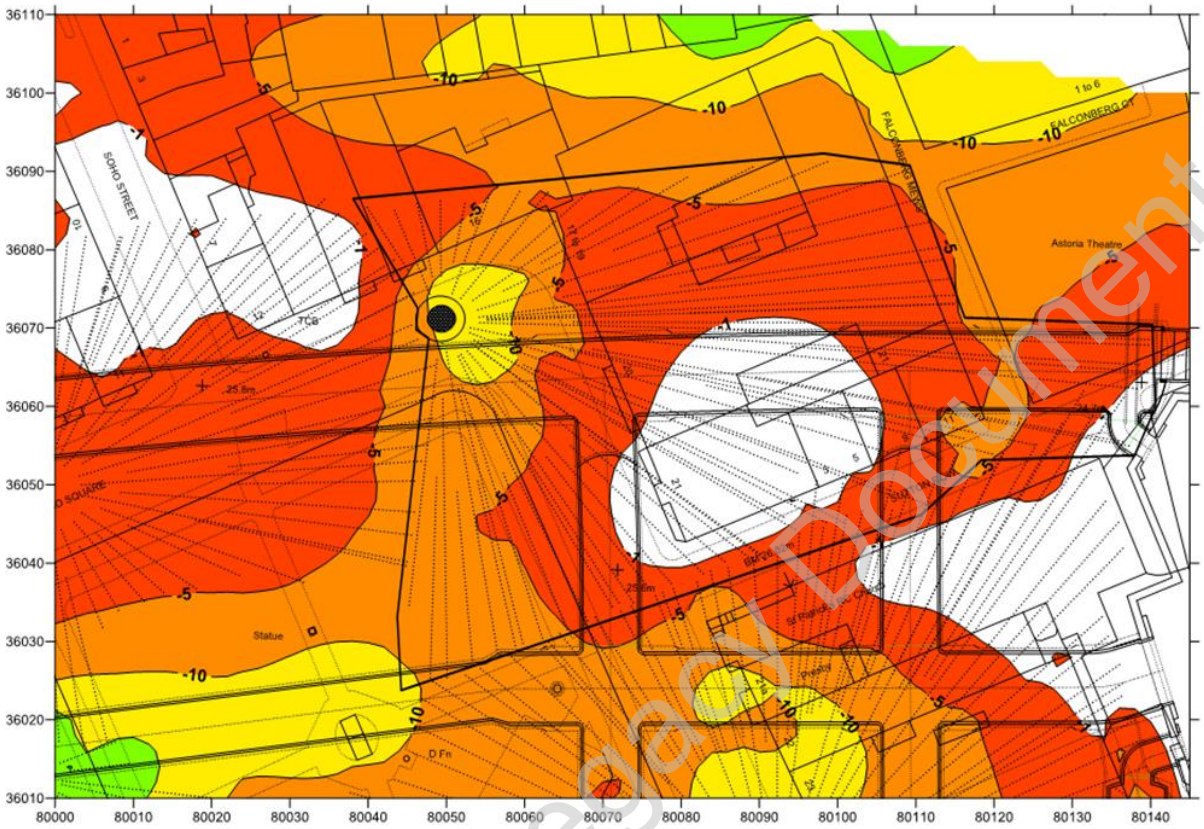


Figure 3.3.2 Period B: Distribution of grout injected from TCR GS4: Concurrent Grouting. Grout Intensity (mm).

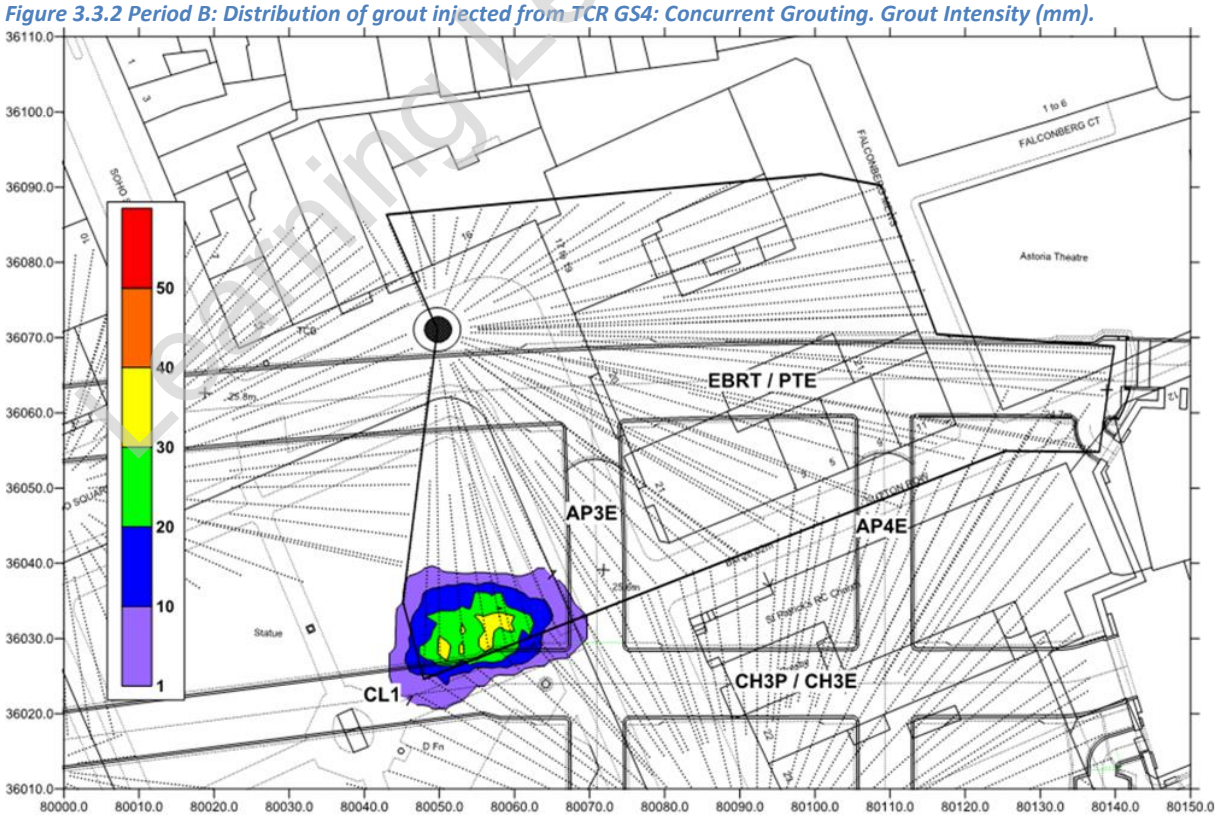


Figure 3.3.1(a) shows the calculated volume loss contour associated with CL1 and the initial section of CH3 (both pilot and enlargement). The maximum settlement in the GS4 area is just less than 30mm.

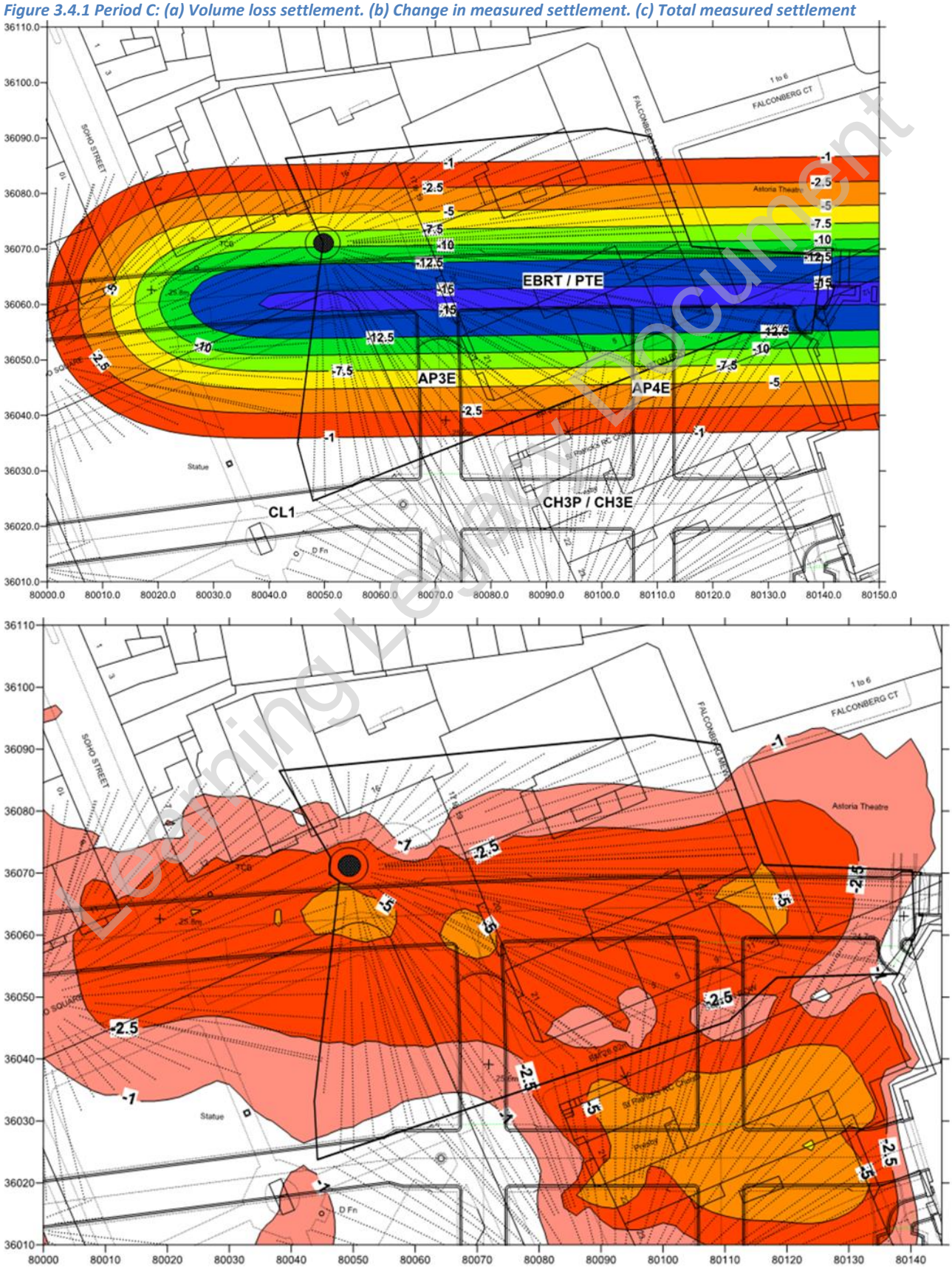
Figure 3.3.1(b) shows that there was a maximum of 10mm recorded in Period B at the south-west corner. No concurrent grouting was undertaken with CL1 and it is evident that the grouting with CH3P and CH3E was effective in reducing movements generated by this tunnel. Negligible change is indicated within the remainder of the GS4 arrays, outside the ZoI of the tunnelling.

The settlement resulting from CL1 is more clearly shown in the total settlement contour presented in Figure 3.3.1(c).

The concurrent grouting undertaken with CH3 from GS4 is limited to the south-west corner (Figure 3.3.2). The majority of injections were undertaken from GS5 TaMs. The location of the injections is coincident with the area of reduced settlement.

3.4. Period C: 07/08/13 – 24/09/13 EBRT

Figure 3.4.1 Period C: (a) Volume loss settlement. (b) Change in measured settlement. (c) Total measured settlement



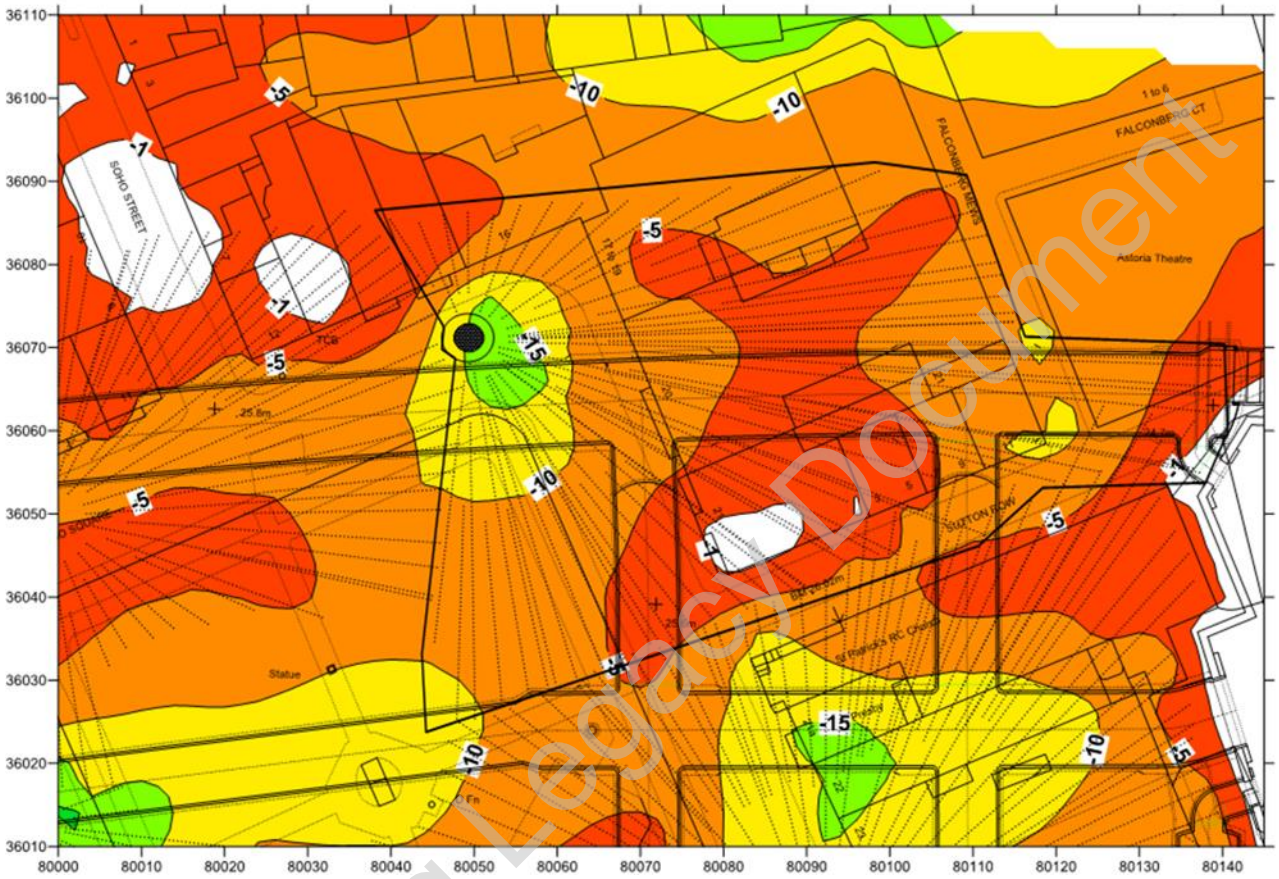


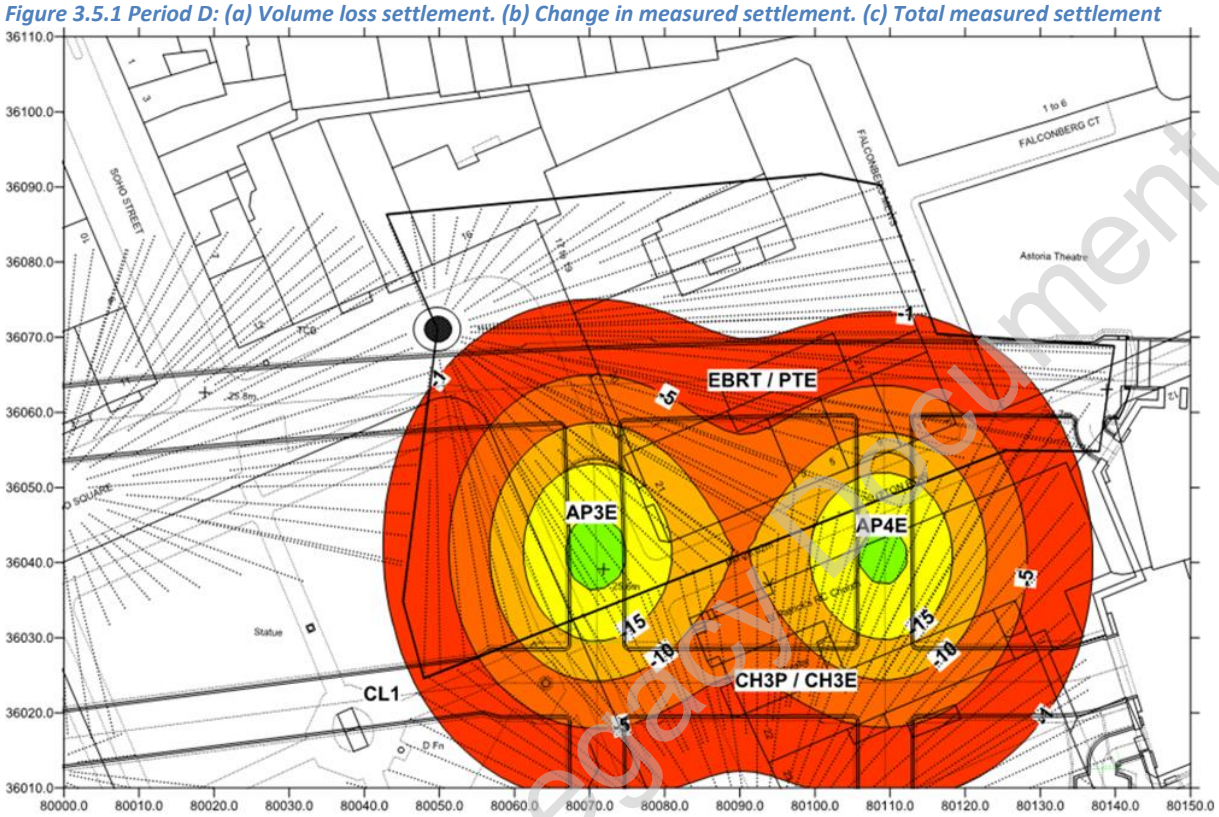
Figure 3.4.1(a) shows that over 15mm volume loss settlement was anticipated for the EBRT. Figure 3.4.1(b) shows the recorded settlement which has a maximum of ~5mm locally over the EBRT. No compensation grouting was undertaken based on a VE proposal (C300-PMI-00434, see Section 2.3) and it can therefore be inferred that the actual volume loss was much smaller than the specified limit of 1%. From Figure 3.4.1(b), settlement of up to 10mm is evident to the south of the GS4 area due to the completion of CH3.

