C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - TCR GS2

CRL Document No. C300-BFK-C4-RGN-CRT00_ST005-51226

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1. Contractor Document Submittal History

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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.

Sign: _____ Name: _____ Role: _____ Date: _____

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2b. Review by Stakeholder (if required):

Stakeholder Organisation	Job Title	Name	Signature	Date	Acceptance
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					☐

3. Acceptance by *Crossrail:*

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☐	Code 3.	Not Accepted. Revise and resubmit. Work may not proceed
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Contents

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 2 and associated automatic monitoring at TCR Station

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 2 were completed by early June 2014. One small grout jacking episode was implemented immediately after the completion of tunnelling which was also completed in June 2014. An abridged version of this report was issued under C300-CCM-08869 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.

This report aims to summarise the relevant construction, compensation grouting and monitoring information for Grout Shaft 2 at TCR Station and includes manual monitoring up to September 2015 when most of the manual monitoring was de-scoped under C300-PMI-01858. Within the GS2 area, monitoring of the French Protestant Church was continued until January 2016: further monitoring of this building was de-scoped under C300-PMI-01914. 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 the instrumentation.

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

- H&S file – submitted separately for construction and 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.

The “as-built record and status” 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 "close-out" report is not required, since the 2mm/year criterion does not apply. Examples of data from the HLC and other special instruments in the GS2 area are included in Appendix B.

Table 2.1 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.

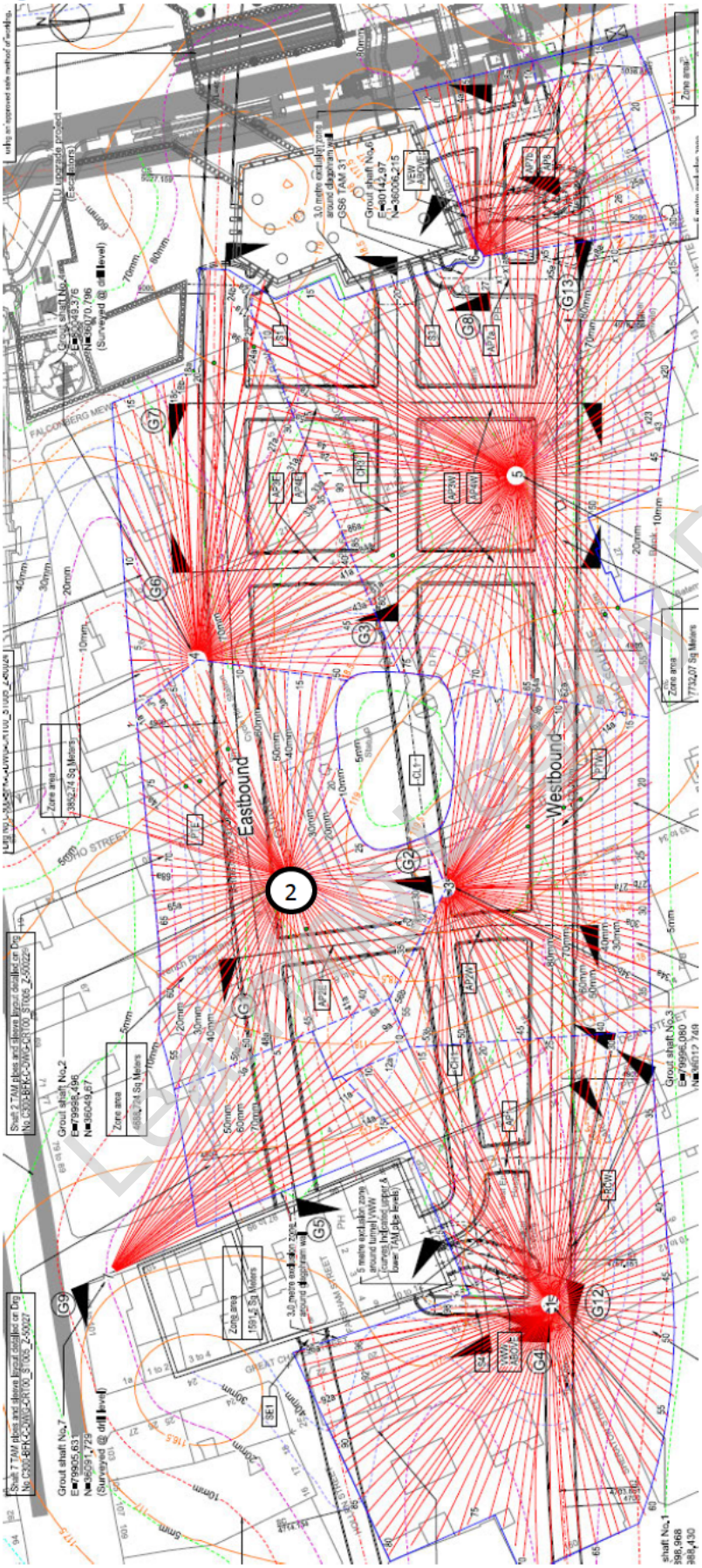
KX10.2113 Final Report

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 2.1.1 and Figure 2.1.1 show the tunnel construction works undertaken within the footprint of the compensation grouting arrays installed from Grout Shaft 2 at TCR Station.

Table 2.1.1. Progress of C300/C410 works at TCR GS2 area.

PERIOD	TUNNEL	START DATE	END DATE
C	Lower Concourse Tunnel 1 Extension (CH1Ext)	18/05/2013	29/05/2013
	Central Link 1 (CL1)	30/05/2013	20/06/2013
D	Eastbound Running Tunnel (EBRT)	03/08/2013	11/08/2013
	Access Passage 2 West (AP2W)	02/09/2013	04/09/2013
	Access Passage 2 East (AP2E)	07/09/2013	19/09/2013
F	Platform Tunnel Eastbound (PTE)	30/04/2014	21/06/2014
	Access Passage 2 East Stub	23/05/2014	25/05/2014

Figure 2.1.1 Tunnels within extent of grout array from Grout Shaft 2

2.2. Other construction works

Works by BFK prior to the commencement of tunnelling included:

- Drilling for installation of TaMs
- Pre-treatment grouting
- Excavation of Western Ticket Hall (WTH) box
- Sinking of Grout Shaft 2

Works by Others prior to the start of tunnelling included:

- Construction of Western Ticket Hall (WTH) diaphragm-walls

Works by Others during tunnelling comprised:

- Redevelopment of 61 Oxford Street

Works by Others after completion of tunnelling include:

- Installation of permanent structure within the WTH

N.B. Adjustments have been applied to allow for CRL works by Others prior to the commencement of monitoring for C300/C410 Works (see Section 3.2).

2.3. Compensation Grouting

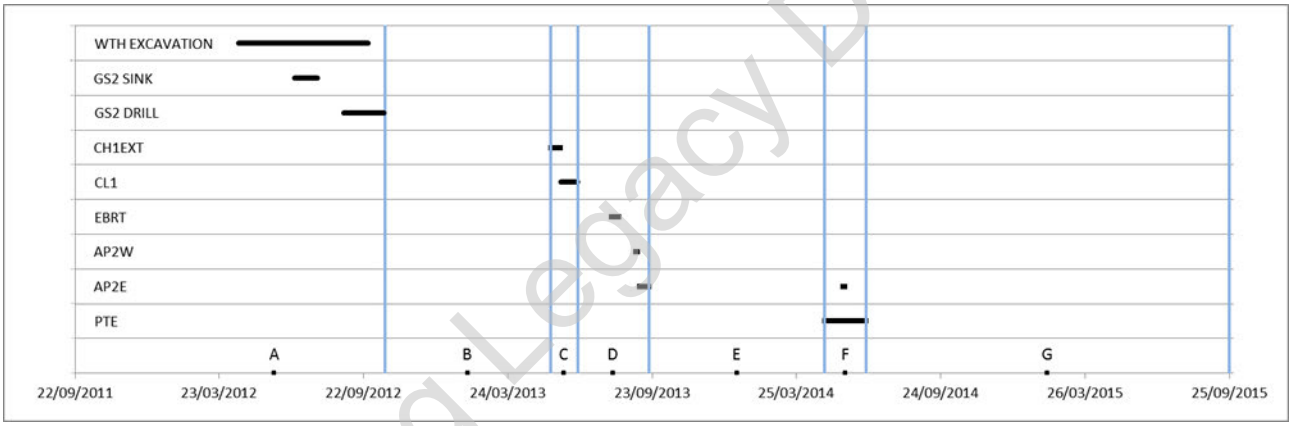
The volume of grout injected from TCR GS2 is plotted against time on Figure 2.3.1 together with a plot of when each of the tunnels was constructed. Figure 2.3.1 shows that pre-treatment comprised approximately 35m^3 injected prior to tunnelling, concurrent grouting 120m^3 and grout jacking just over 10m^3. Concurrent grouting was undertaken with all tunnels except the EBRT and CL1. A VE proposal was implemented to avoid any delays to the running tunnel drive which allowed grouting to be undertaken pre- and post- tunnelling – the volume of grout associated with this is included under grout jacking. CL1 is a temporary tunnel below the centre of Soho Square and CRL deemed that concurrent compensation grouting was not mandatory (C300-PMI-00434).

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 GS2 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 2.3.1 Construction Periods for works in TCR GS2 area

Period	Start Date	End Date	Main Works
A	30/09/2011	19/10/2012	GS2 Sink, GS2 TaM installation, WTH excavation
B	19/10/2012	17/05/2013	GS2 Pre-treatment
C	17/05/2013	21/06/2013	CH1Ext excavation, CL1 excavation, concurrent grouting
D	21/06/2013	19/09/2013	EBRT passage, AP2W excavation, AP2E excavation, concurrent grouting, jack grouting
E	19/09/2013	30/04/2014	Jack grouting
F	30/04/2014	21/06/2014	AP2E Stub excavation, PTE excavation, concurrent grouting, jack grouting
G	21/06/2014	25/09/2015	Jack grouting

Figure 2.3.1 Volume of grout injected from TCR GS2 by grouting type.