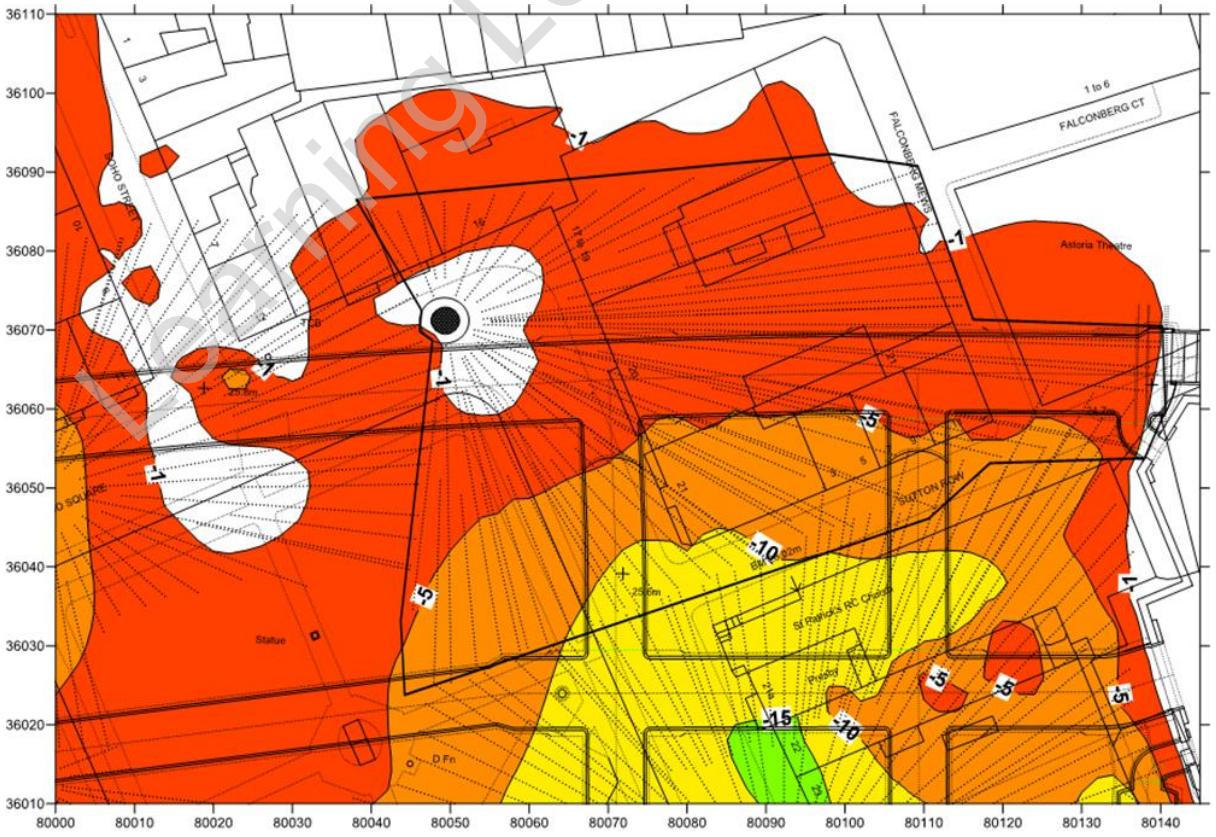
The maximum movement within the TCR GS4 area at the end of Period C had increased to almost 20mm. (Figure 3.4.1(c)) locally close to the shaft. Over the majority of the area, settlement remained at less than 10mm.

No grout jacking was carried out in this period.

3.5. Period D: 24/09/13 - 13/06/14 AP3E; AP4E, concurrent grouting

Figure 3.5.1 Period D: (a) Volume loss settlement. (b) Change in measured settlement. (c) Total measured settlement





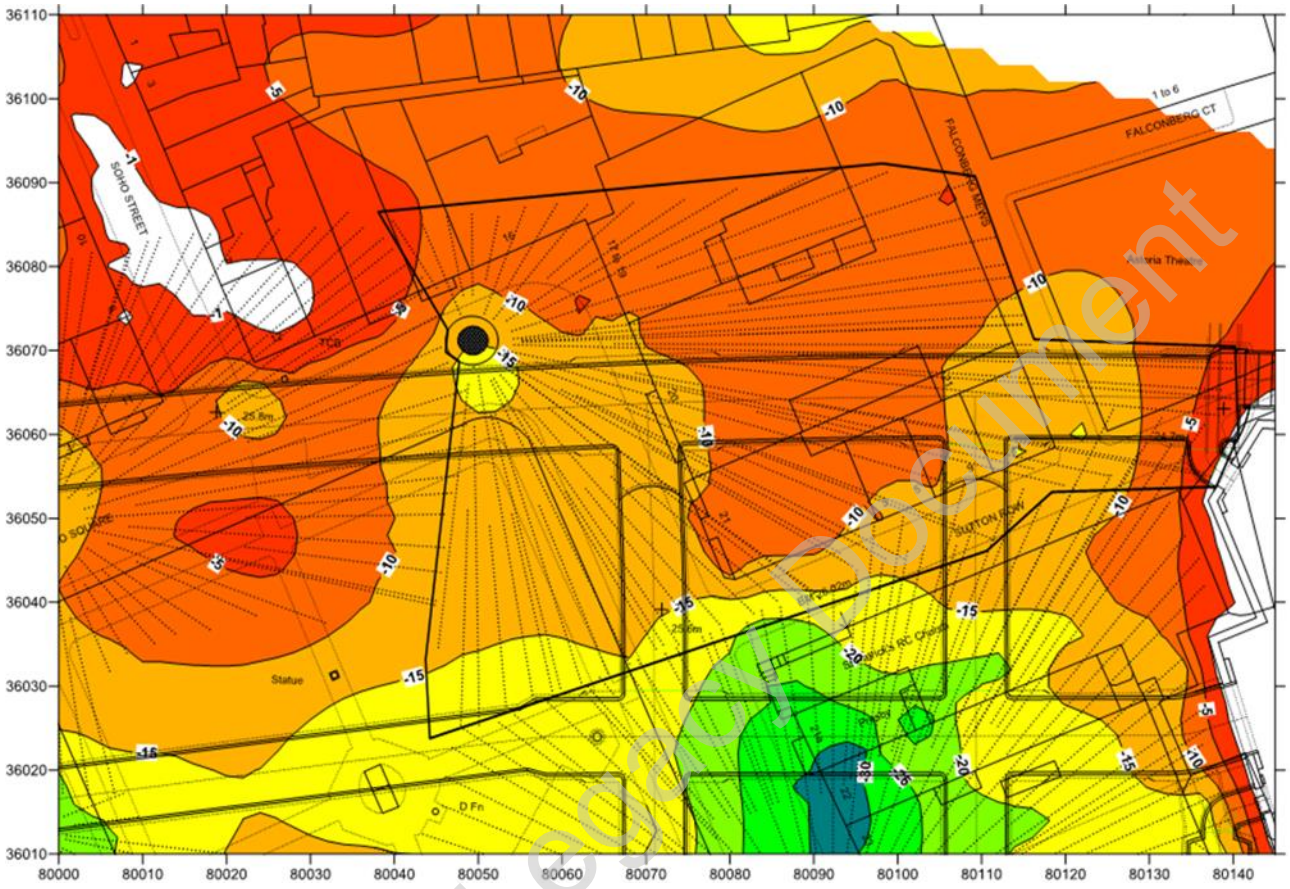
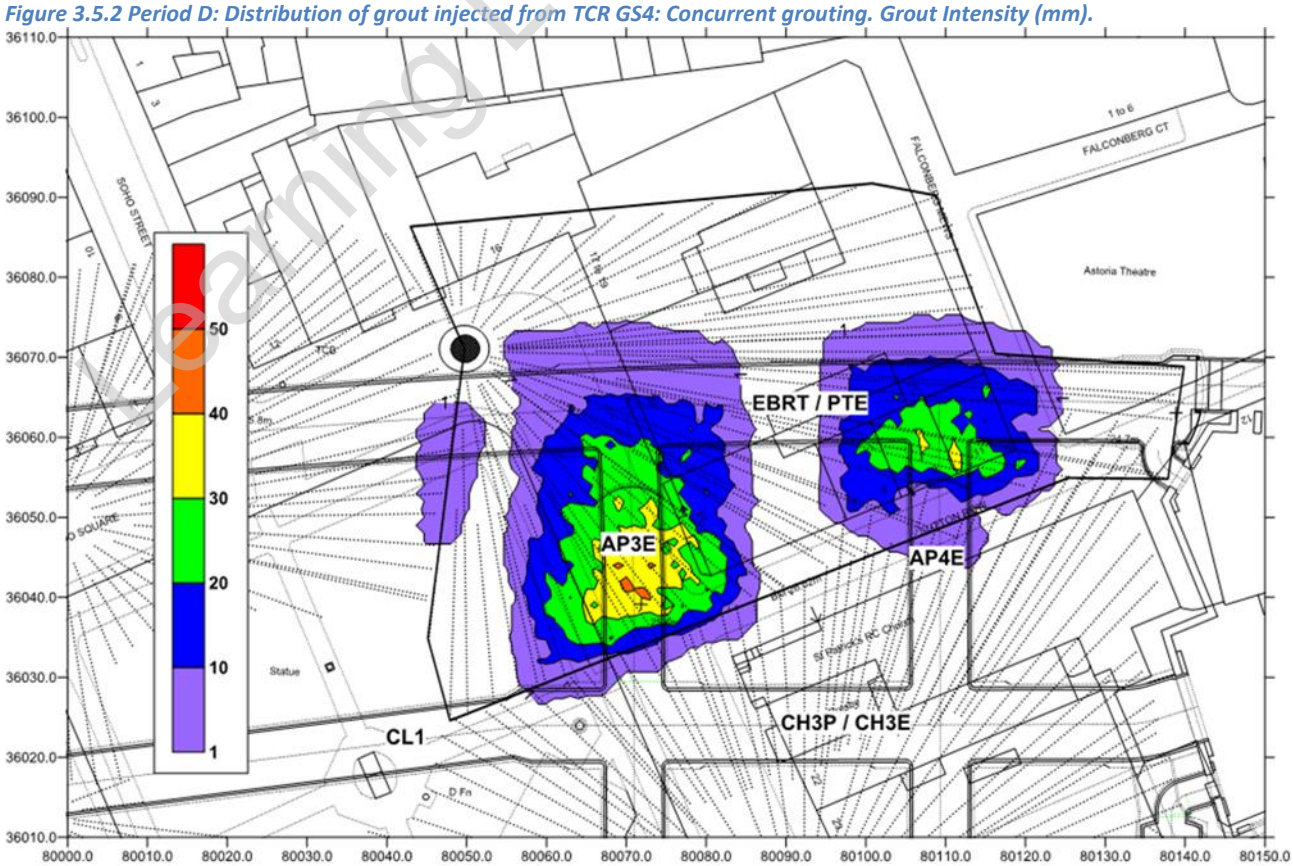


Figure 3.5.2 Period D: Distribution of grout injected from TCR GS4: Concurrent grouting. Grout Intensity (mm).

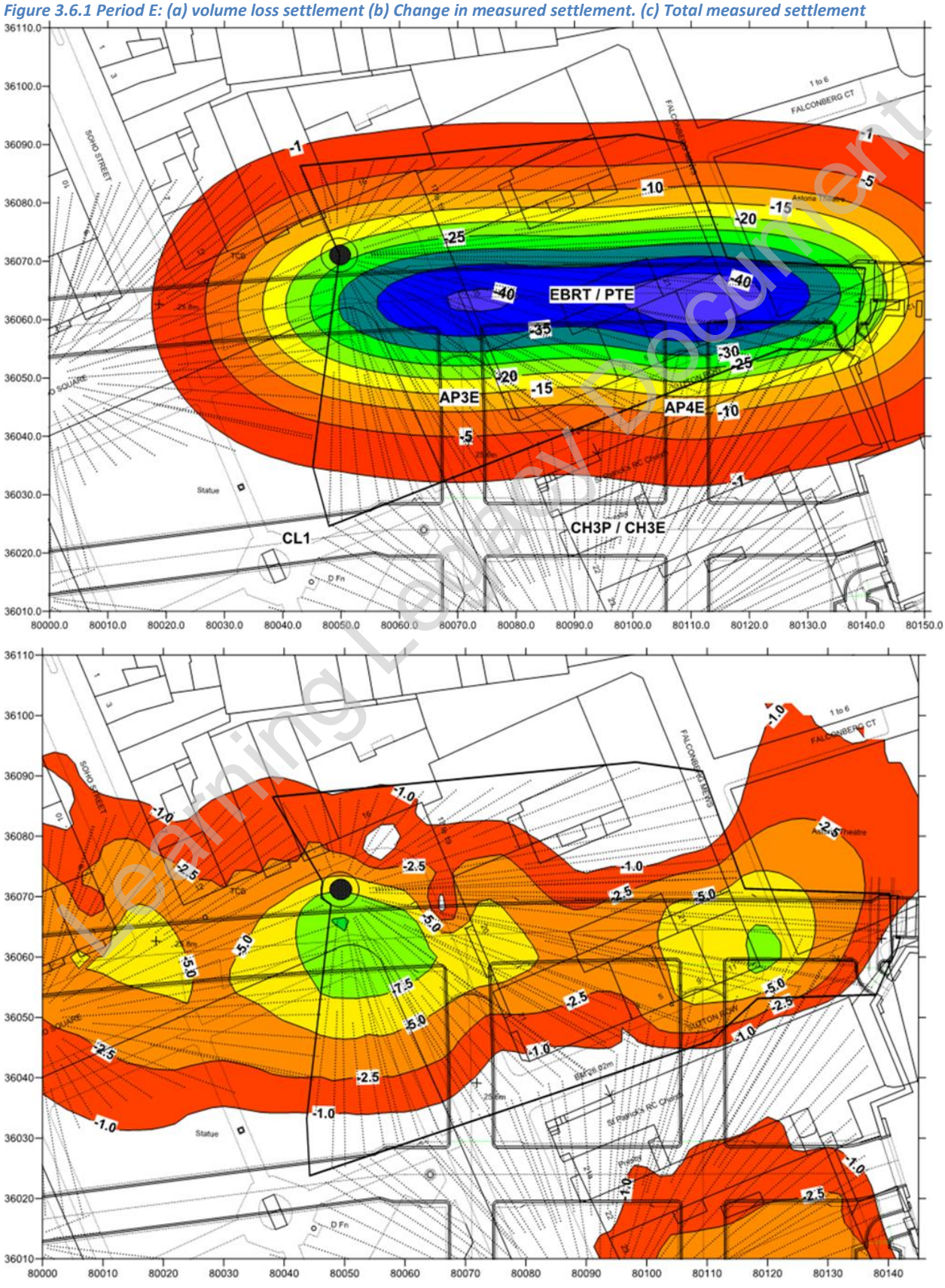


The calculated volume loss settlement from construction of AP3E and AP4E is shown in Figure 3.5.1(a) which indicates a maximum of 20mm settlement over the centre of each tunnel. The maximum observed increase in settlement in Period D within the GS4 area was 10mm but this is attributable to the CH3 works to the south (Figure 3.5.1(b)). Volume loss settlement associated with AP3E and AP4E was controlled by concurrent grouting (Figure 3.5.2) as evidenced by the form of the settlement contours which does not reflect that indicated by the calculated volume loss movements.

The maximum total settlement in the GS4 area increased to 20mm as a result of the movements generated in the GS5 area to the south as shown in Figure 3.5.1 (c).

3.6. Period E: 13/06/14 – 04/09/14 PTE, AP3E & AP4E Junctions; concurrent & jack grouting

Figure 3.6.1 Period E: (a) volume loss settlement (b) Change in measured settlement. (c) Total measured settlement



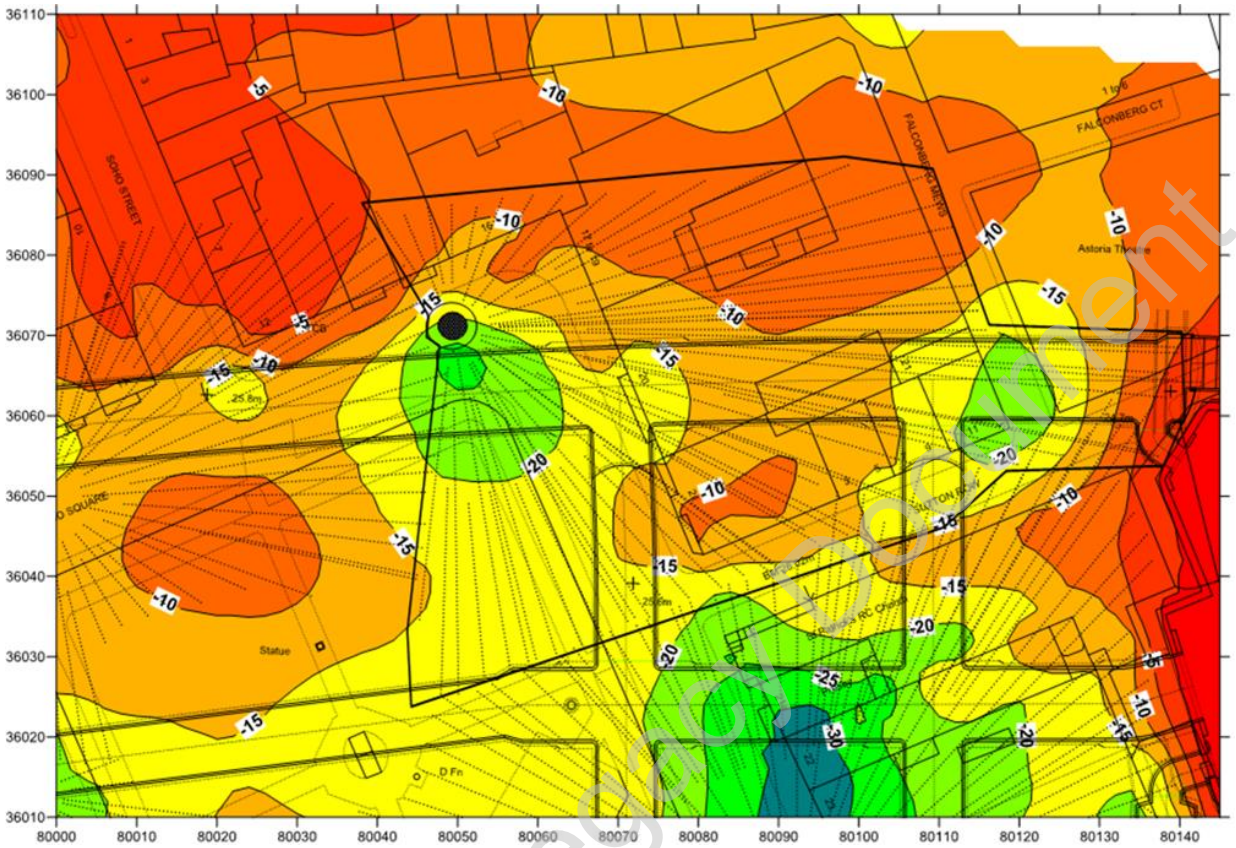


Figure 3.6.2 Period D: Distribution of grout injected from TCR GS4: Concurrent grouting. Grout Intensity (mm).