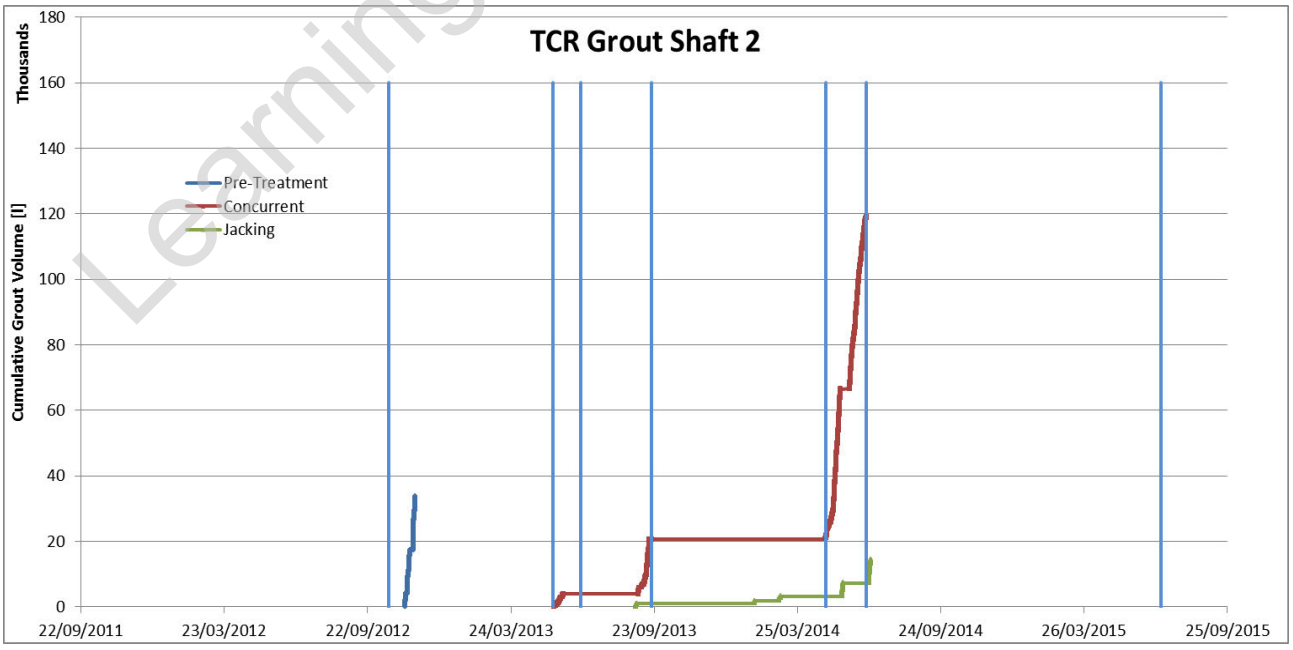


Figure 2.3.2 Distribution of grout injected from TCR GS2: Pretreatment grouting. Grout Intensity (mm).

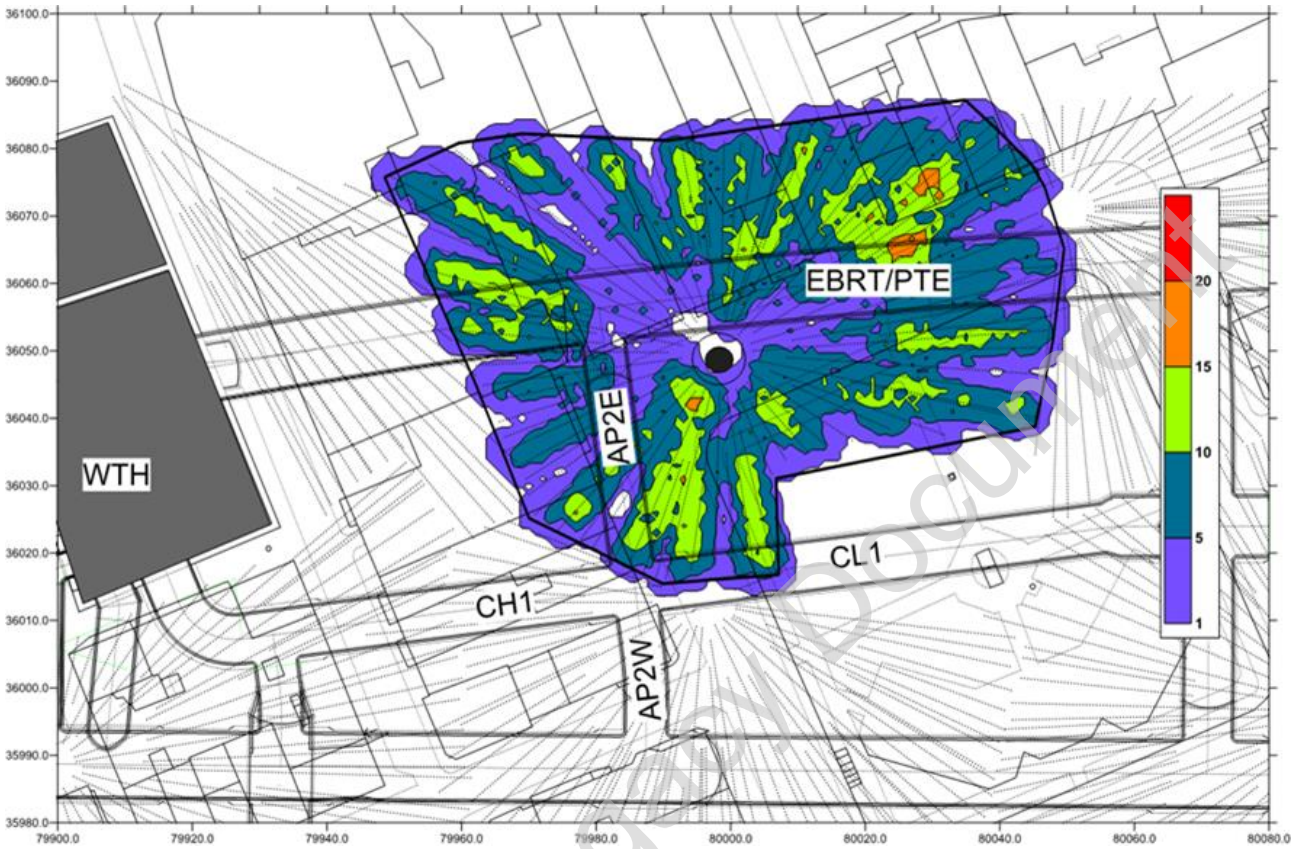


Figure 2.3.3 Distribution of grout injected from TCR GS2: Concurrent grouting. Grout Intensity (mm).

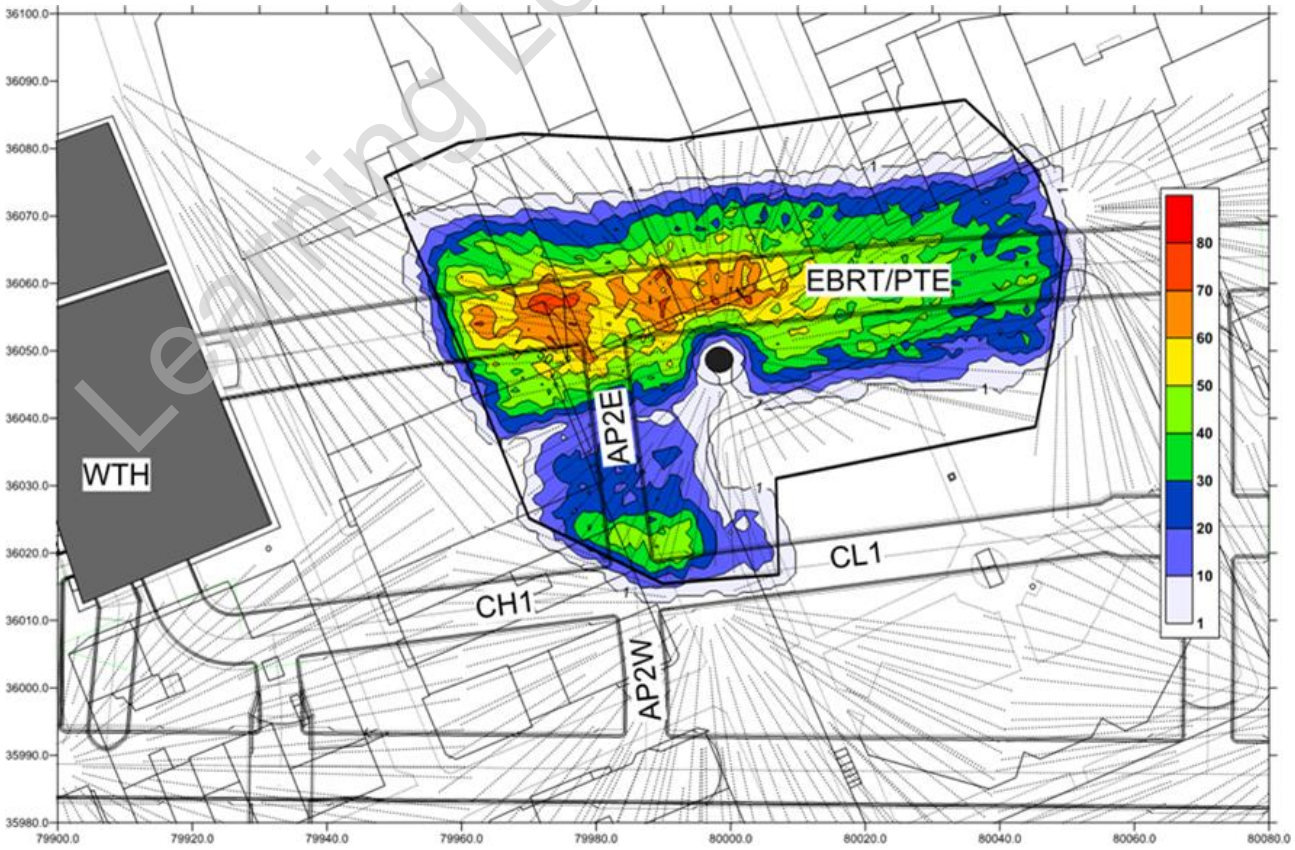


Figure 2.3.4 Distribution of grout injected from TCR GS2: Jack grouting. Grout Intensity (mm).