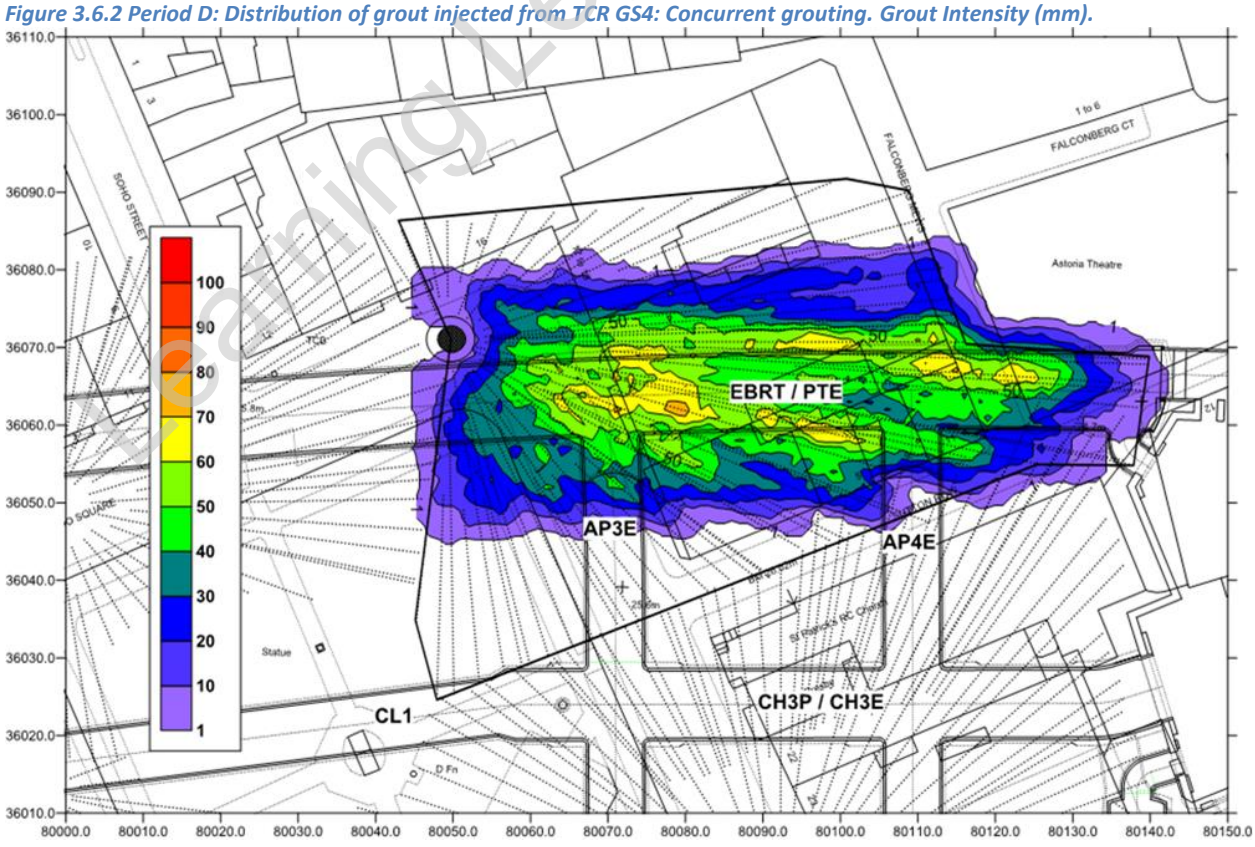


Figure 3.6.3 Period D: Distribution of grout injected from TCR GS4: Grout Jacking. Grout Intensity (mm).

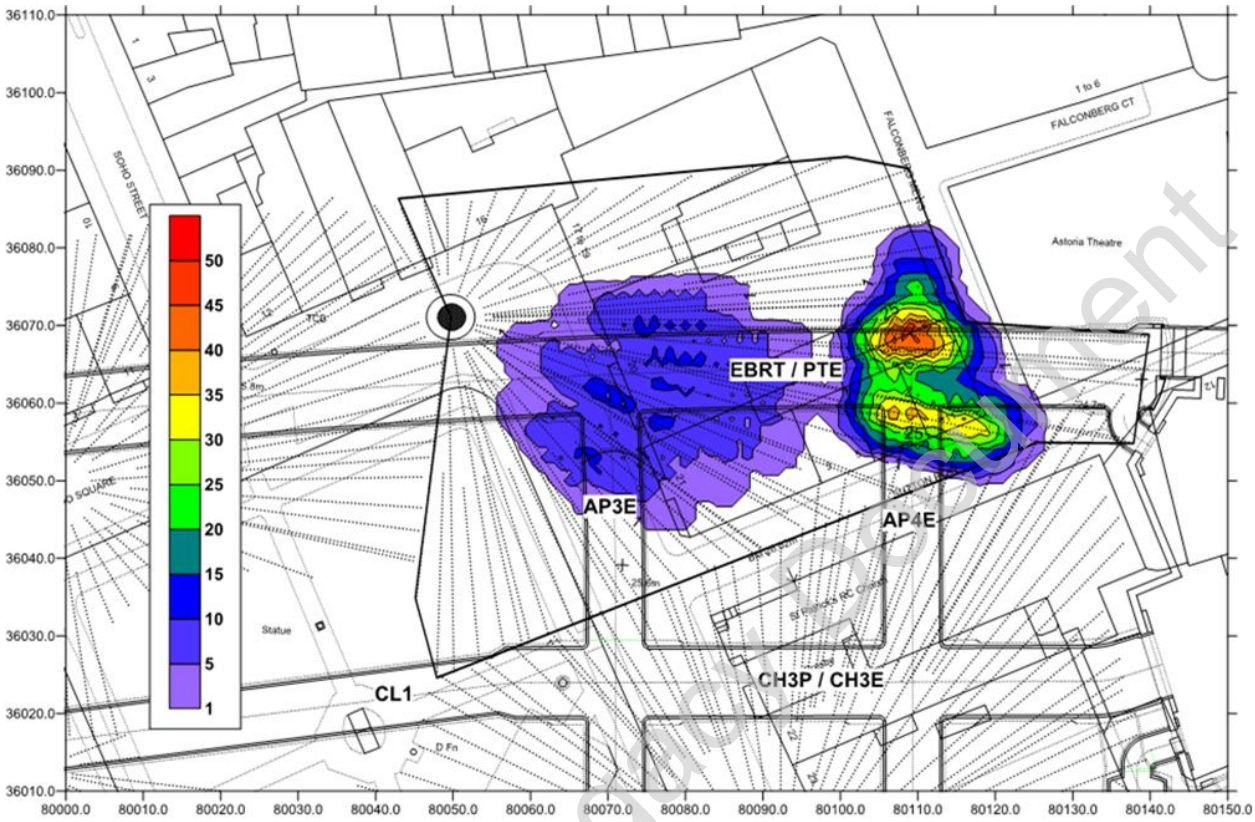


Figure 3.6.1(a) shows that up to 40mm volume loss settlement was predicted for the PTE enlargement and the AP3E and AP4E junctions. The observed settlement indicates less than 10mm occurred as a result of these tunnels due to the concurrent grouting undertaken with the PTE (Figure 3.6.2) and the grout jacking undertaken after completion of the AP3E and AP4E junctions (Figure 3.6.3).

3.7. Period F: 04/09/14 – 25/09/15 Post Construction

Figure 3.7.1 Period F: (a) Change in measured settlement. (b) Total measured settlement

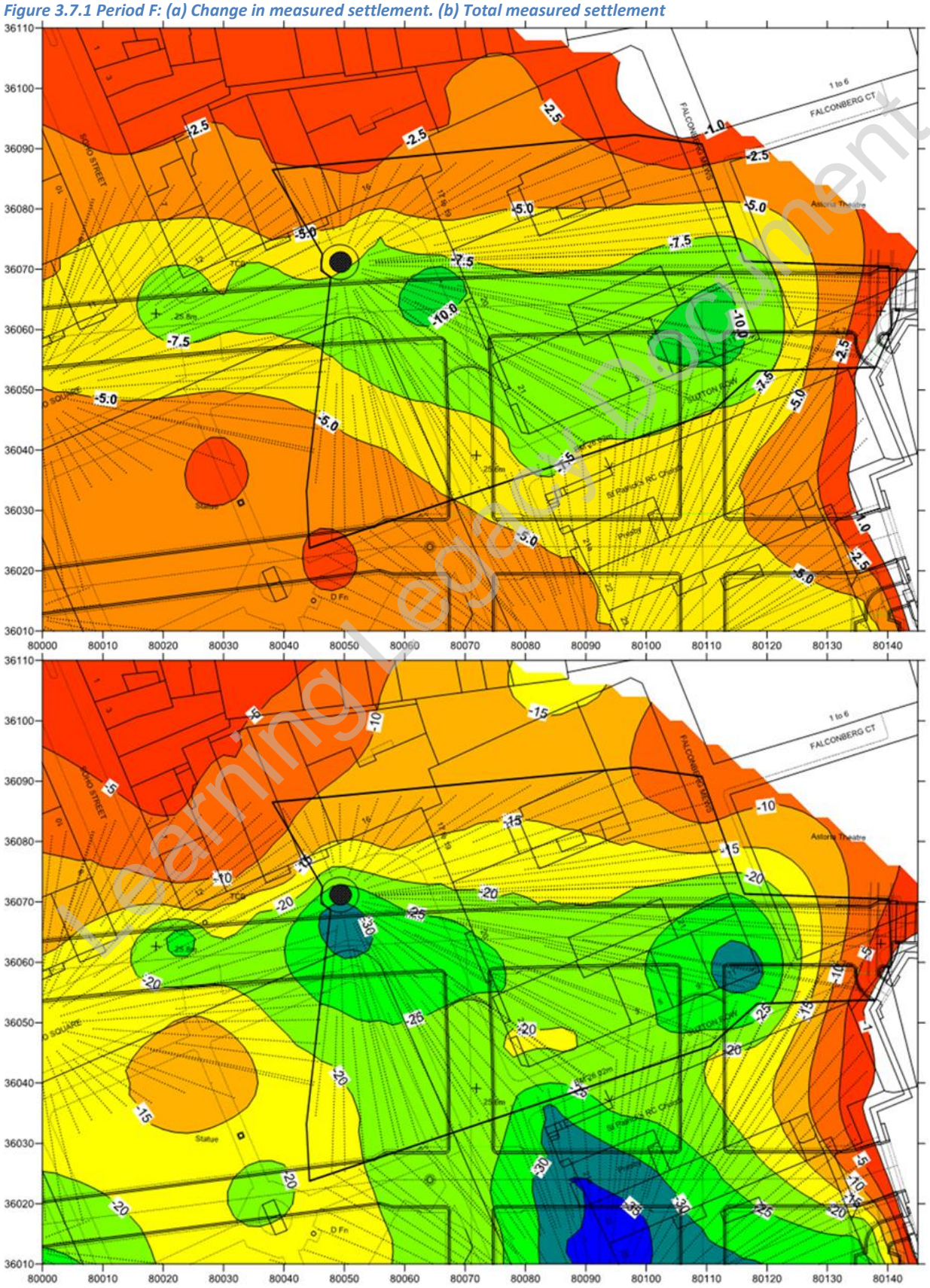


Figure 3.7.1(a) shows an increase of settlement of up to 10mm during the 12 months since the completion of tunnelling from consolidation settlement. The maximum movement is located above the PTE and the contours are approximately aligned with the tunnel.

The total settlement at the end of Period F is shown on Figure 3.7.1(b) with around 20mm to 25mm settlement over the PTW but locally up to 30mm on the corner of Sutton Row and Falconberg Mews.

There was no concurrent grouting in Period F since tunnelling had been completed. No grout jacking was deemed necessary based on reviews of data at SRG and CTC meetings.

4. BUILDING SETTLEMENT AND SLOPES

4.1. Slope triggers

The locations where slope triggers have been exceeded are shown for BRE monitoring of building facades on Figure 4.1. By inspection no deflection ratio triggers have been breached. A larger version of Figure 4.1 is included in Appendix D. Details are given in Table 4.1.

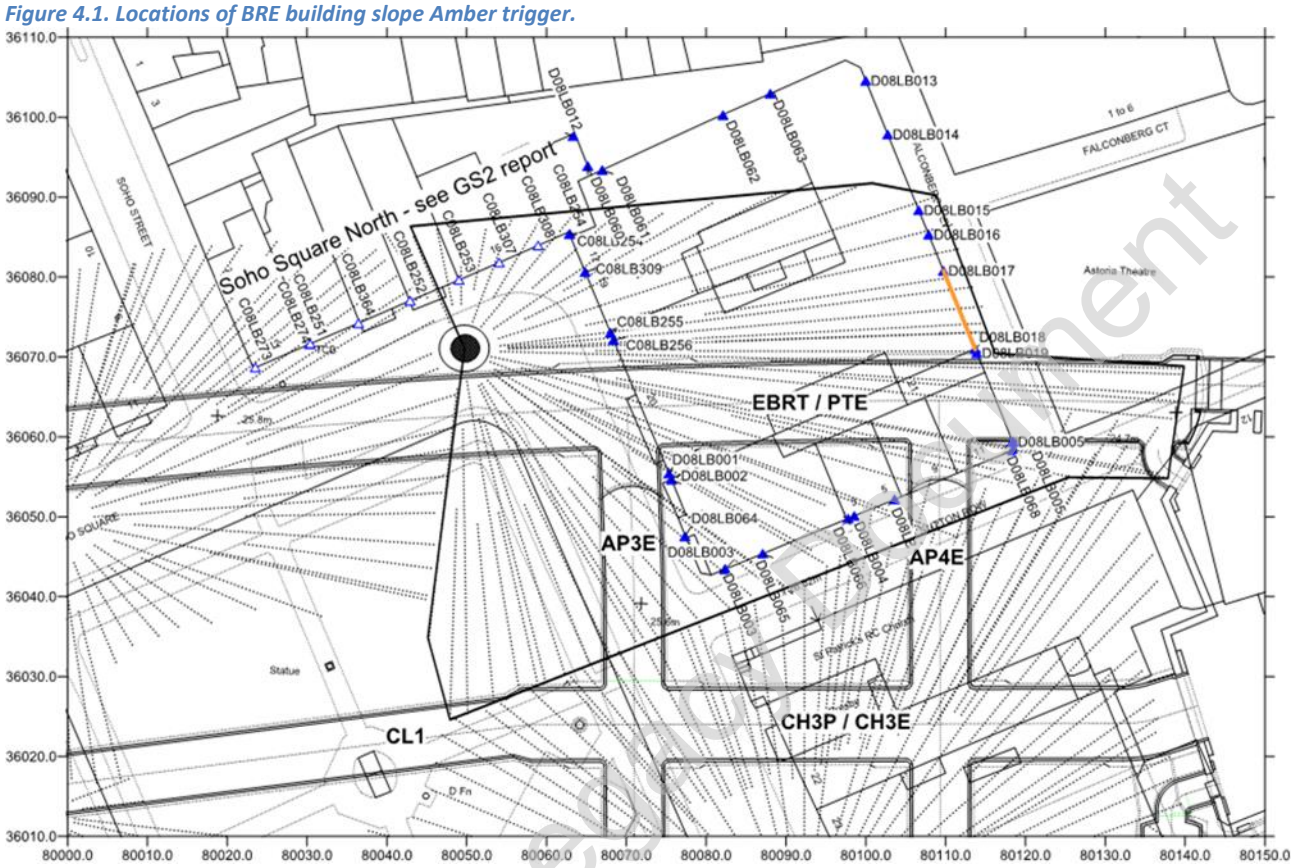
Slope triggers are as follows:

- GREEN 1:1250 0.8mm/m
- AMBER 1:1000 1.0mm/m
- RED 1:500 2.0mm/m

Table 4.1 Details of Amber trigger breaches on BRE

BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Soho Square East – North: NONE					
Sutton Row – North: NONE					
Falconberg Mews – West:					
D08LB018-D08LB017	Amber	Trigger as a result of post construction movements.	29/09/14	1.28	1.28
Falconberg Mews - South: NONE					

Figure 4.1. Locations of BRE building slope Amber trigger.

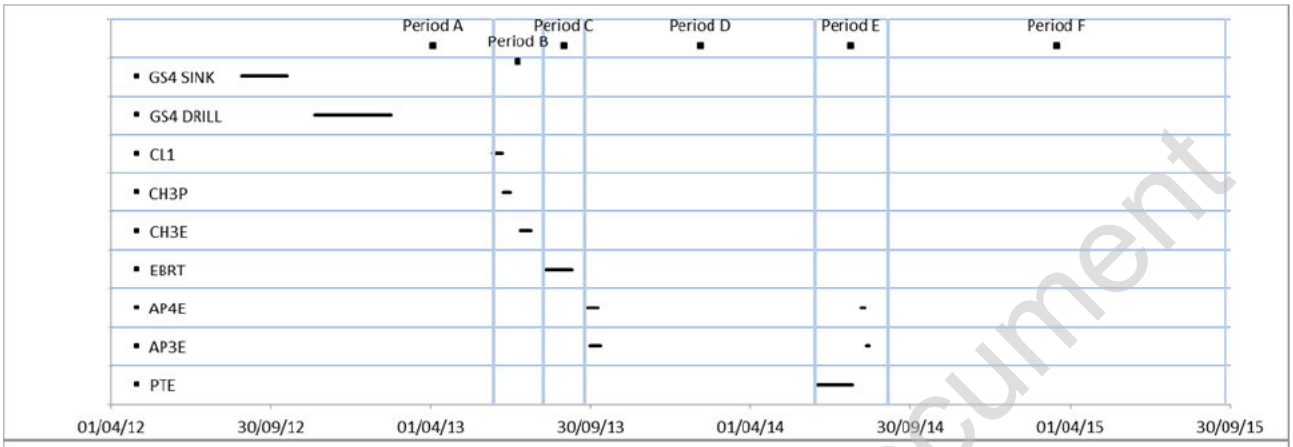


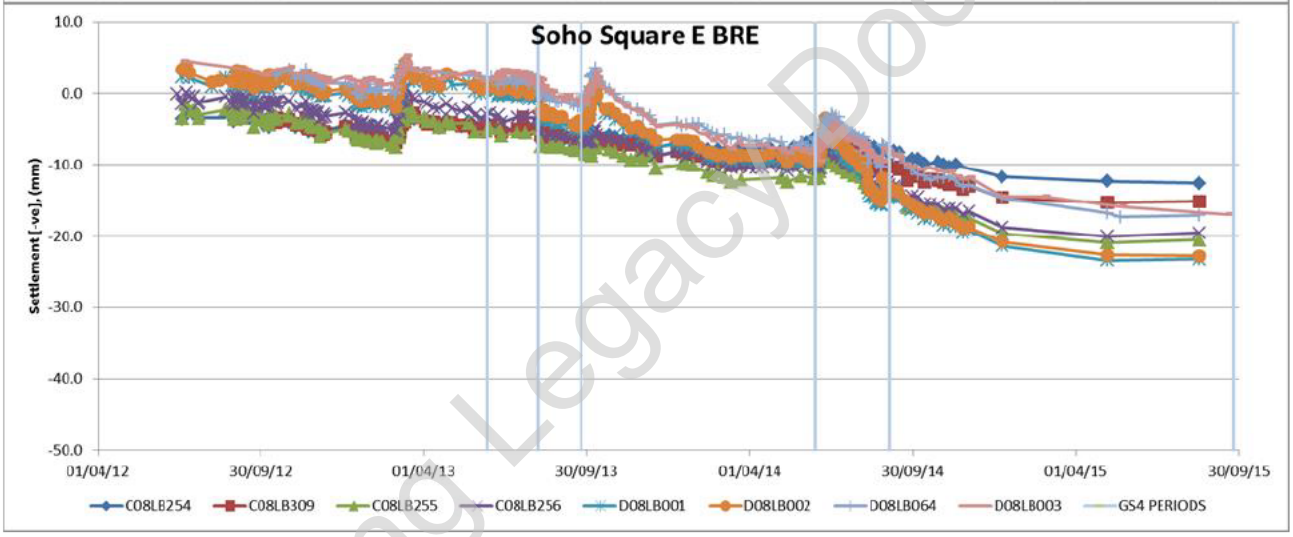
BRE monitoring data from the facades within the footprint of GS4 are presented in the following sections, namely Soho Square east, Sutton Row North, and Falconberg Mews west and south. The plots presented for each comprise, as appropriate:

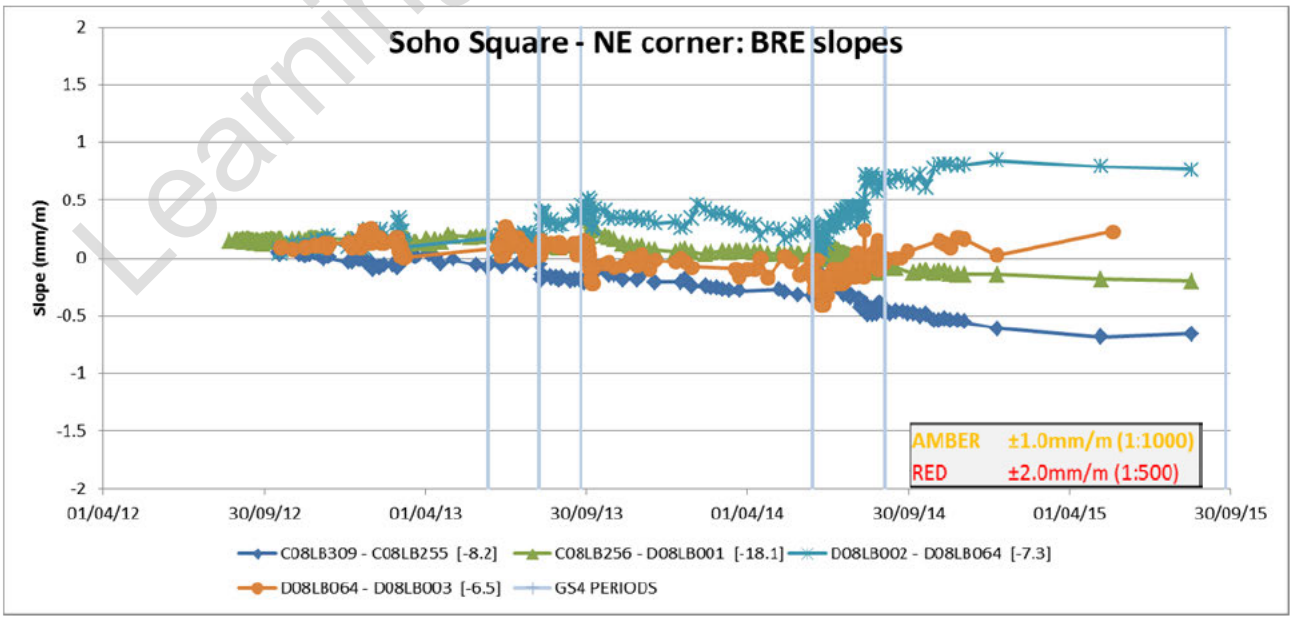
1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres shown in the legend in square brackets

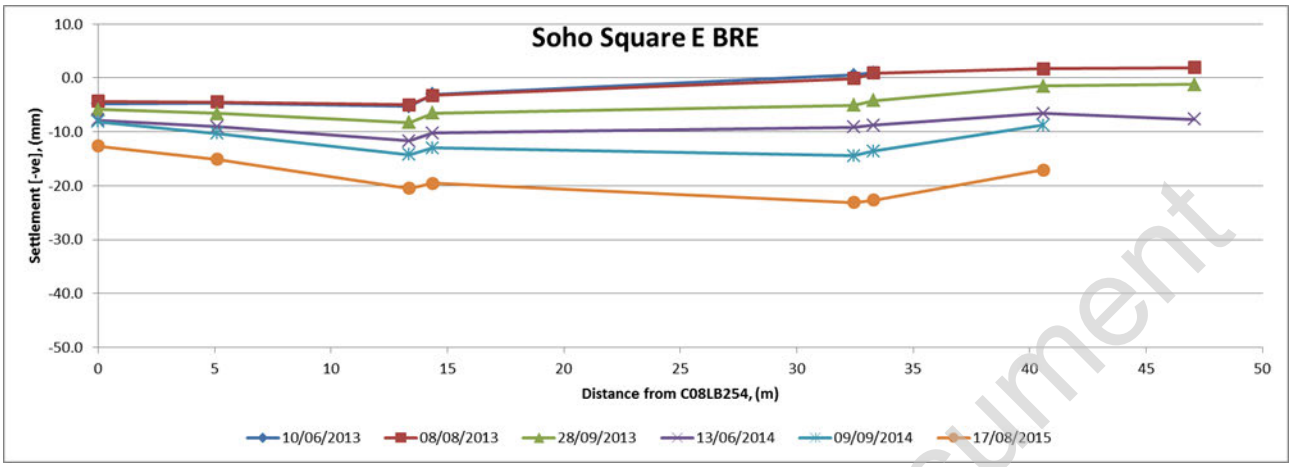
Data are presented for the BRE located on the east facade of Soho Square to the north of Sutton Row (see GS5 report for points south of Sutton Row). The points at the north end of the Falconberg Mews west façade and all of those on the Falconberg Mews south façade are outside the plan extent of the GS4 arrays. The Soho Square north façade data has been presented in the GS2 report and is not repeated herein.

4.2. Soho Square East - North





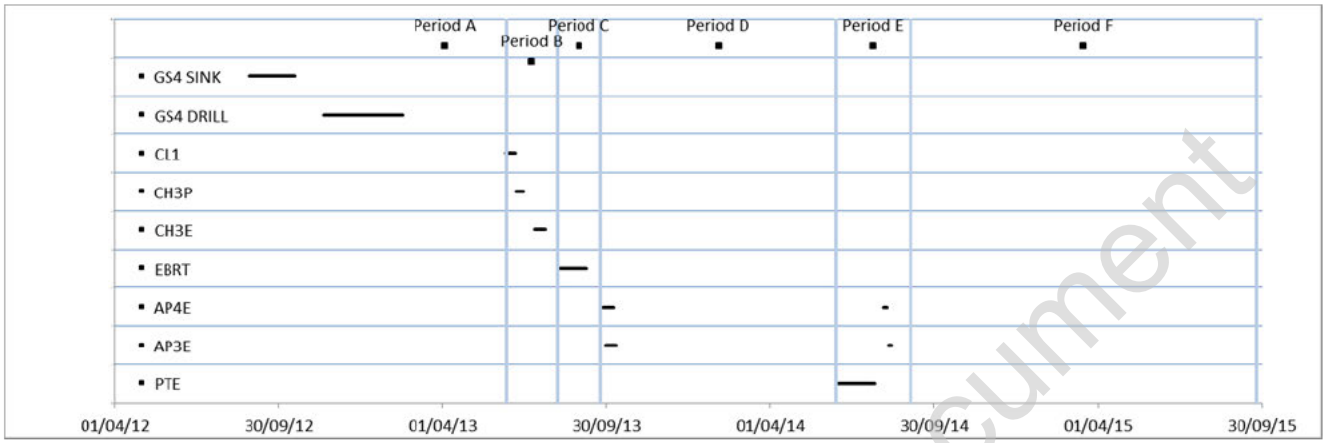


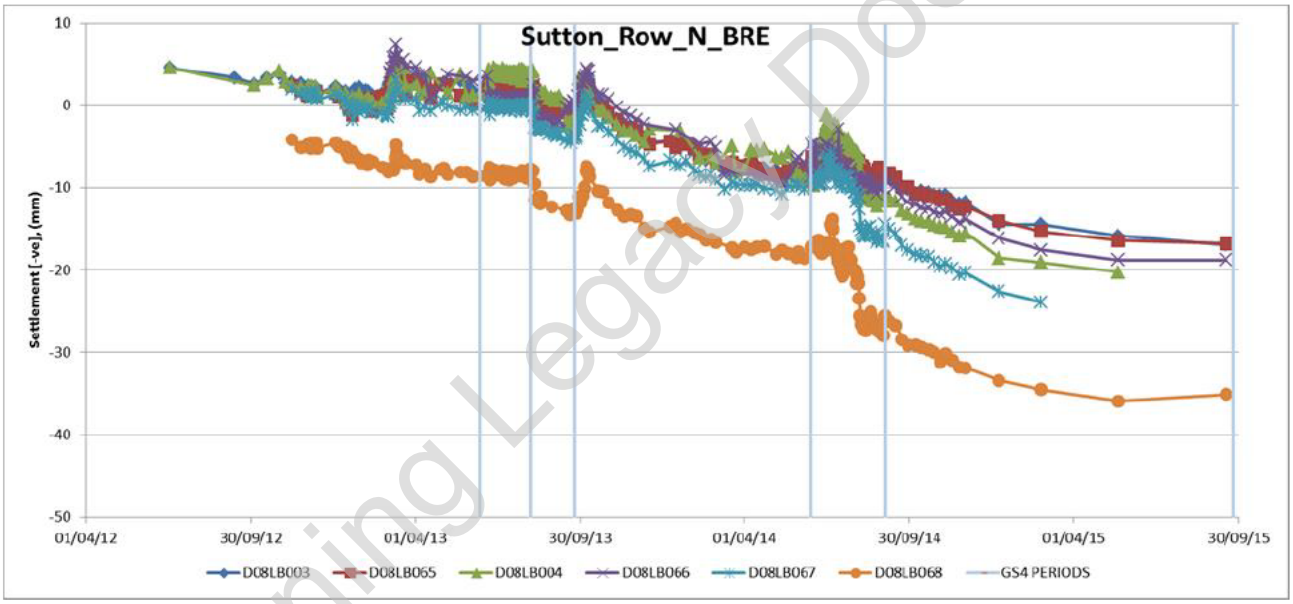


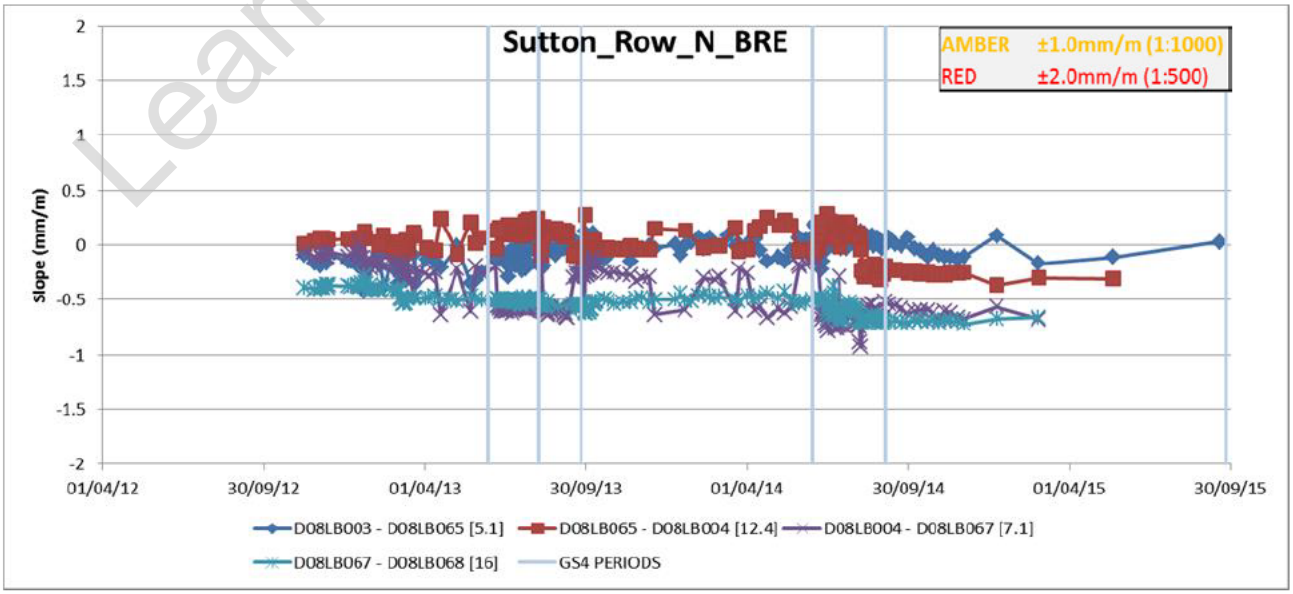
The following points are noted:

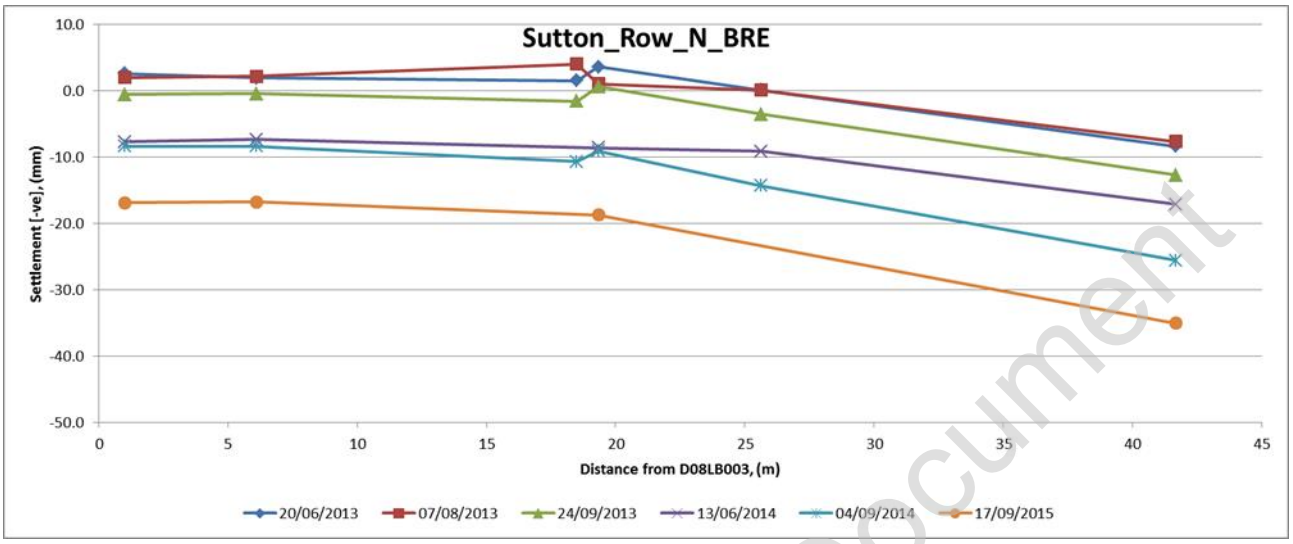
- Data are presented for the BRE located on the east facade of Soho Square to the north of Sutton Row (see GS5 report for points south of Sutton Row).
- Overall settlement was ~5mm or less at the end of Period A as a result of pretreatment reversing settlement associated with TCRSU works and TaM installation. There was no significant change in Period B and a small increase in settlement associated with the EBRT in Period C giving a maximum of 9mm.
- Heave is evident at the start of Period D as a result of concurrent grouting with the AP3E and AP4E tunnels. Most of this uplift dissipated and ongoing consolidation over the remaining 8 months of Period D resulted in a small net increase in maximum settlement to 12mm.
- The effect of concurrent compensation grouting during PTE enlargement is evident at the start of Period E with uplift followed by settlement. Settlement associated with the junction with AP3E and AP4E was reversed by grout jacking resulting in negligible net change in movement. Overall a small increase in maximum settlement to ~15mm was observed in Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions with a final measured settlement of about 24mm.
- Slopes were less than the Amber trigger value throughout construction and subsequently during Period F.