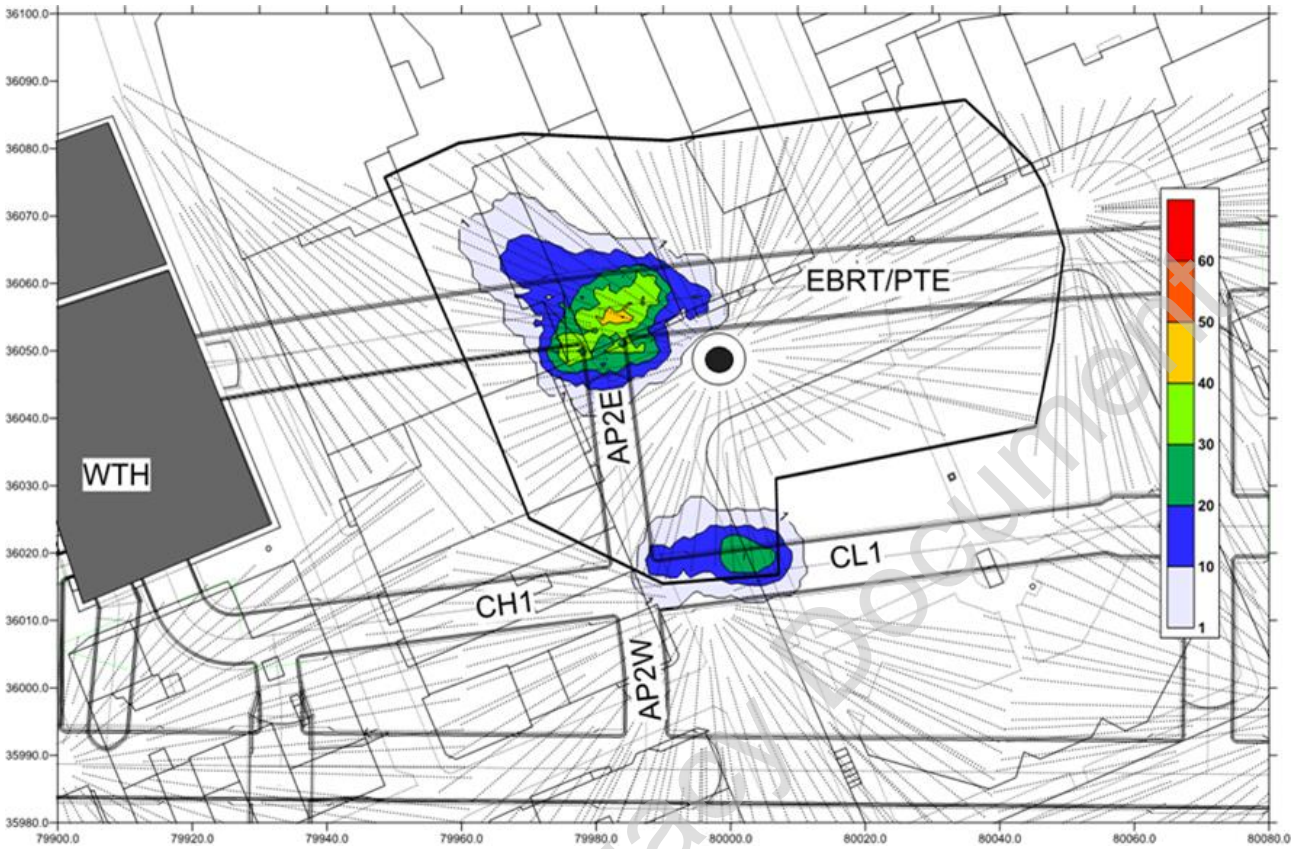
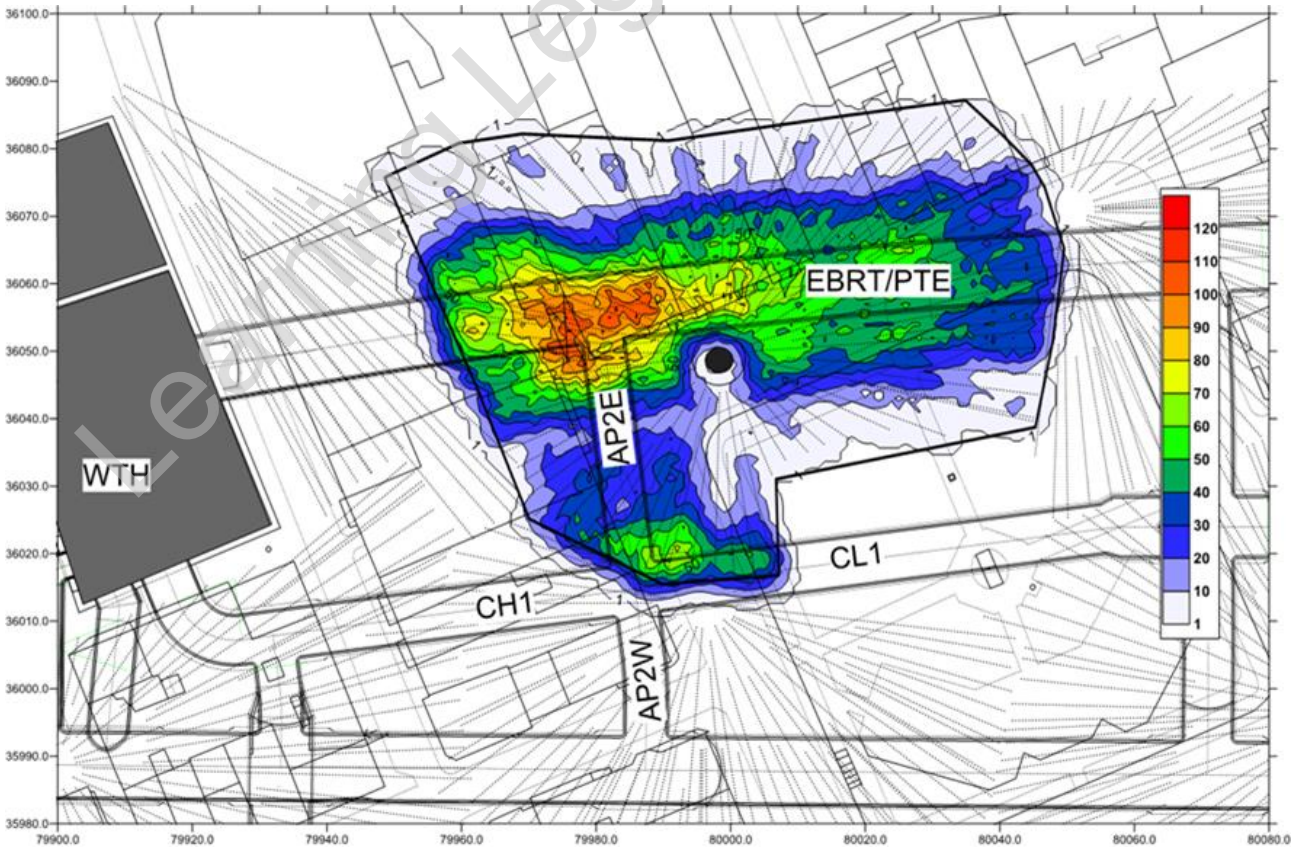


Figure 2.3.5 Distribution of grout injected from TCR GS2: All grouting. Grout Intensity (mm).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. Settlement Overview

Contours of total predicted short term greenfield settlement (supplied by C122) is shown in Figure 3.1.1. The measured settlement at the end of construction in June 2014, including consolidation settlement and effects of compensation grouting during the period of construction, is shown in Figure 3.1.2.

The following points are noted:

- Within the GS2 area, settlements are significantly less than the predicted values, notwithstanding that the observed movements include a significant proportion of consolidation settlement over the 3 ½ year construction period.
- The maximum observed settlement is just above 20mm compared with over 60mm for the prediction contours.
- The most obvious differences between the predictions and the observations are:
    - The Zone of influence (1mm contour) is much smaller than expected;
    - The slopes (as indicated by the number and spacing of contours) are significantly reduced.

Figure 3.1.1. Predicted greenfield settlement contour (supplied by C122)