4.3. Sutton Row North





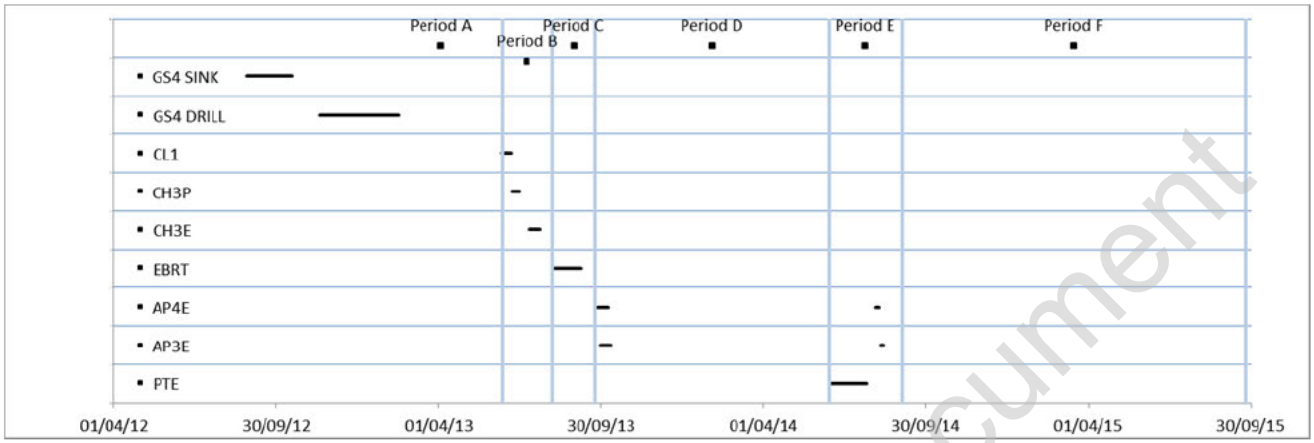


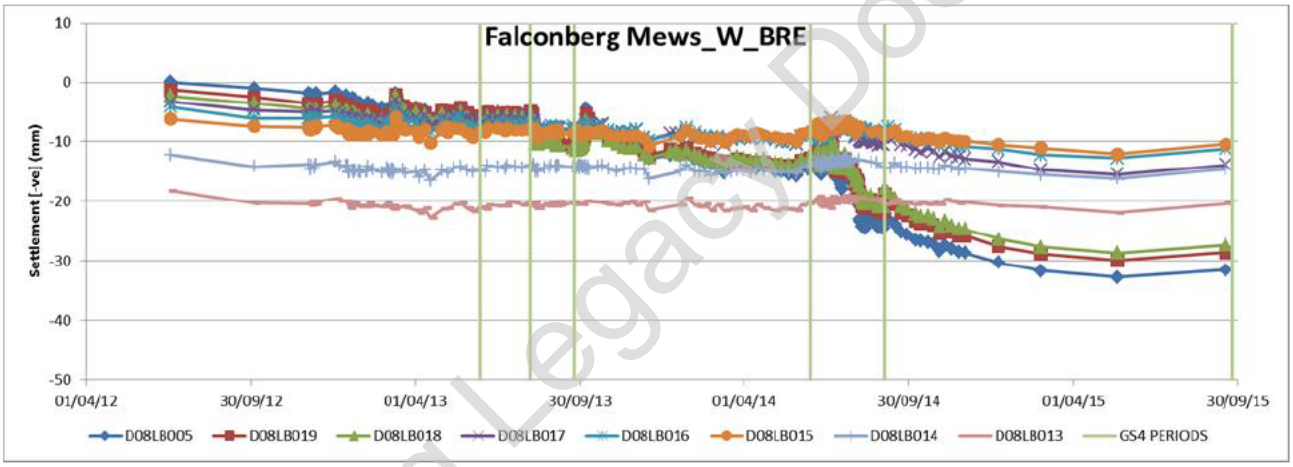


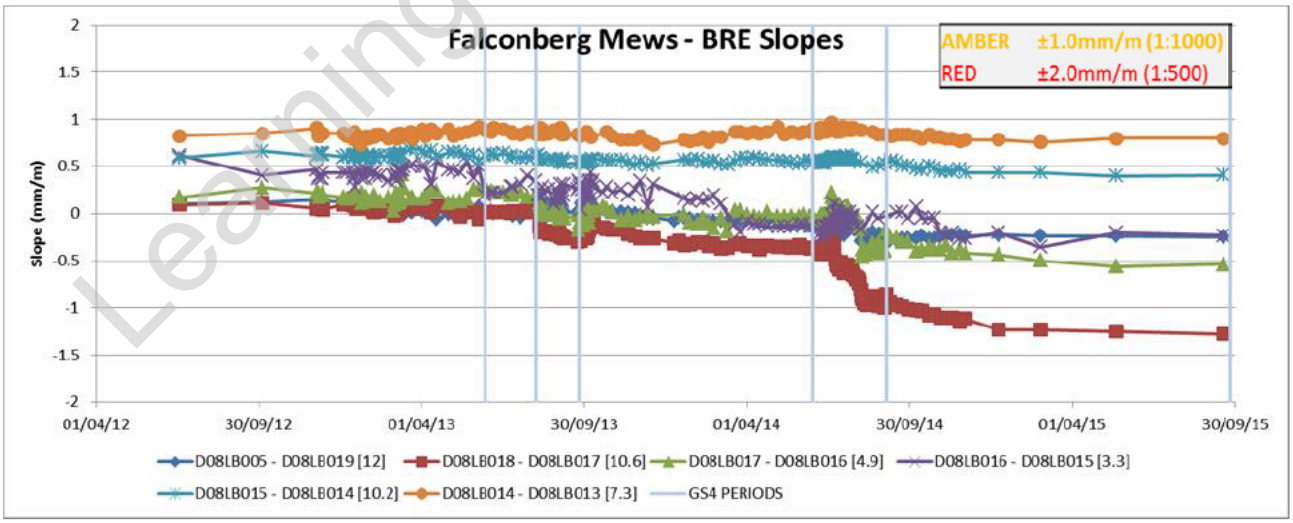
The following points are noted:

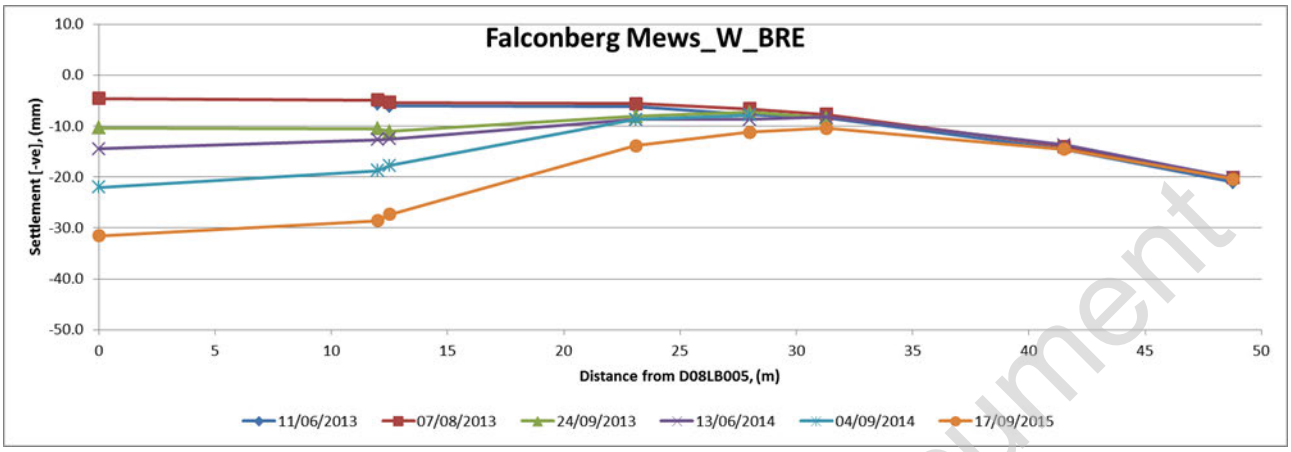
- Data are presented for the BRE located on the north façade of Sutton Row. All points are within the plan extent of the GS4 arrays.
- Significant differential movement had been generated by TCRSU works prior to any BFK works with local settlement at the corner of Falconberg Mews (at distance 42m) adjacent to the TCRSU worksite.
- Small settlements which occurred during TaM installation were reversed as a result of pretreatment such that the net effect was an increase in settlement of less than 3mm. Maximum settlement prior to the start of tunnelling was about 9mm. There was no significant change in Period B and a small increase in settlement associated with the EBRT in Period C giving a maximum of 13mm.
- Heave is evident at the start of Period D as a result of concurrent grouting with the AP3E and AP4E tunnels. Most of this uplift dissipated and ongoing consolidation over the remaining 8 months of Period D resulted in a small net increase in maximum settlement to 18mm.
- The effect of concurrent compensation grouting during PTE enlargement is evident at the start of Period E with uplift followed by settlement. The grouting was less effective at the eastern end of PTE as a result of the limited TaMs available and the exclusion zones around the TCRSU structures.
- Settlement associated with the junction with AP3E and AP4E was reversed by grout jacking resulting in negligible net change in movement. Overall a small increase in maximum settlement to ~27mm was observed in Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions with a final measured settlement of about 35mm.
- Slopes were less than the Amber trigger value throughout construction and subsequently during Period F.

4.4. Falconberg Mews West - North





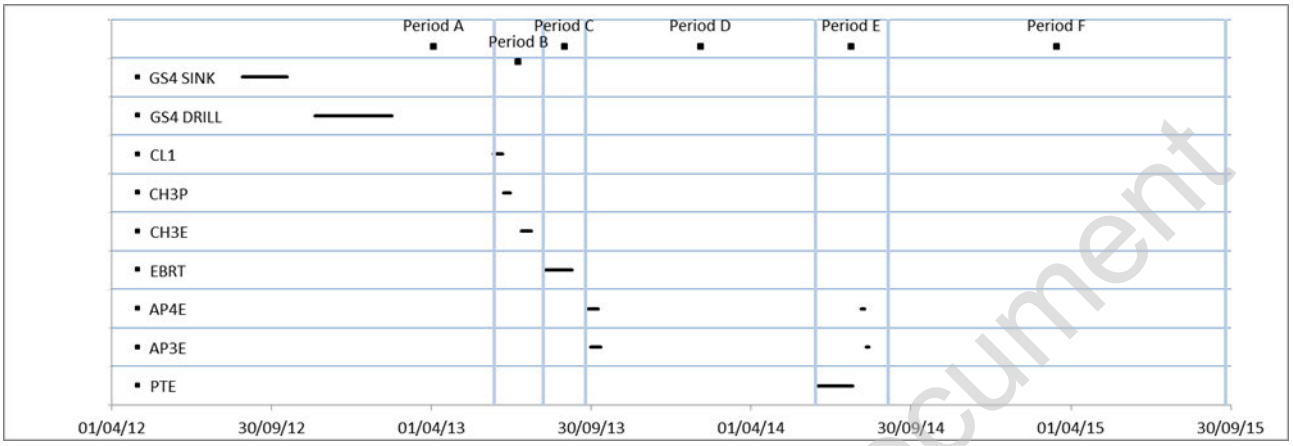


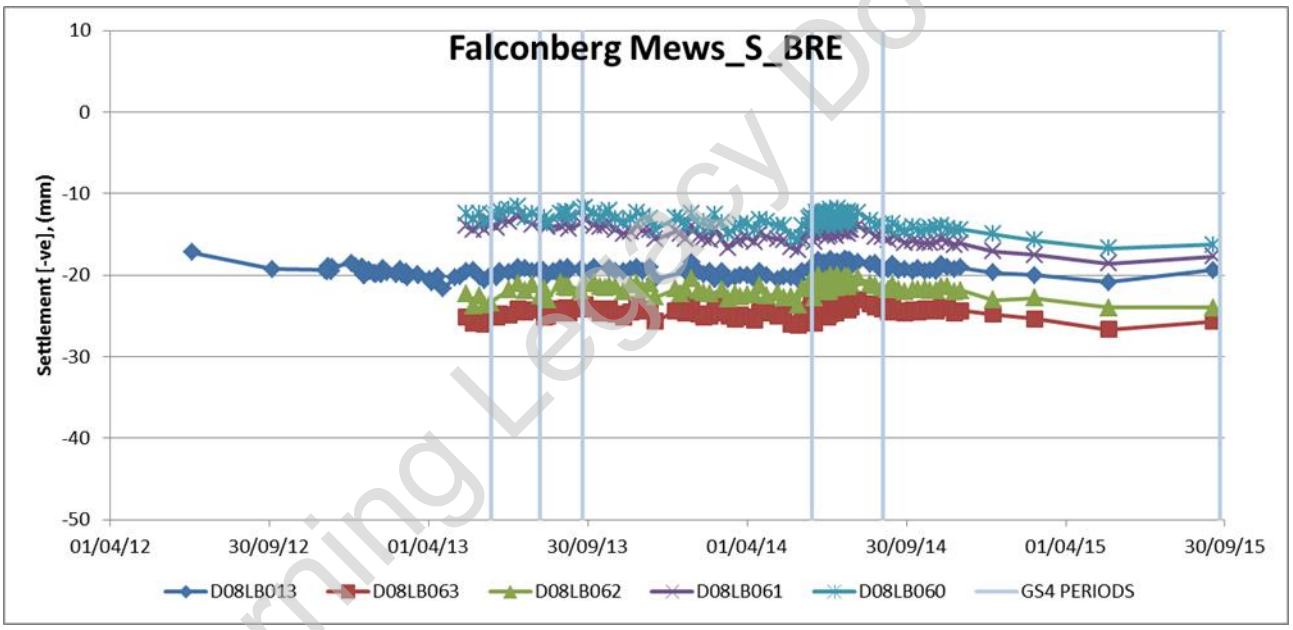


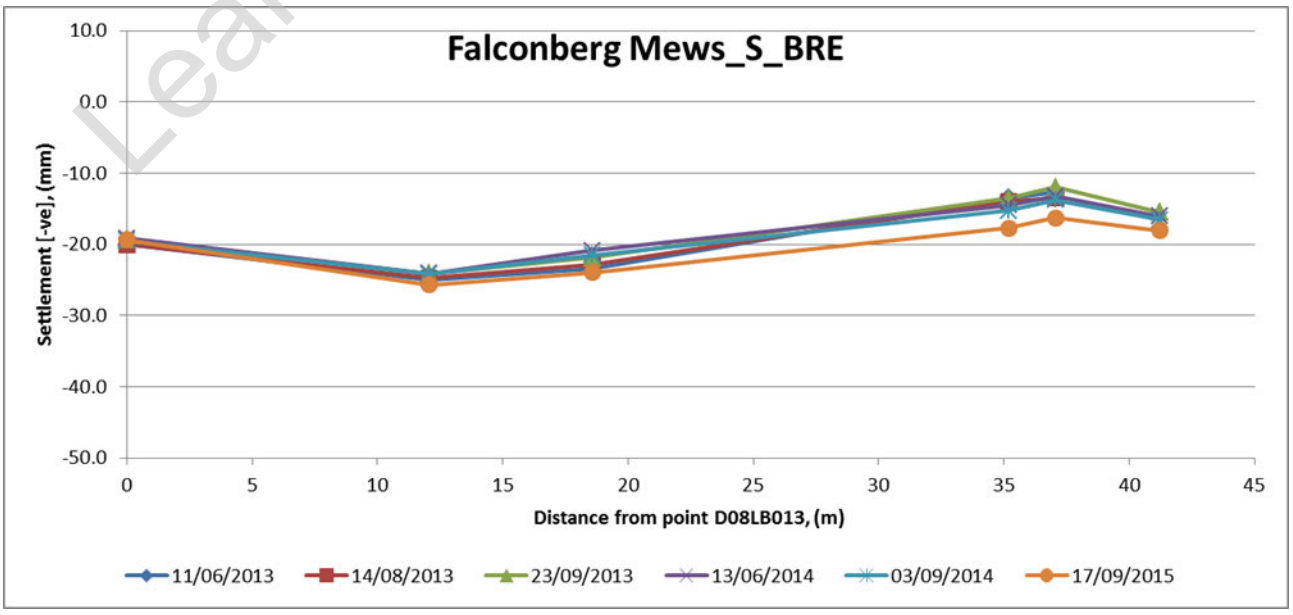
The following points are noted:

- Data are presented for the BRE located on the west façade of Falconberg Mews. Points up to 35m from Sutton Row (D08LB005) are within the plan extent of the GS4 arrays.
- Significant differential movement had been generated by TCRSU works prior to any BFK works with up to 20mm settlement at the north end of the facade. However, there was little subsequent change in movement and the comment below relate to the points within the GS4 area.
- Small settlements which occurred during TaM installation were reversed as a result of pretreatment such that the net effect was negligible. Maximum settlement prior to the start of tunnelling was about 8mm. There was no significant change in Period B and a small increase in settlement associated with the EBRT in Period C on points within the GS4 area giving a maximum of 12mm at the end of Period C.
- Heave is evident at the start of Period D as a result of concurrent grouting with the AP3E and AP4E tunnels. Most of this uplift dissipated and ongoing consolidation over the remaining 8 months of Period D resulted in a small net increase in maximum settlement to 15mm.
- The effect of concurrent compensation grouting during PTE enlargement is evident at the start of Period E with uplift followed by settlement. The grouting was less effective at the eastern end of PTE as a result of the limited TaMs available and the exclusion zones around the TCRSU structures.
- Settlement associated with the junction with AP3E and AP4E was reversed by grout jacking resulting in negligible net change in movement. Overall a 10mm increase in maximum settlement to ~25mm was observed in Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions with a final measured settlement of about 32mm.
- Slopes were less than the Amber trigger value throughout construction but the value between D08LB017 and D08LB018 increased during Period E and grout jacking was undertaken which stabilized the slope at just below the Amber value. Subsequently, during Period F, the slope did exceed the Amber value but no further grout jacking was deemed necessary, since the rate of increase was slow and decreasing with time. Details are given in Table 4.1

4.5. Falconberg Mews – south







The following points are noted:

- Data are presented for the BRE located on the south façade of Falconberg Mews. All points are outside the plan extent of the GS4 arrays.
- Significant movement had been generated by TCRSU works prior to any BFK works and there was very limited effect throughout the BFK construction period with a maximum increase in settlement of less than 5mm.

5. GROUND SETTLEMENT AND SLOPES

5.1. Slope Triggers

The locations where slope triggers have been exceeded are shown for PLP monitoring of ground level on Figure 5.1. By inspection no deflection ratio triggers have been breached. A larger version of Figure 5.1 is included in Appendix D. Details are given in Table 5.1.

Slope triggers are as follows:

- GREEN 1:1250 0.8mm/m
- AMBER 1:1000 1.0mm/m
- RED 1:500 2.0mm/m

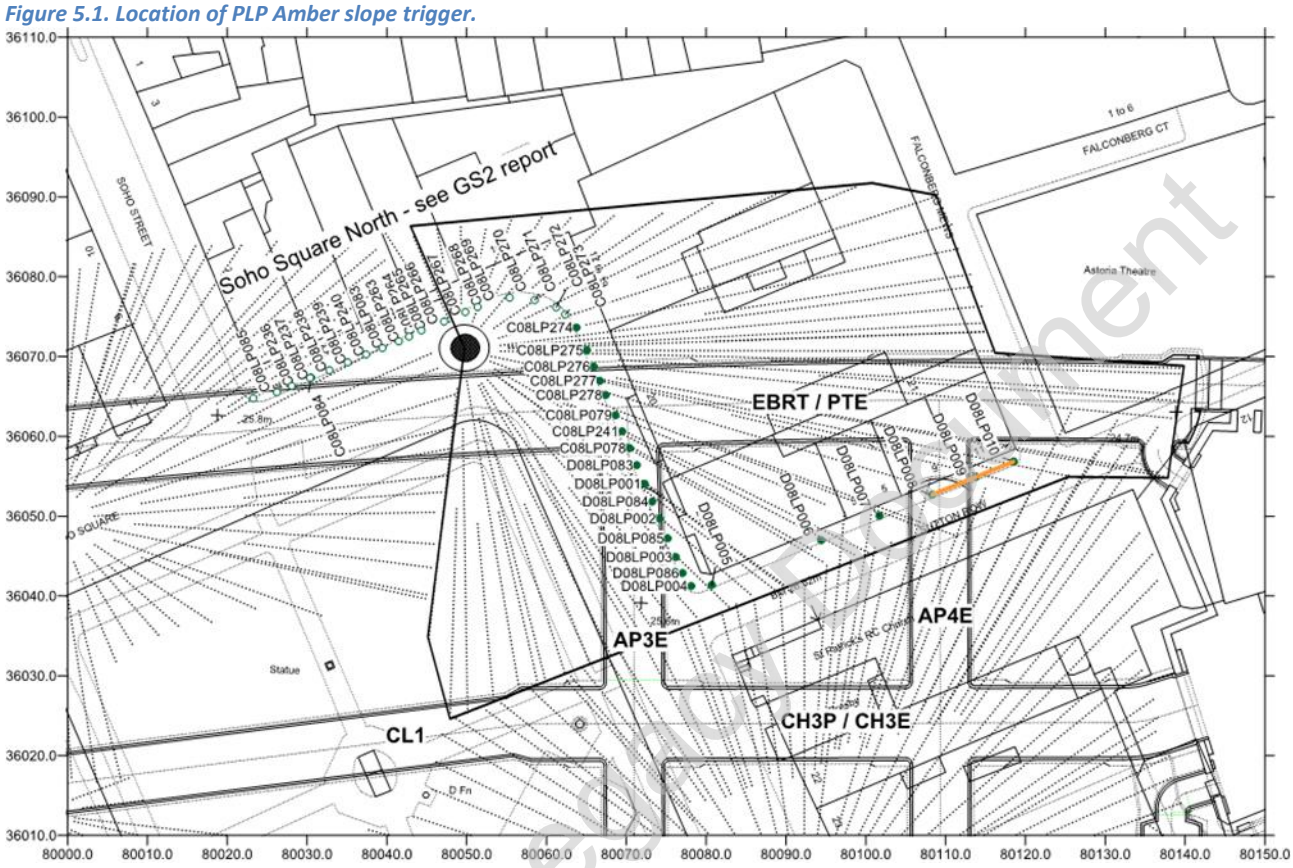
PLP monitoring data from the kerb lines within the footprint of GS4 are presented in the following sections, namely Soho Square East-North and Sutton Row North. The plots presented for each comprise:

1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres shown in the legend in square brackets

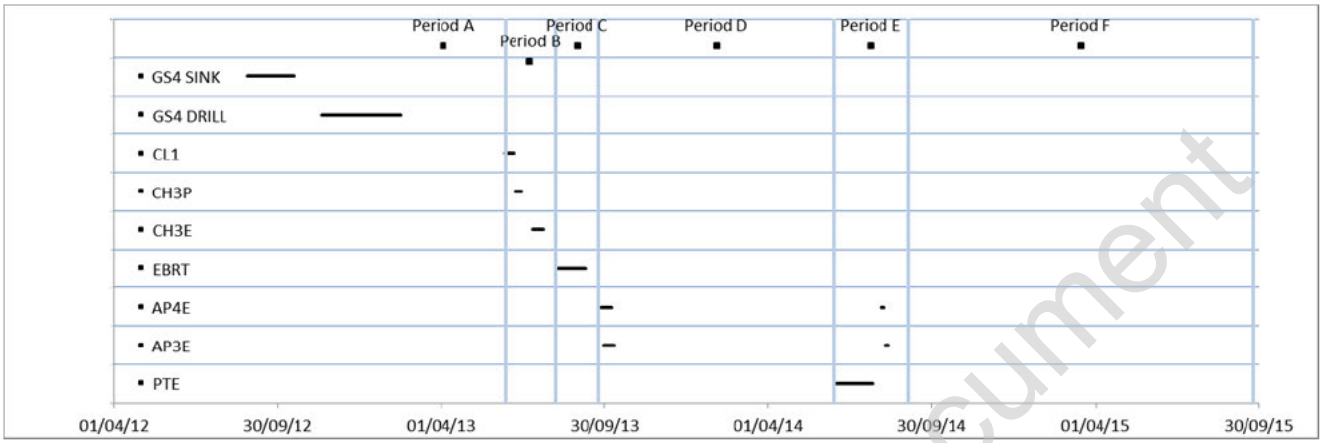
Table 5.1 Details of Amber trigger breaches on PLP

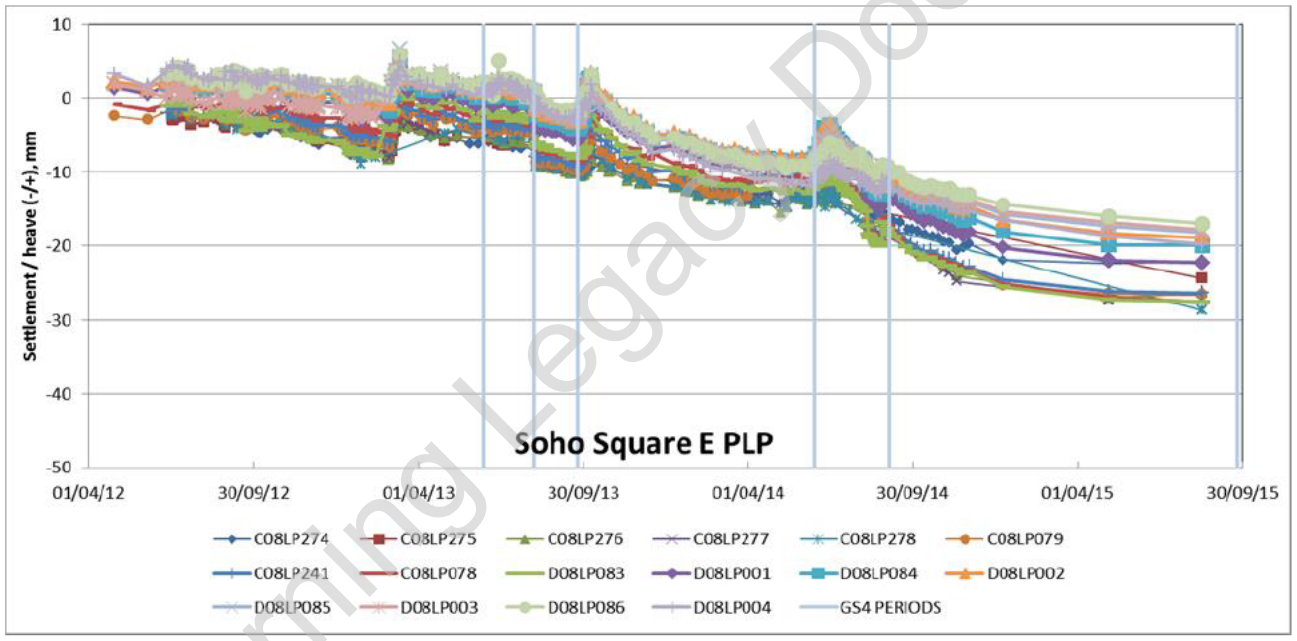
Kerb Line		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Soho Square East – North: NONE					
Sutton Row - North: NONE					
D08LP008 – D08LP010	Amber	Slope 0.84mm/m prior to BFK works – no instruction was issued by CRL to undertake grout jacking	28/09/13	1.17	1.07

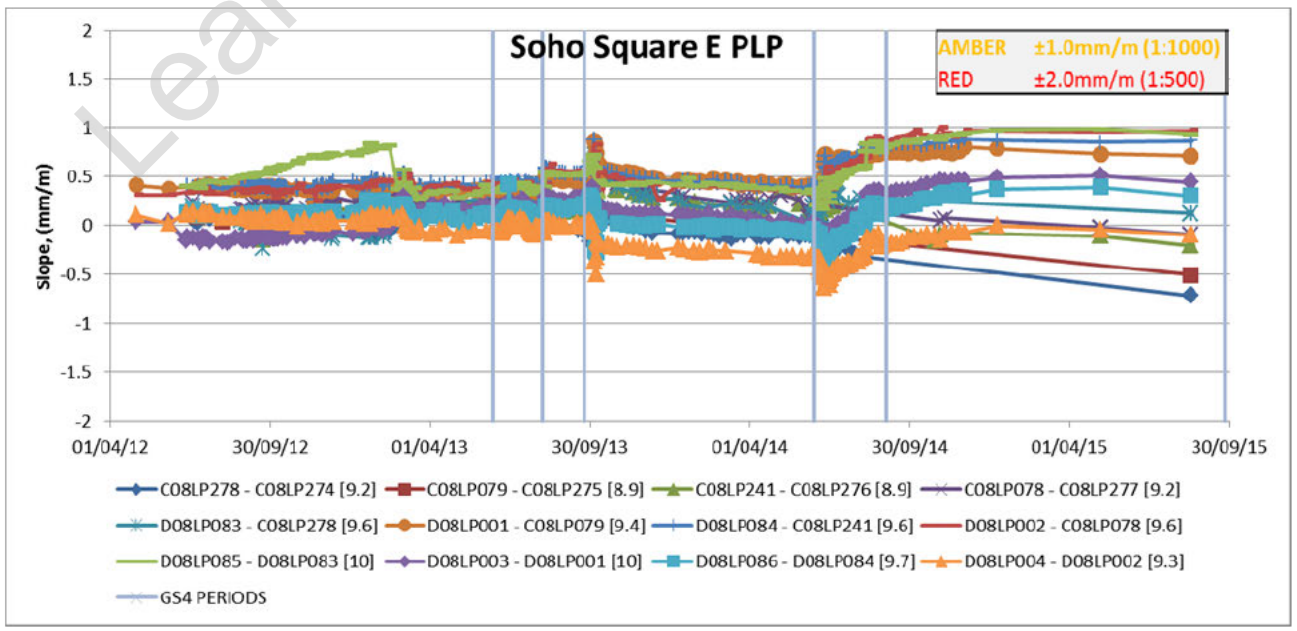
Figure 5.1. Location of PLP Amber slope trigger.

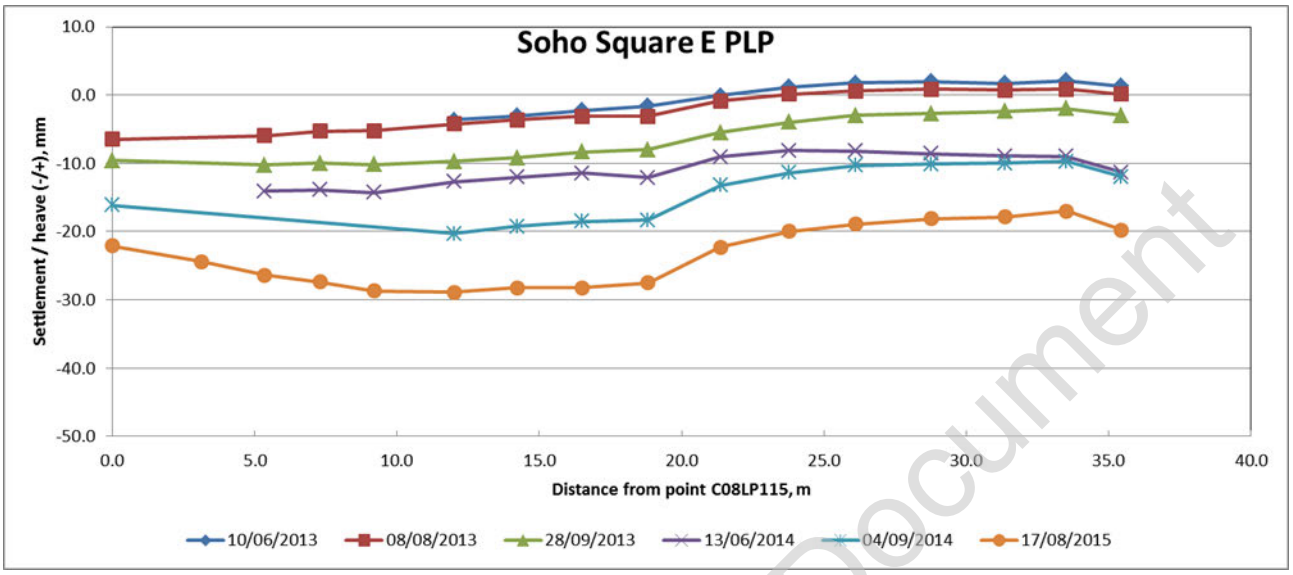


5.2. Soho Square East - north





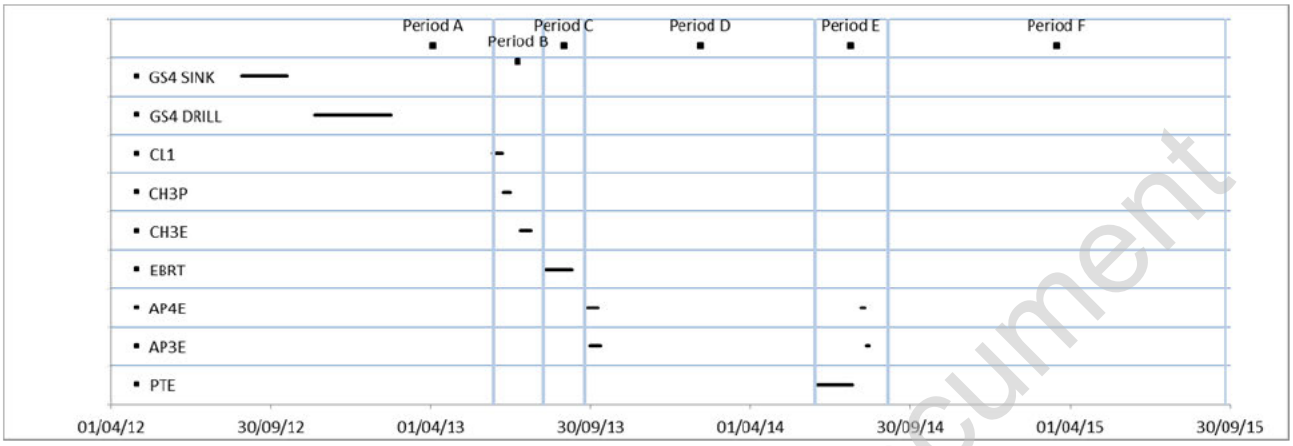


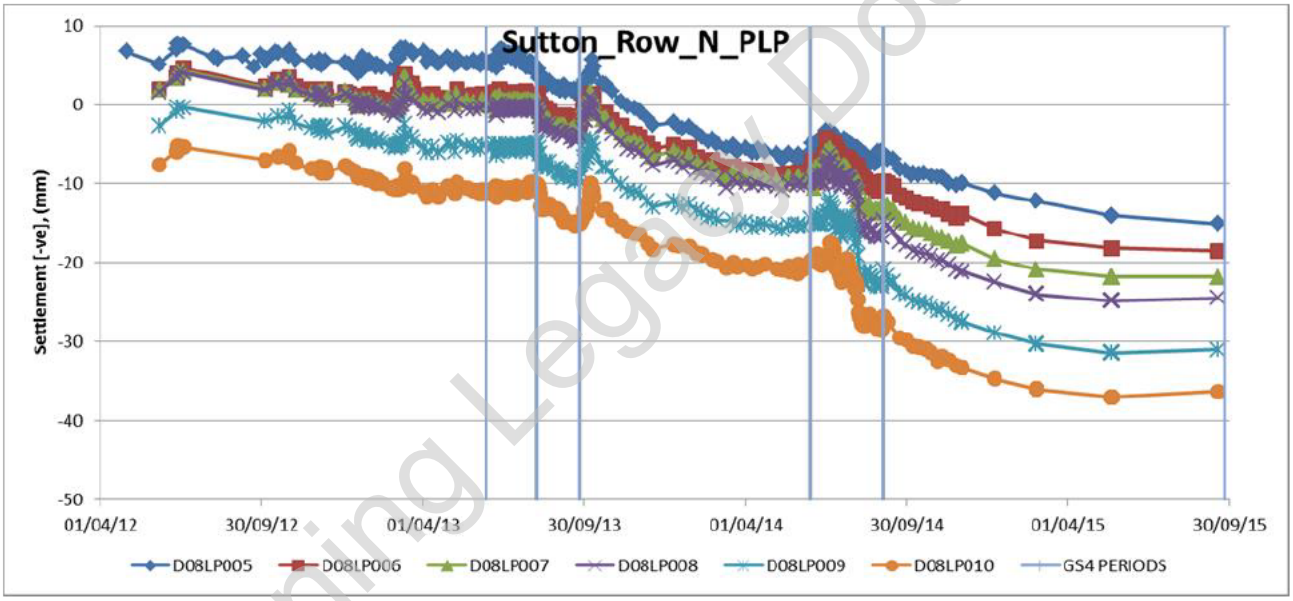


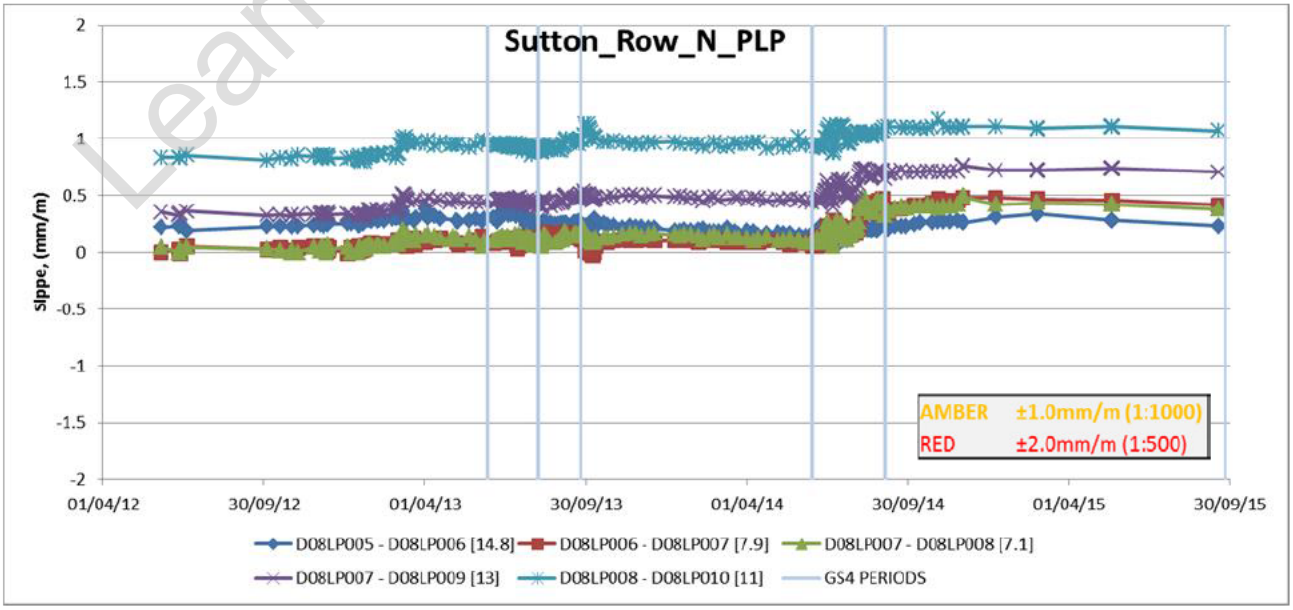
The following points are noted:

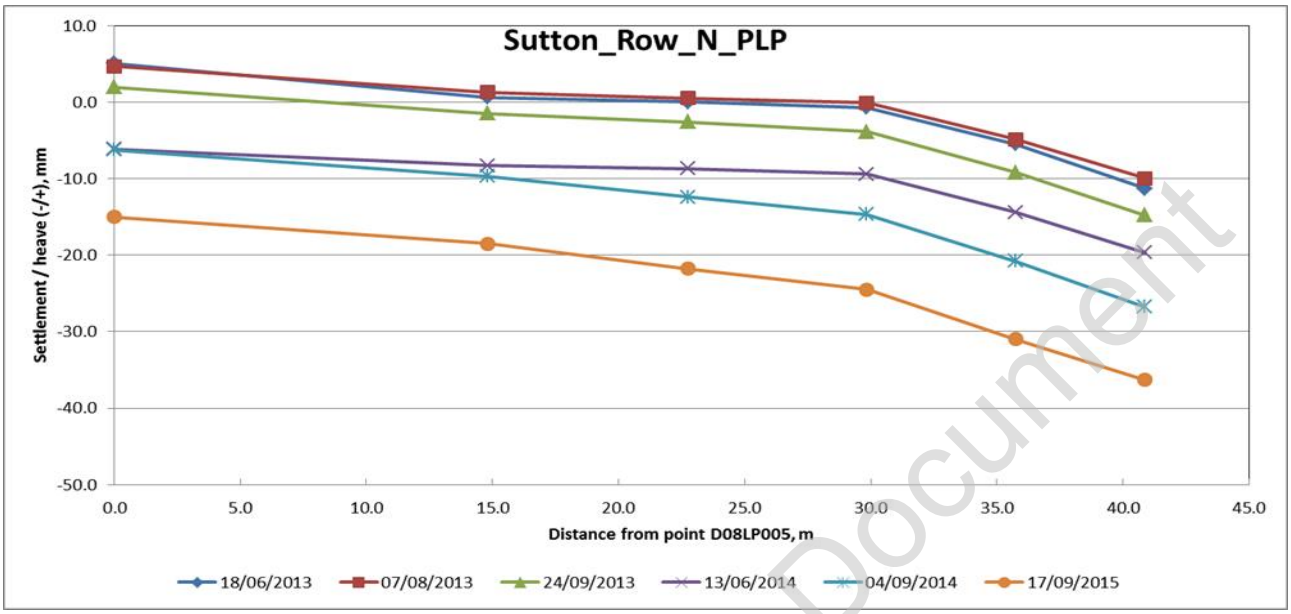
- Data are presented for the PLP located on the east kerb line of Soho Square to the north of Sutton Row (see GS5 report for points south of Sutton Row).
- Overall settlement was ~5mm or less at the end of Period A as a result of pretreatment reversing settlement associated with TCRSU works and TaM installation. There was no significant change in Period B and a small increase in settlement associated with the EBRT in Period C giving a maximum of 10mm.
- Heave is evident at the start of Period D as a result of concurrent grouting with the AP3E and AP4E tunnels. Most of this uplift dissipated and ongoing consolidation over the remaining 8 months of Period D resulted in a small net increase in maximum settlement to 13mm.
- The effect of concurrent compensation grouting during PTE enlargement is evident at the start of Period E with uplift followed by settlement. Settlement associated with the junction with AP3E and AP4E was reversed by grout jacking resulting in negligible net change in movement. Overall a small increase in maximum settlement to ~20mm was observed in Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions with a final measured settlement of about 29mm.
- Slopes were less than the Amber trigger value throughout construction and subsequently during Period F.