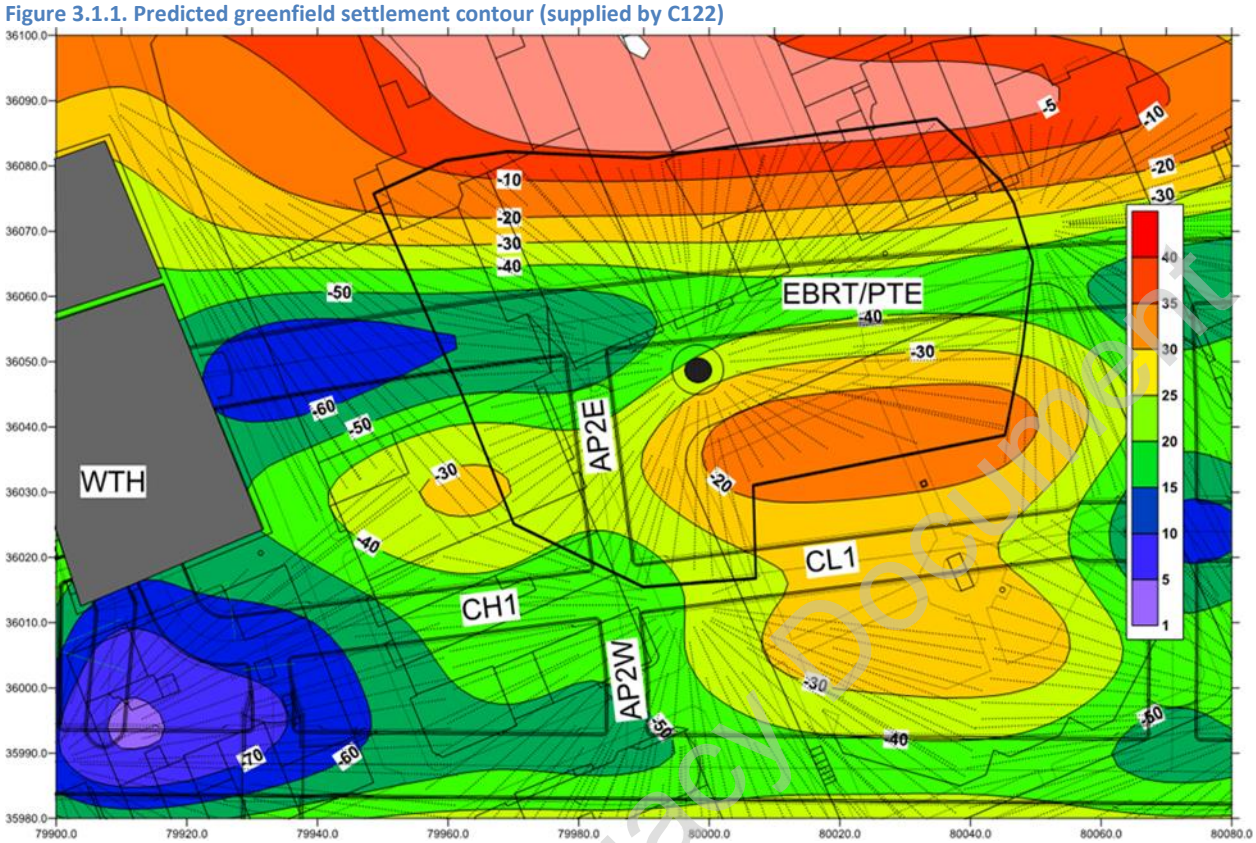
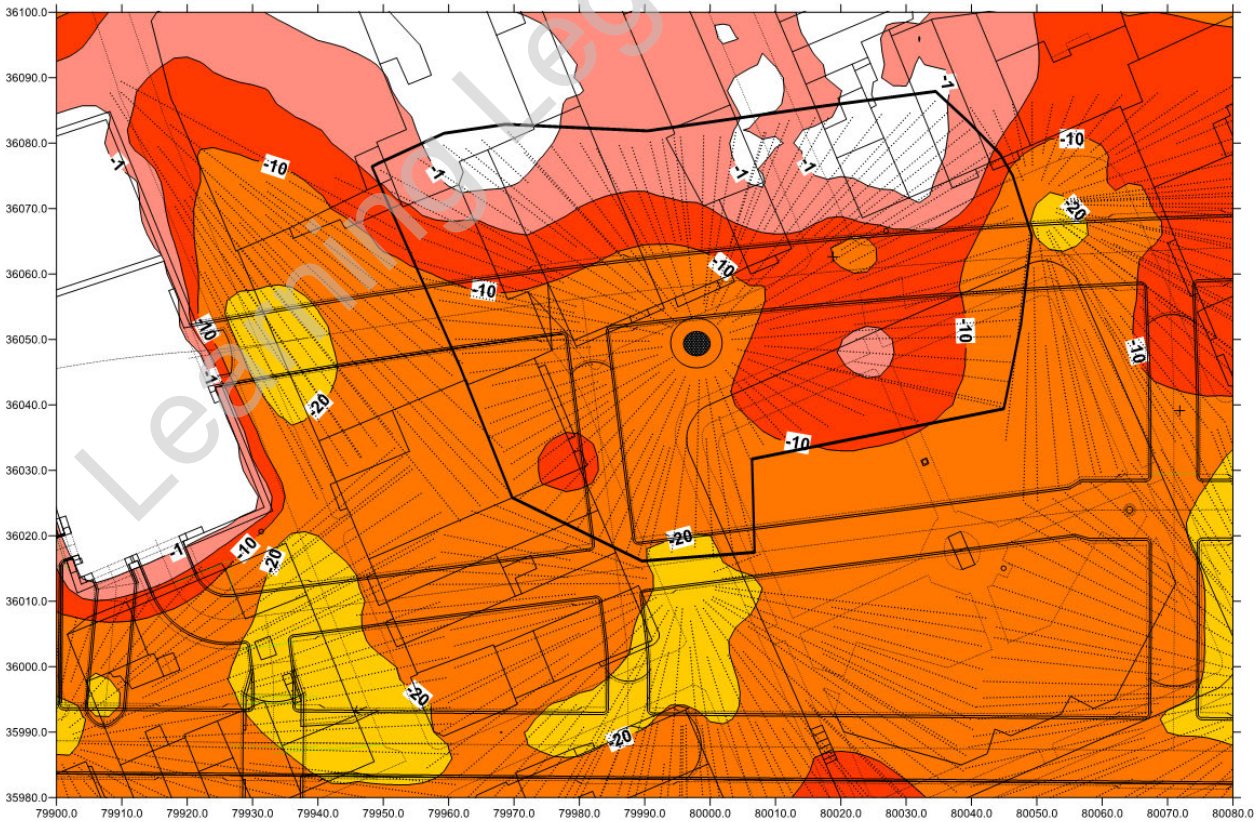


Figure 3.1.2 Observed settlement contour in June 2014 (end of construction – Period F)



In order to compare the predicted and actual movements at various stages of construction, the overall monitoring period from September 2011 to the cessation of general monitoring in September 2015 has been divided into a number of periods, based largely on tunnel excavation progress. The dates of the construction activities in each period are summarised in Table 2.1.1.

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: 30/09/11 – 19/10/12 – Prior to tunnelling

Period A includes all of the preparatory work by Others prior to the commencement of tunnelling, including demolition, piling and diaphragm walling for the Western Ticket Hall. BFK works comprised excavation of the WTH south box, sinking GS2 and drilling of TaMs from TCR GS2. Adjustments have been applied to the BFK monitoring based on the contour shown in Figure 3.2.1 which shows the settlement recorded by C421 at completion of their works (surveys on 08/02/12 and 09/02/12): the effects within the GS2 area are negligible.

Settlement had also been generated by the LU TCRSU project at the eastern end of the station. Significant movements had been generated to the east of Soho Street. Adjustments to allow for these movements have been made to the BFK data based on the contour re-produced as Figure 3.2.2. 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 at the completion of BFK Grout Shaft 2 sinking and TaM drilling.

The calculated short term movements associated with excavation of the Western Ticket Hall south box are shown in Figure 3.2.3 (as supplied by C122). Greatest settlement is ~20mm at the walls of the excavation. It is understood that this is intended to include wall installation effects. The observed settlements (adjusted to allow for movements prior to the start of BFK monitoring) are shown on Figure 3.2.4, which indicate much more localized and smaller movements with a maximum value of ~10mm and less than 1mm in the GS2 area.

The maximum settlement within the GS2 area is less than 5mm as a result of installation of the compensation grouting facilities.

Figure 3.2.1 Contours of settlement based on C421 data at completion of their works (February 2012)

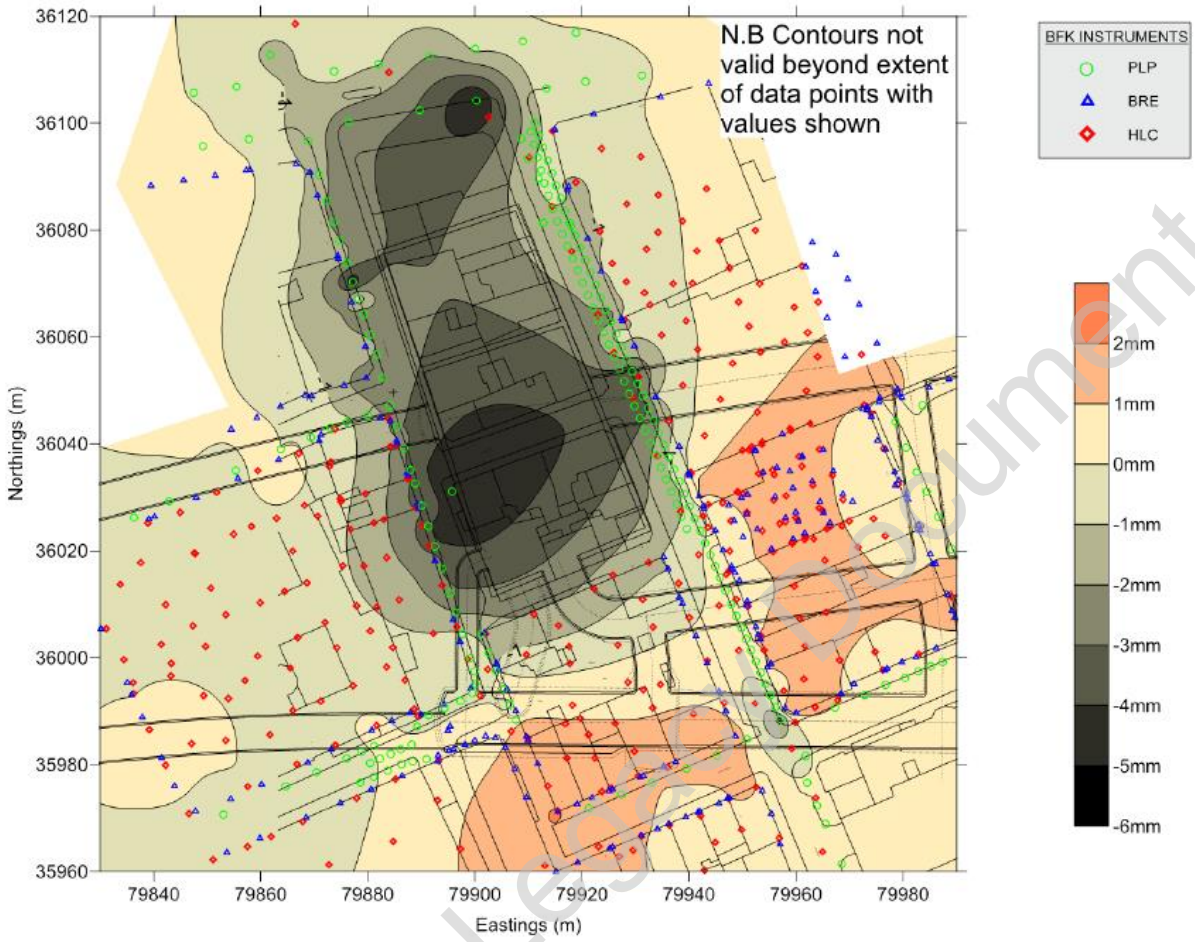


Figure 3.2.2 Contours of settlement from TCRSU works prior to and during Periods A and B