5.3. Sutton Row North









The following points are noted:

- Data are presented for the PLP located on the north kerb line of Sutton Row. All points are within the plan extent of the GS4 arrays.
- Significant differential movement had been generated by TCRSU works prior to any BFK works with local settlement at the corner of Falconberg Mews, from distance 30m, adjacent to the TCRSU worksite.
- Small settlements which occurred during TaM installation were reversed as a result of pretreatment such that the net effect was an increase in settlement of less than 3mm. Maximum settlement prior to the start of tunnelling was about 10mm. There was no significant change in Period B and a small increase in settlement associated with the EBRT in Period C giving a maximum of 15mm.
- Heave is evident at the start of Period D as a result of concurrent grouting with the AP3E and AP4E tunnels. Most of this uplift dissipated and ongoing consolidation over the remaining 8 months of Period D resulted in a small net increase in maximum settlement to 20mm.
- The effect of concurrent compensation grouting during PTE enlargement is evident at the start of Period E with uplift followed by settlement. The grouting was less effective at the eastern end of PTE as a result of the limited TaMs available and the exclusion zones around the TCRSU structures.
- Settlement associated with the junction with AP3E and AP4E was reversed by grout jacking resulting in negligible net change in movement. Overall a small increase in maximum settlement to ~28mm was observed in Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions with a final measured settlement of about 37mm.
- The slope between points D08LP008 and D08LP010 was 0.84mm/m prior to the commissioning of the compensation grouting array from GS4 as a result of movements generated by TCRSU. No grout jacking was instructed by CRL under ScoGM Clause 3.2.6.2. The slope temporarily exceed the Amber trigger value at the start of Period D during construction of AP3E and AP4E with a maximum value of 1.13mm/m. The slope was less than 1mm/m until June 2014 during PTE excavation when it again exceeded the amber value. The slope has remained stable throughout Period F with a maximum value of 1.17mm/m recorded.

6. DISCUSSION

The preceding presentation of settlement monitoring data shows that the Compensation Grouting Performance Criteria (CGPC) on slope has been exceeded at two locations within the footprint of the arrays installed from Grout Shaft 4.

There was only one Amber trigger breach on a building facade (Falconberg Mews west) which was controlled by grout jacking during construction but exceeded the Amber value in the post construction period. The monitoring data was reviewed at SRG and CTC meeting and it was deemed that no further grout jacking was necessary. It is noted that this façade is in close proximity to TCRSU structures which restricted the ability to control movement. It can be directly concluded that there were no deflection ratio triggers exceeded on BRE.

The one Amber slope trigger breach on PLP was primarily a result of movements generated prior to the commissioning of the GS4 arrays. It was not deemed necessary to undertake grout jacking which resulted in a marginal breach of the trigger value (maximum value 1.17mm/m). It can be directly concluded that there were no deflection ratio triggers exceeded on PLP.

It is BFK's view that the prime purpose of compensation grouting is to reduce the volume loss settlements associated with tunnelling since the associated slopes and curvatures are used to determine the need for protective measures: this objective has been successfully achieved.

7. CONCLUSION

It was concluded that no further grouting from TCR GS4 would be required based on an abridged version of this report submitted in October 2014: Grout Shaft 4 was subsequently decommissioned (C300-CCM-09098 and C300-CCM-09389).

The key factor which lead to this conclusion was that, in the 8 months after the completion of tunnelling and compensation grouting, ongoing post construction settlements were kept under continual review at daily, weekly and monthly review meetings and no grout jacking was deemed necessary. Thus, it was concluded that
the grout shaft could be decommissioned.

Manual monitoring within the GS4 area was terminated under C300-PMI-01858, and consequently this report comprises a Final and Close Out report.

Appendix A

Assumptions used to produce contour plots of grout intensity

A method of producing a visualisation of the quantity and distribution of grout injected during compensation grouting is useful in interpreting performance. For each injection the volume and the location of the port used are known. The model used is intended to approximate the distribution of grout within the ground at the level of injection not to estimate the potential heave / settlement reduction from the grouting. Of course the actual
distribution of grout in the ground cannot be determined since this is determined by the stress conditions at the time of injection which is constantly changing during the construction process. It is known that in London Clay the grout enters the ground by hydrofracturing along pre-existing fissures, but the direction of travel is not fully known.

The model used adopts the simple assumption that the grout spreads uniformly in all directions radially from the point of injection to form a disc of uniform thickness, t. The radius, r, to which the grout spreads from each
individual injection point is therefore a function of the grout volume, V, according to the relationship:

$$V = \pi r^2 t$$

Or, rearranging:

$$r = \sqrt{\left(\frac{V}{\pi t}\right)}$$

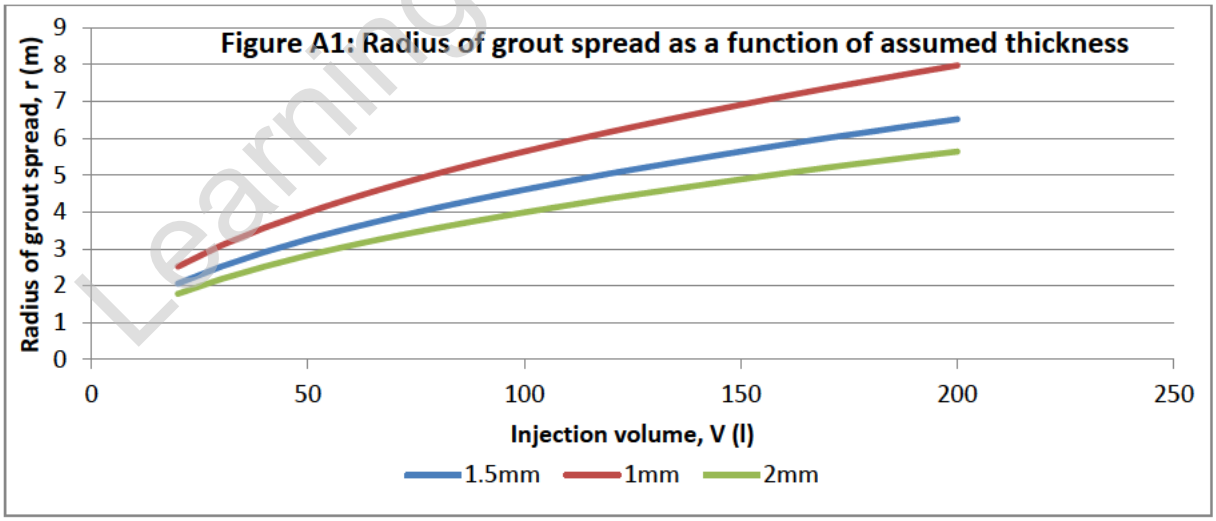


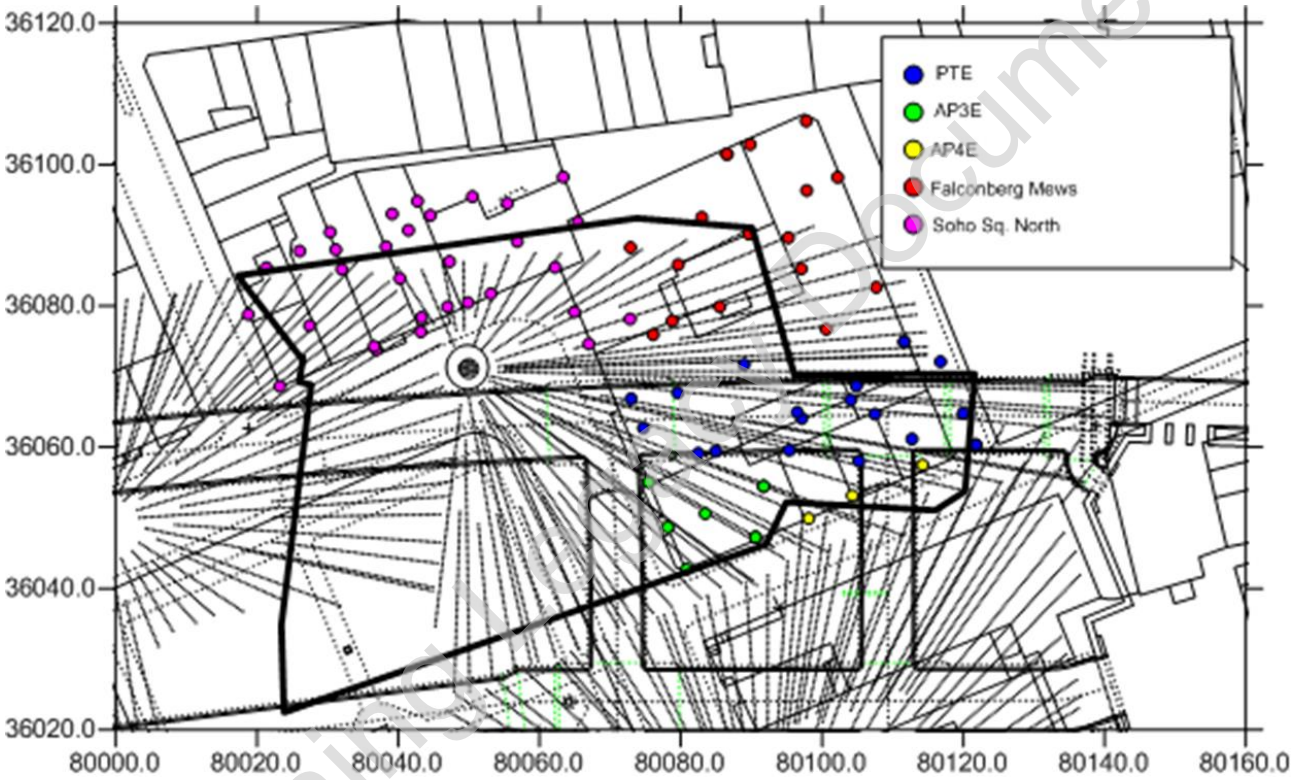
Figure A1: Radius of grout spread as a function of assumed thickness

Observations of grout in the ground suggests that a thickness of 1 – 2mm is predominantly achieved. All of the plots included in this report are based on an assumed thickness of 1.5mm. Figure A1 shows the variation in radius for thicknesses of 1.0, 1.5 and 2.0mm.

The contribution of each injection within a specified data set are summed at each node within a grid. This grid file is then contoured within Surfer.