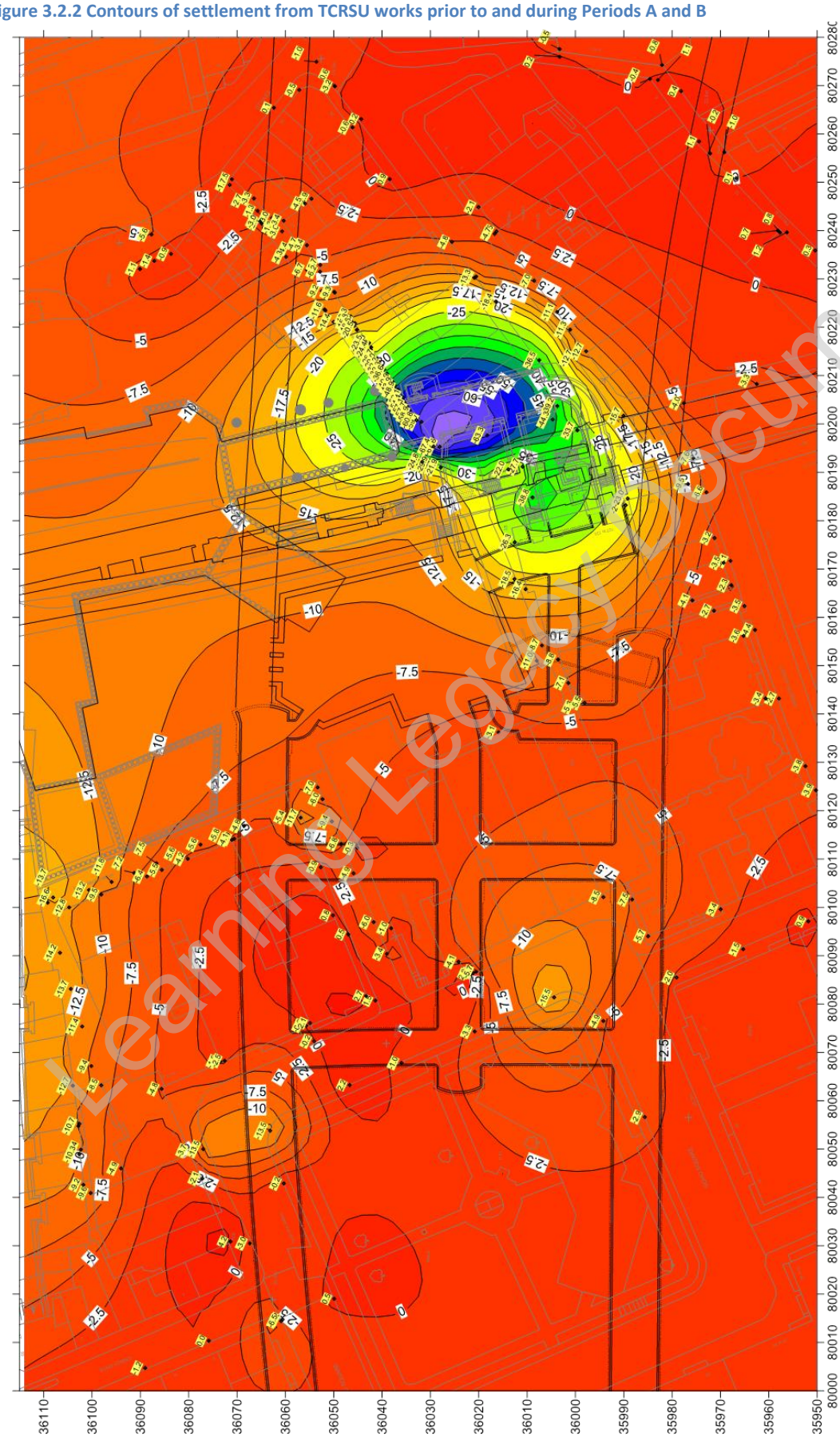


Figure 3.2.3. Period A: Total predicted greenfield settlement contours (supplied by C122)

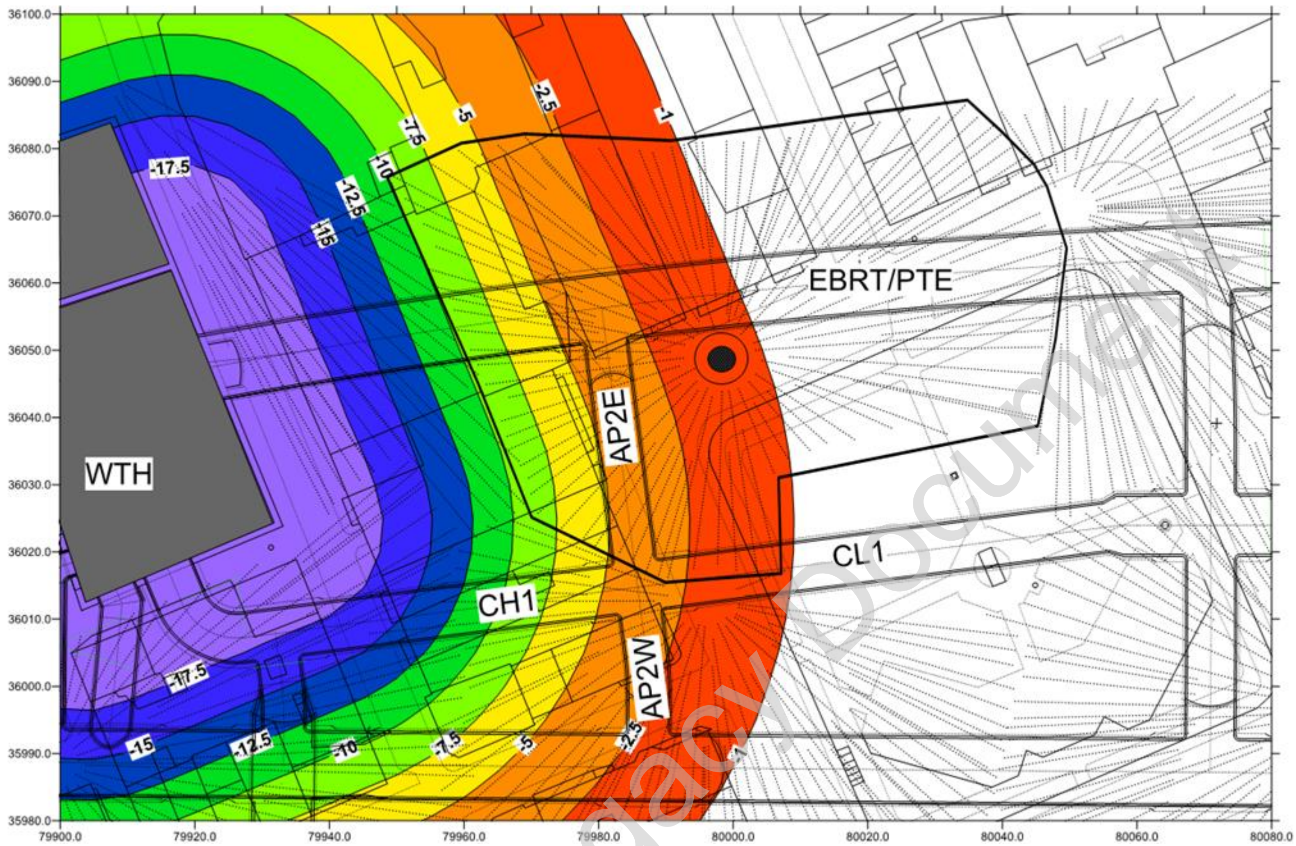
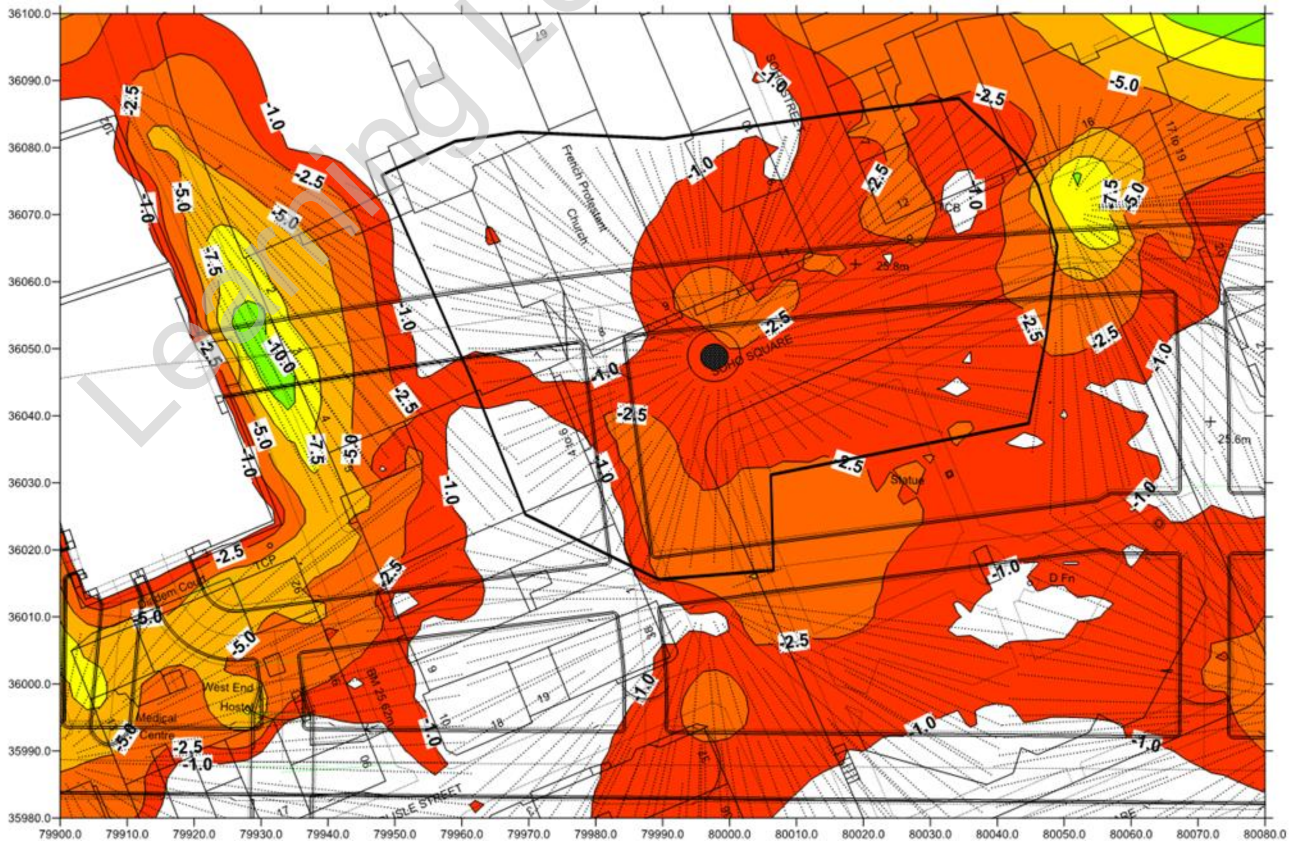


Figure 3.2.4 Period A: Total measured settlement



3.3. Period B: 19/10/12- 17/05/13 No tunnelling within GS2 area, pre-treatment.

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

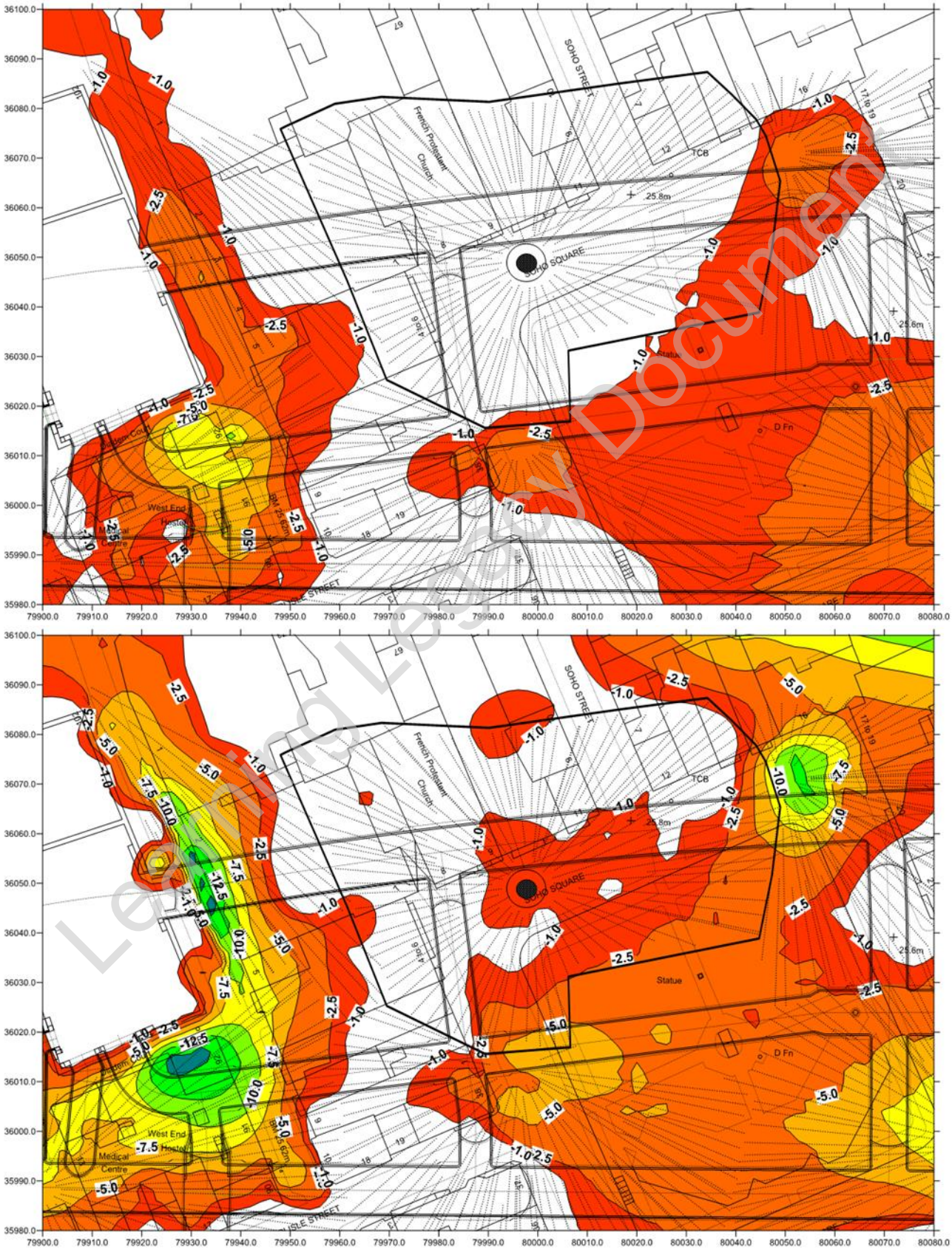


Figure 3.3.2 Period B: Distribution of grout injected from TCR GS2: Pre-treatment grouting. Grout Intensity (mm).

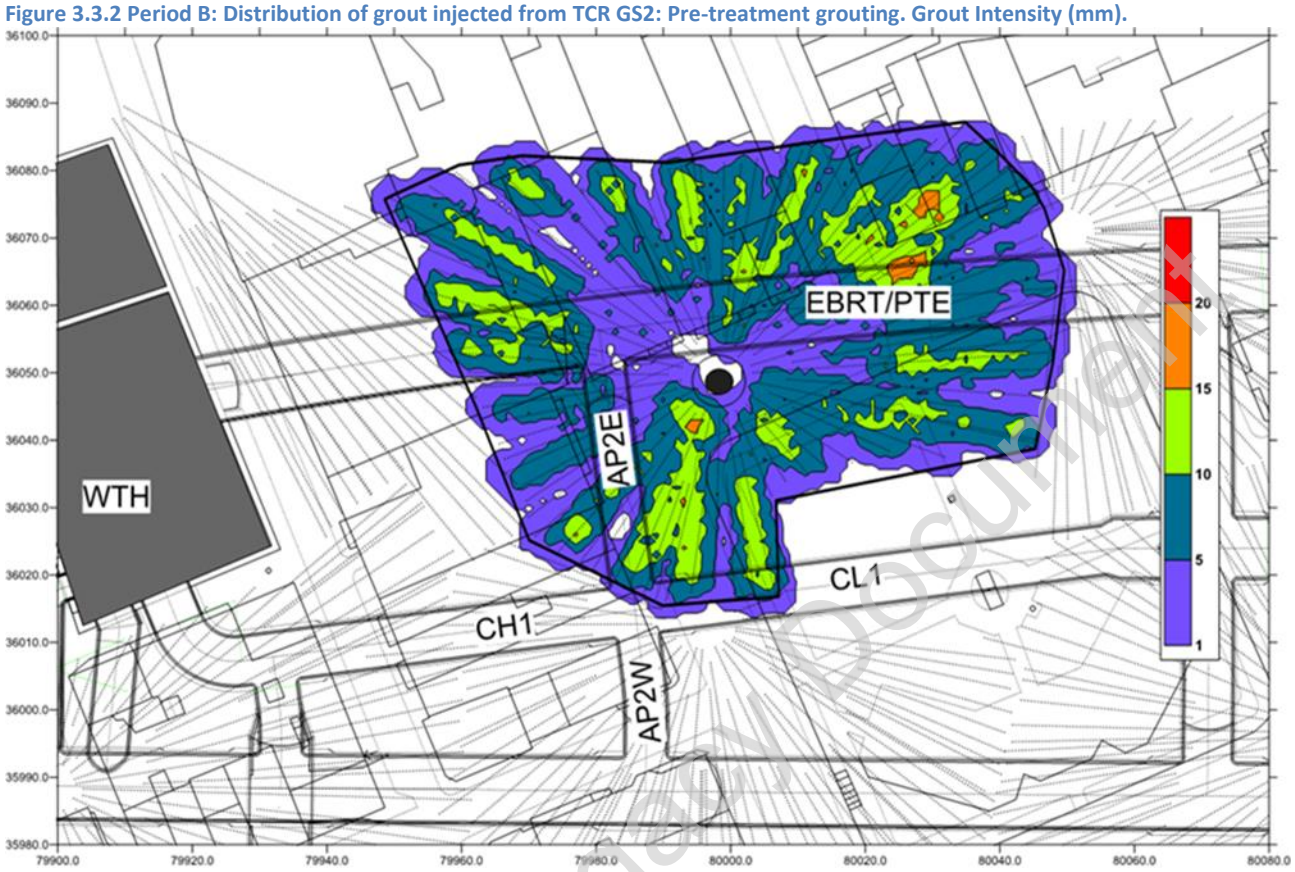
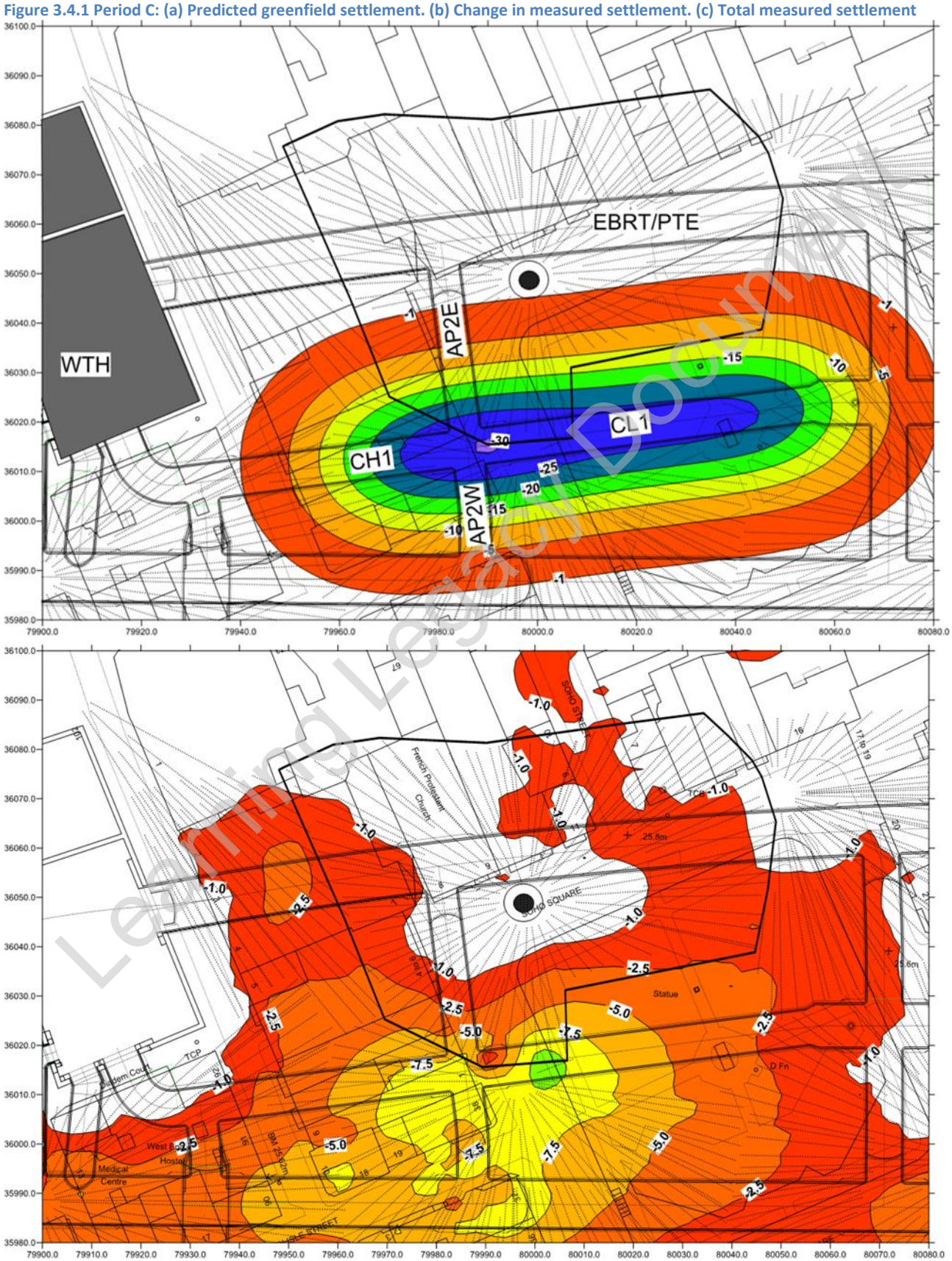


Figure 3.3.1(a) shows some increase in settlement in the GS1 area as a result of the commencement of CH1. The net change in movement in the GS2 area during Period B is negligible since the only works undertaken in this area was pre-treatment grouting. The grouting caused an uplift of up to 5mm but settlement following the completion of drilling and the completion of the grouting gave a very small net change at the end of Period B. Figure 3.3.1(b) indicates a small general reduction in settlement a maximum contour of -7.5mm at the east end of the GS2 arrays, adjacent to GS4.