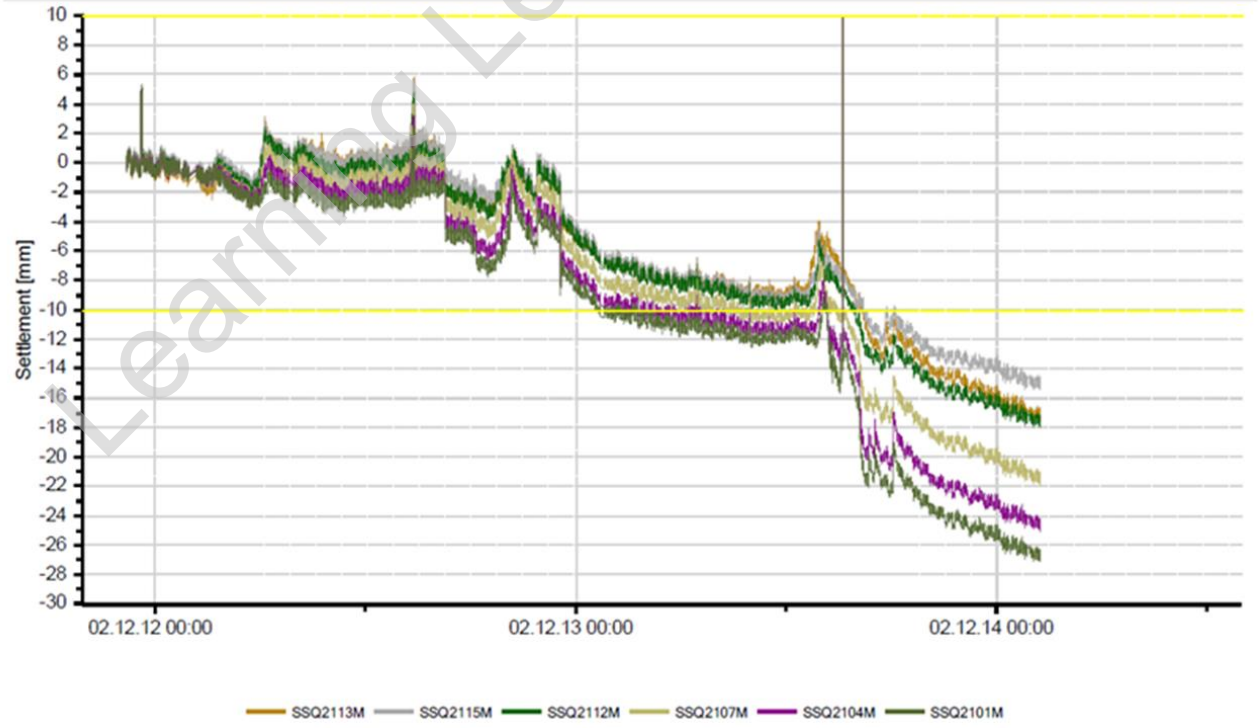
Appendix B

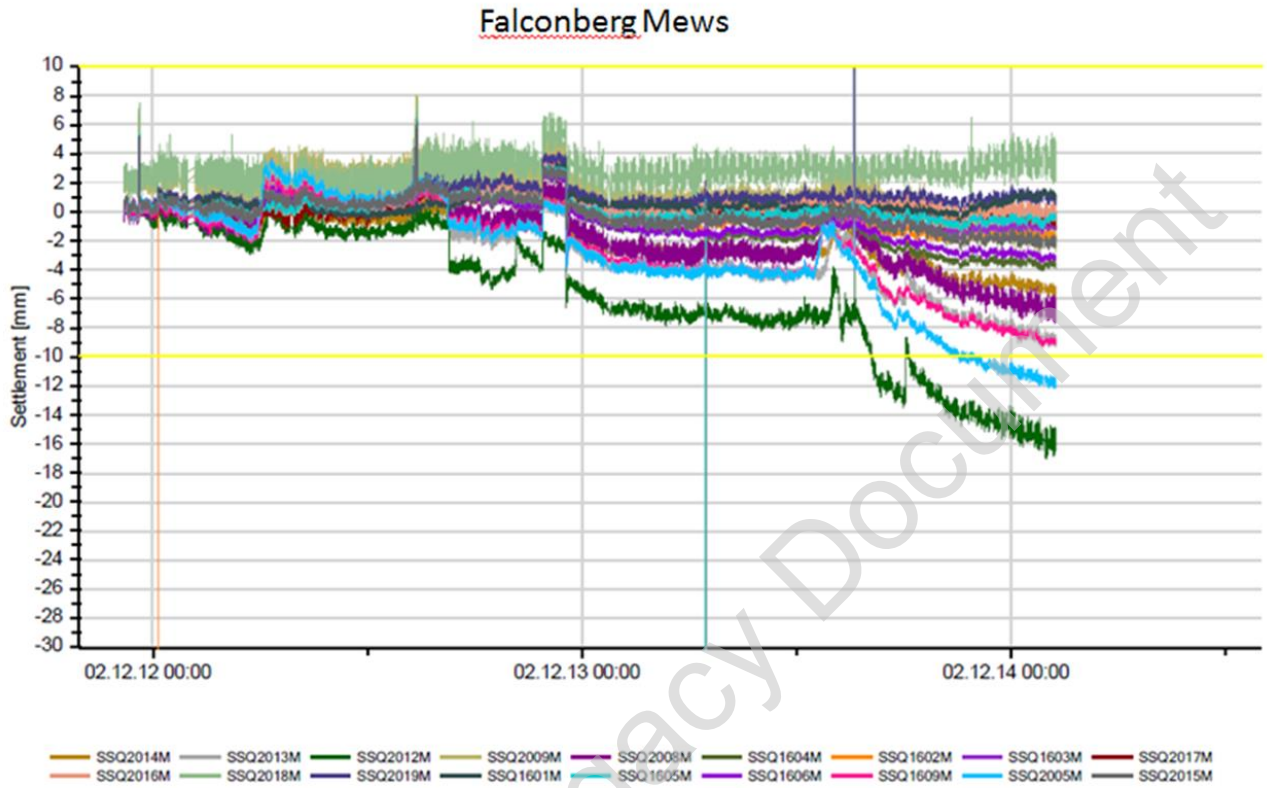
Example plots of HLC data

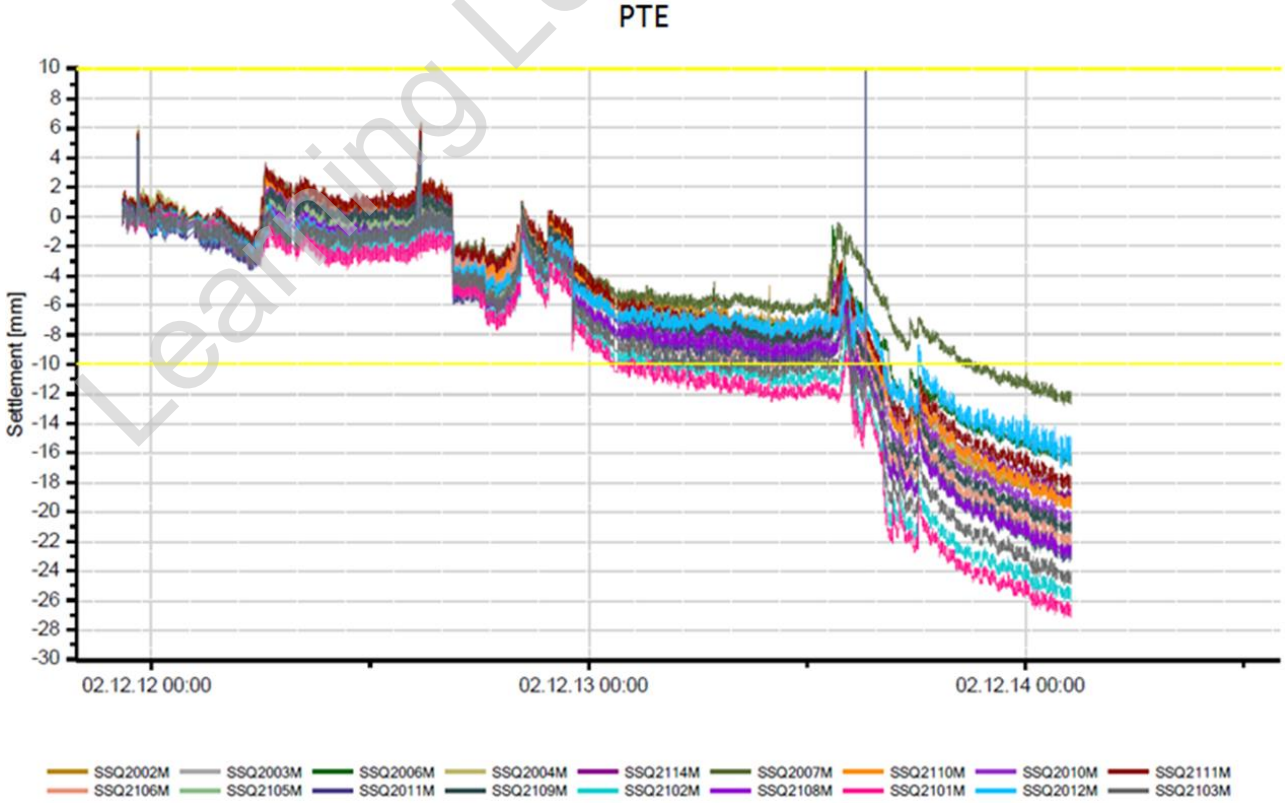


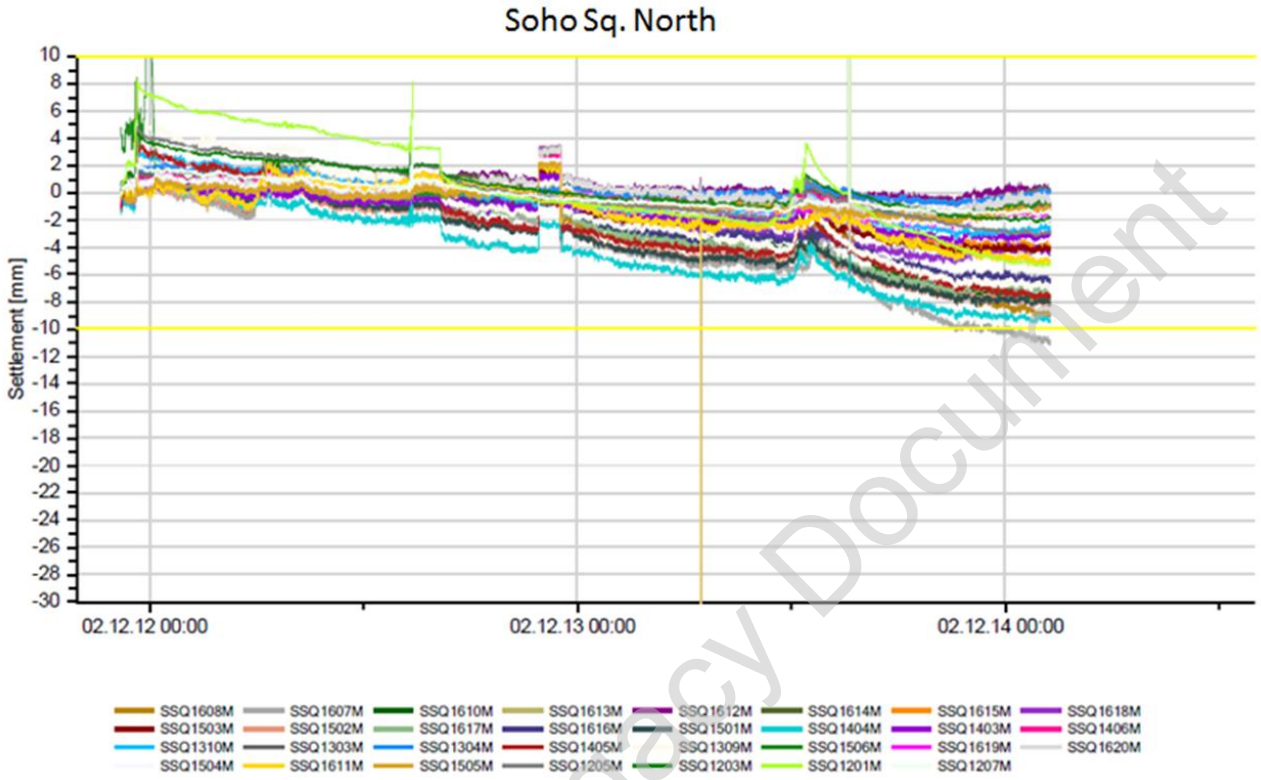
AP3E

AP4E

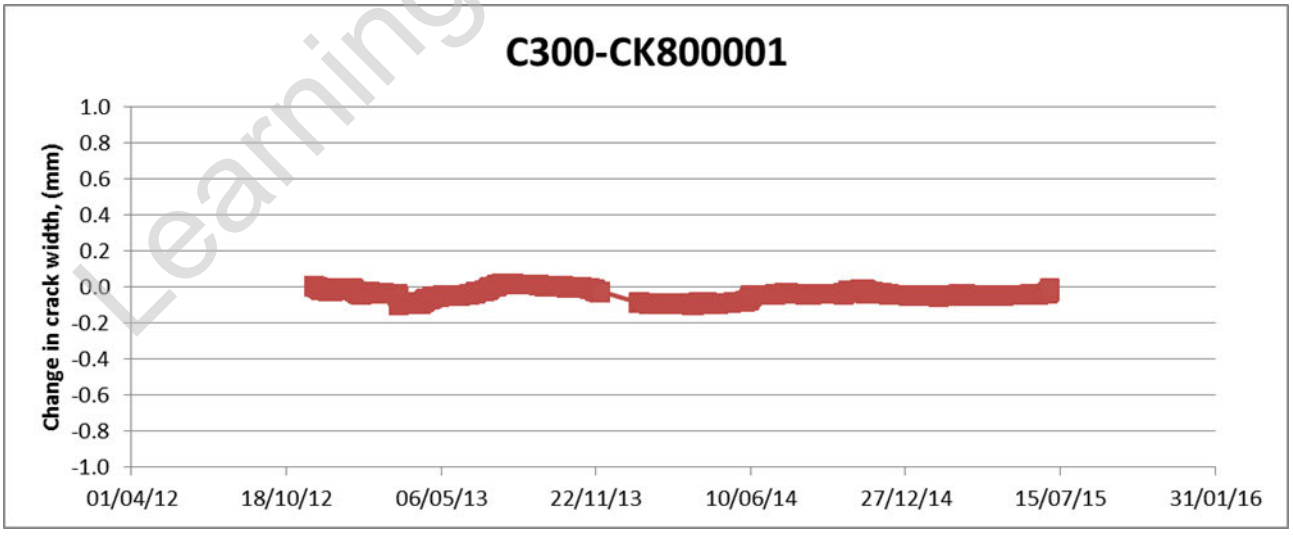








Crack meter data – 17 Soho Square



Appendix C

Summary of TCRSU construction dates (Provided by C122)

Table 1: Surface excavation

Completed Surface Excavations	Maximum Depth of Excavation	Main Dates of Excavation
Falconburg Shaft	98.25 mATD	14/02/2011 - 27/05/2011
Falconburg Basement	110.25 mATD	01/10/2012 - 28/11/2012
Ticket Hall	112.6 mATD	27/05/2011 - 06/09/2012
Goslett Yard Box	97.0 mATD	11/01/2012 - 14/10/2013
Goslett Yard Decline	106.0 mATD	04/04/2012 - 25/01/2013
Oxford Street Entrance	119.6 mATD	02/06/2011 - 21/05/2012
Northern Line Escalator	94.9 mATD	05/11/2010 - 16/06/2011

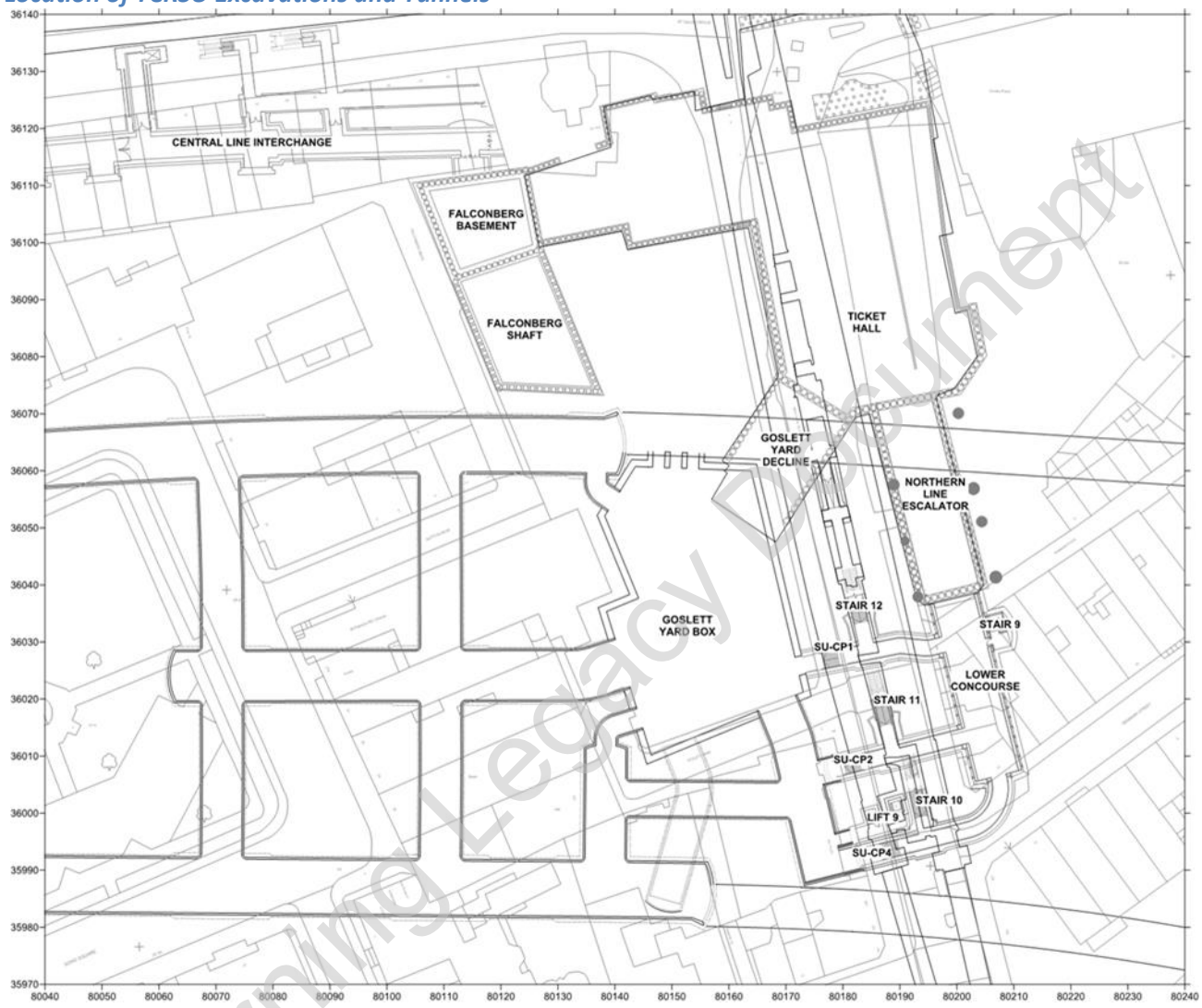
Table 2: Goslett Yard Detailed Excavation Dates

Construction Stage	From	To
Install Diaphragm Walls	08/11/2010	20/04/2011
Excavate Level -1 West Side	11/01/2012	09/02/2012
Excavate Level -1 East Side	08/02/2012	17/02/2012
Excavate Level -2 West	12/04/2012	14/05/2012
Excavate Level -2 East	14/05/2012	29/05/2012
Excavate Level -3	07/09/2012	12/12/2012
Excavate Level -4	07/01/2013	10/05/2013
Excavate Level -5	22/04/2013	12/08/2013
Level -1 Slab Pour	22/03/2012	03/04/2012
Level -2 Slab Pour	07/06/2012	05/09/2012
Level -3 Slab Pour	08/11/2012	24/06/2013
Level -4 Slab Pour	08/02/2013	24/05/2013
Level -5 Slab Pour	15/08/2013	12/10/2013

Table 3: Underground

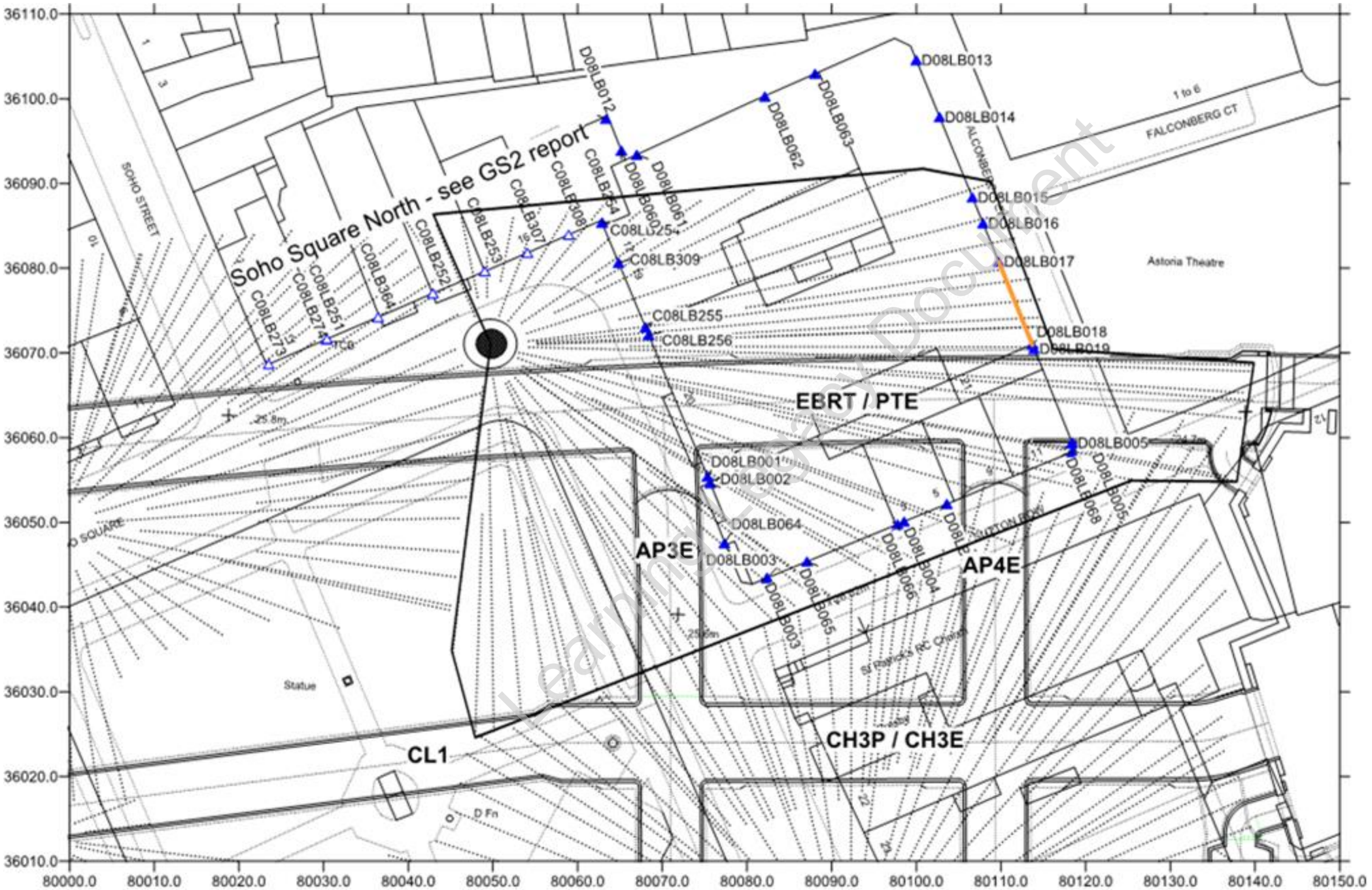
Completed Underground Construction Works	From	To
Northern Line		
Lift 4 Excavation	19-Nov-10	14-Apr-11
Stair 11 Platform Works	09-May-11	03-Sep-11
Stair 12 Platform Works	09-May-11	03-Sep-11
Lift 4 Platform Works	27-Jun-11	05-Nov-11
Northern Line Lower Concourse Excavation	19-Feb-12	10-May-12
CP2 Excavation	12-May-12	23-May-12
CP4 Excavation Stage 1	02-Jul-12	09-Jul-12
CP1 Excavation	10-Jul-12	20-Jul-12
Stair 11 Excavation	24-May-12	24-Aug-12
Stair 12 Excavation	20-Jul-12	05-Nov-12
CP4 Excavation Stage 2	25-Oct-12	09-Nov-12
Stair 10 Excavation	20-Aug-12	21-Dec-12
Lift 9 Excavation	20-Aug-12	21-Dec-12
Lift 2 Works	23-Mar-12	15-May-12
Central Line		
Central Line Interchange Tunnel Excavation	21-Jun-11	28-Nov-11
Overbridge 2 Excavation and primary lining	15-Feb-12	09-Mar-12
Overbridge 1 Excavation and primary lining	06-Mar-12	28-Mar-12

Location of TCRSU Excavations and Tunnels



Appendix D

Enlarged version of Figures 4.1 and 5.1 showing location of monitoring point and slope triggers


Soho Square North - see GS2 report
EBRT / PTE
AP3E
AP4E
CH3P / CH3E
CL1
D08LB012
D08LB013
D08LB014
D08LB015
D08LB016
D08LB017
D08LB018
D08LB019
D08LB062
D08LB063
D08LB061
D08LB060
C08LB254
C08LB309
C08LB307
C08LB308
C08LB253
C08LB252
C08LB364
C08LB251
C08LB274
C08LB273
C08LB255
C08LB256
D08LB001
D08LB002
D08LB064
D08LB003
D08LB065
D08LB066
D08LB004
D08LB068
D08LB005
SOHO STREET
FALCONBERG CT
Astoria Theatre
Statue
36110.0
36100.0
36090.0
36080.0
36070.0
36060.0
36050.0
36040.0
36030.0
36020.0
36010.0
80000.0
80010.0
80020.0
80030.0
80040.0
80050.0
80060.0
80070.0
80080.0
80090.0
80100.0
80110.0
80120.0
80130.0
80140.0
80150.0