Figure 3.3.2 shows the grouting intensity for the pre-treatment grouting with a maximum of 15mm and an average of less than 10mm. Pre-treatment was entirely completed in Period B and, consequently, the contours of grout intensity shown in Figure 3.3.2 are identical to those in Figure 2.3.

3.4. Period C: 17/05/13 – 21/06/13 CH1 Ext., CL1, Concurrent Grouting.

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



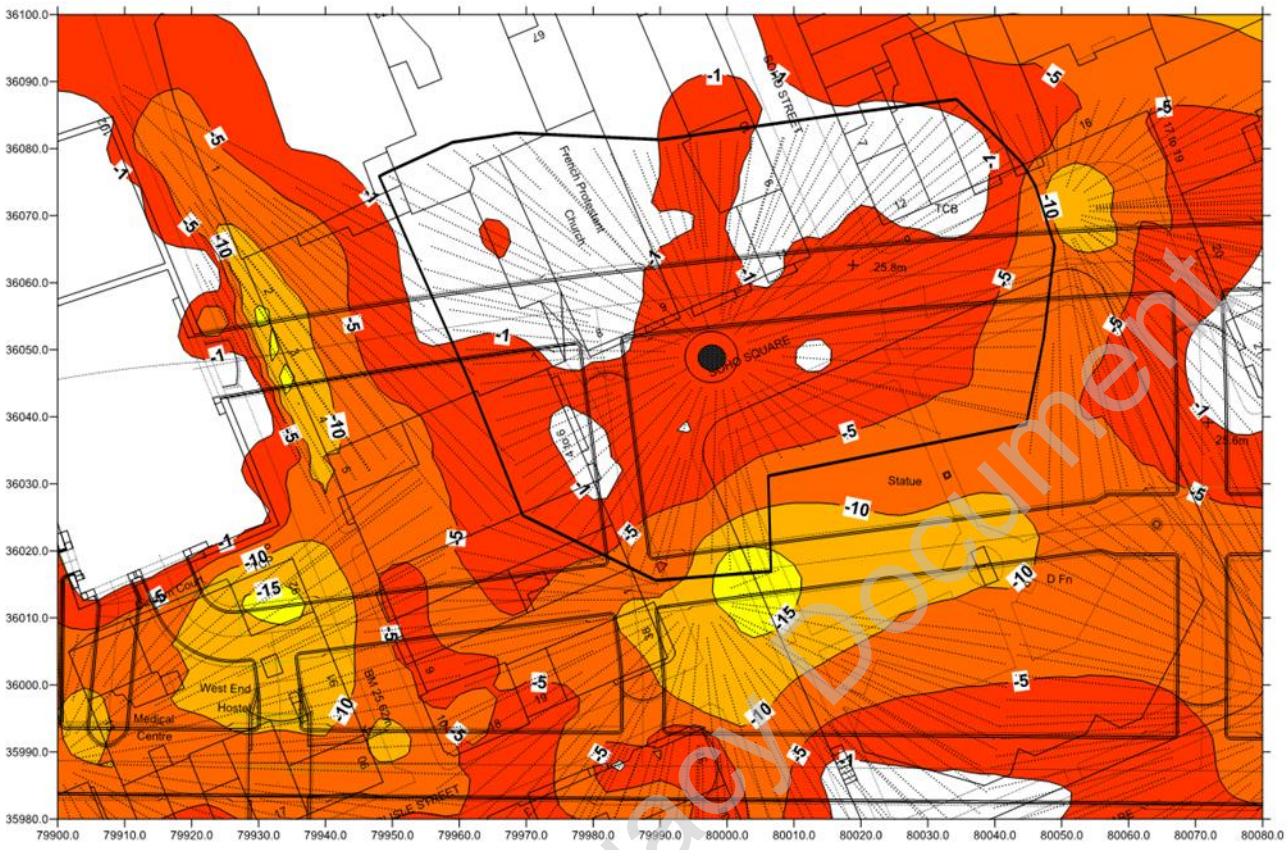


Figure 3.4.2 Period C: Distribution of grout injected from TCR GS2: Concurrent grouting. Grout Intensity (mm).

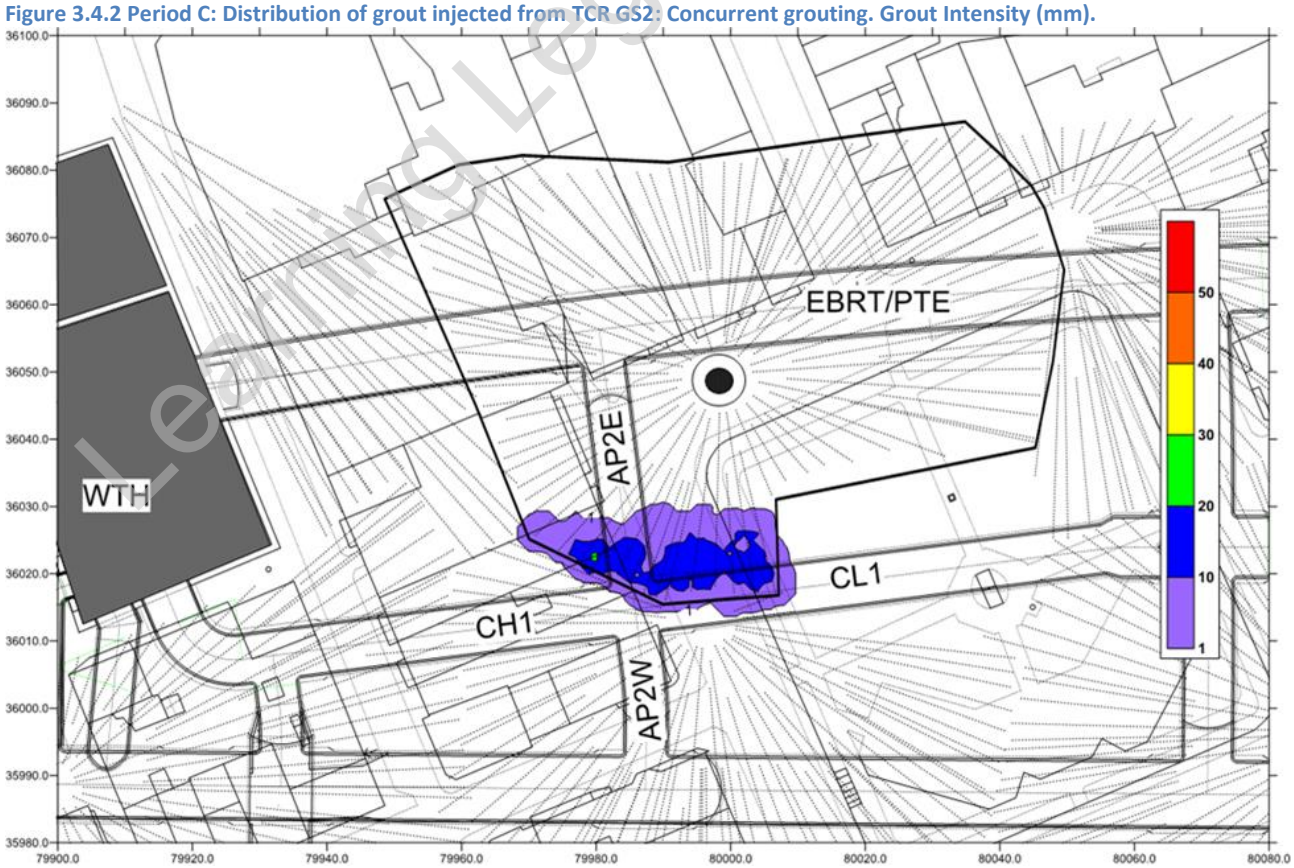


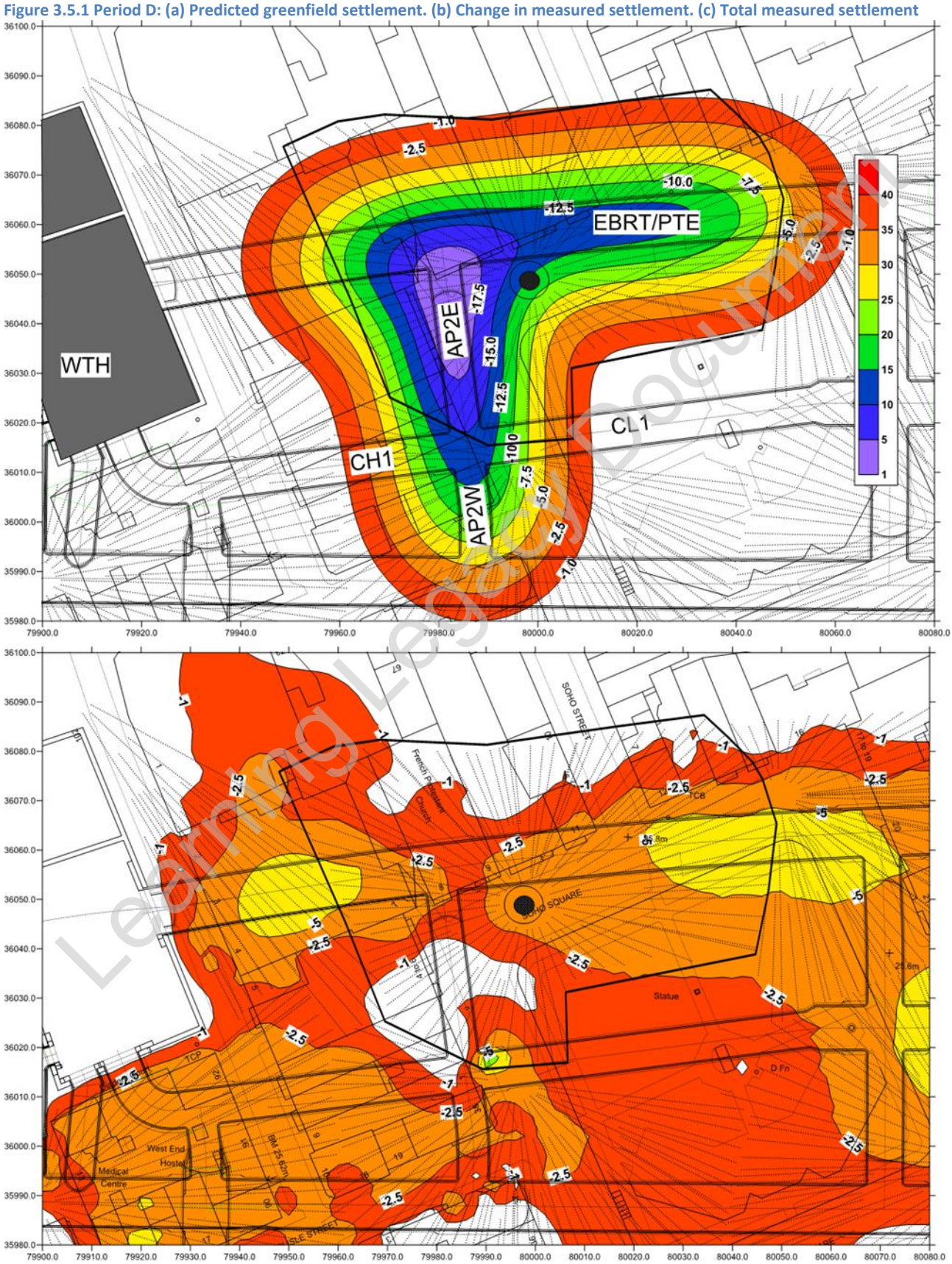
Figure 3.4.1(a) shows that 30mm volume loss settlement was anticipated for CH1Ext / CL1 tunnels at the southern extremity of the TCR GS2 arrays.

Figure 3.4.1(b) shows the recorded settlement with a maximum of ~10mm at the extremity of the TCR GS2 array. The movements within the remainder of the TCR GS2 area were less than 5mm in Period C. At the end of Period C the cumulative movements (Figure 3.4.1(c)) show that the -15mm contour is just within the plan extent of GS2 arrays.

Figure 3.4.2 shows the concurrent grouting undertaken for CH1Ext from TCR GS2. The majority of the grouting was undertaken from GS1 and GS3. It should be noted that no concurrent compensation grouting was undertaken with CL1 since CRL determined that this was no necessary for this additional temporary tunnel (C300-PMI-00434).

3.5. Period D: 21/06/13 – 19/09/13 EBRT, AP2W, AP2E , Concurrent and Jack Grouting.

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



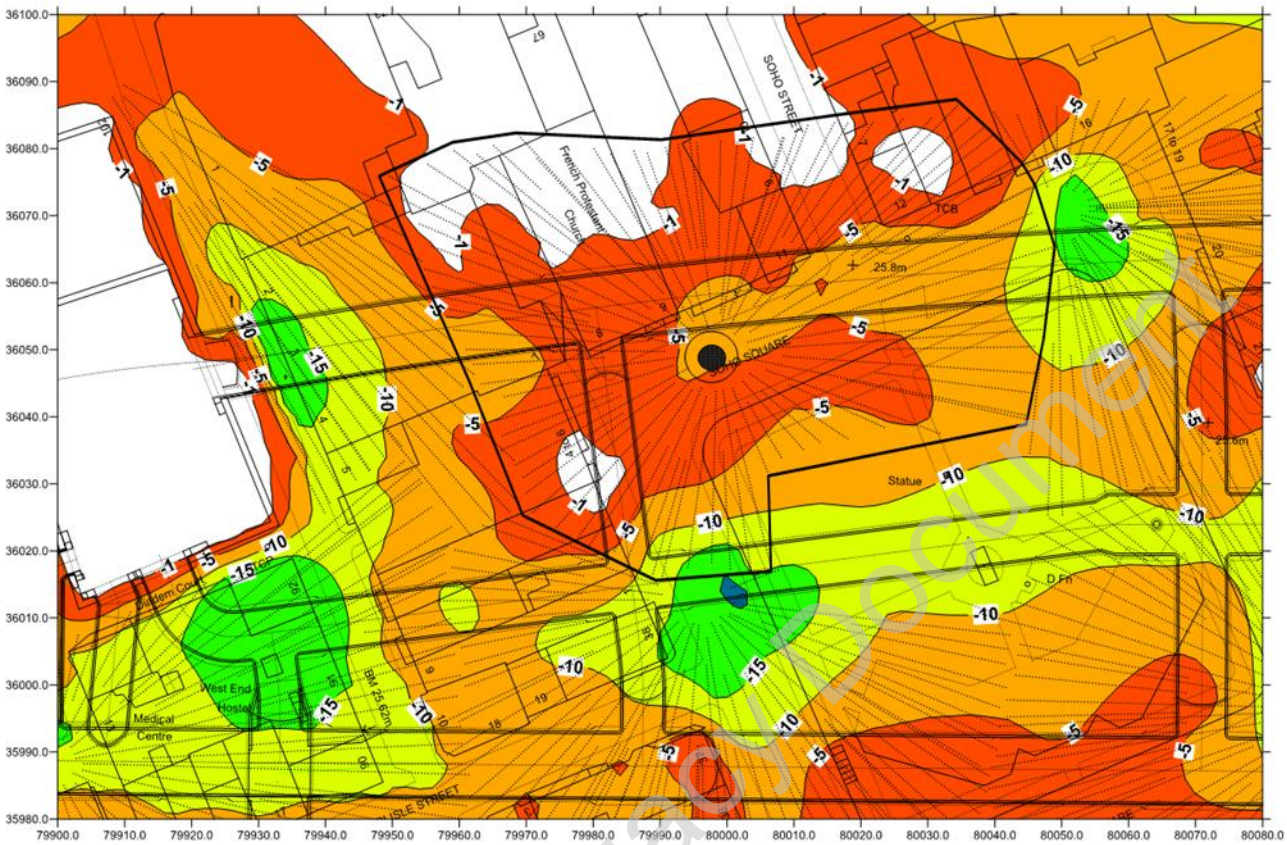


Figure 3.5.2 Period D: Distribution of grout injected from TCR GS2. Concurrent grouting. Grout Intensity (mm).

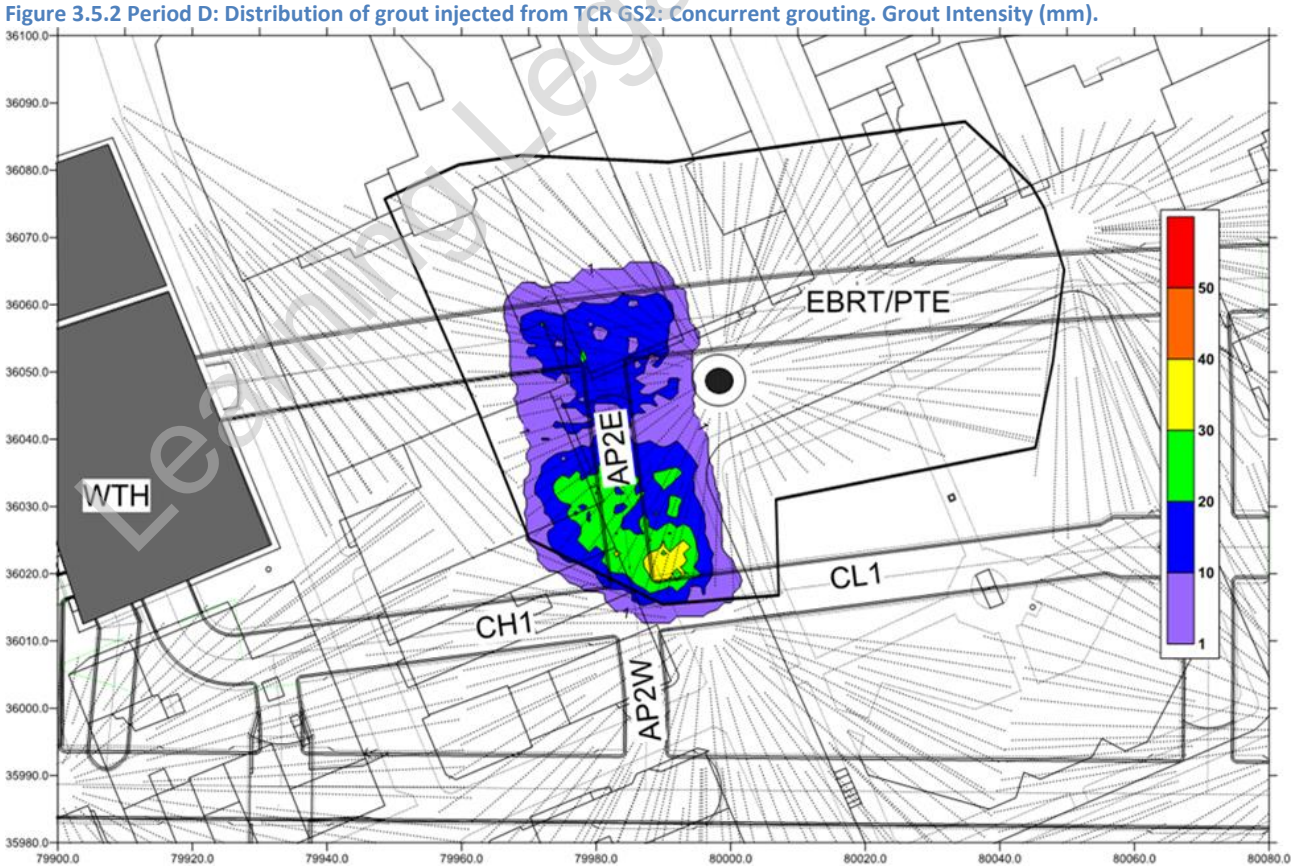
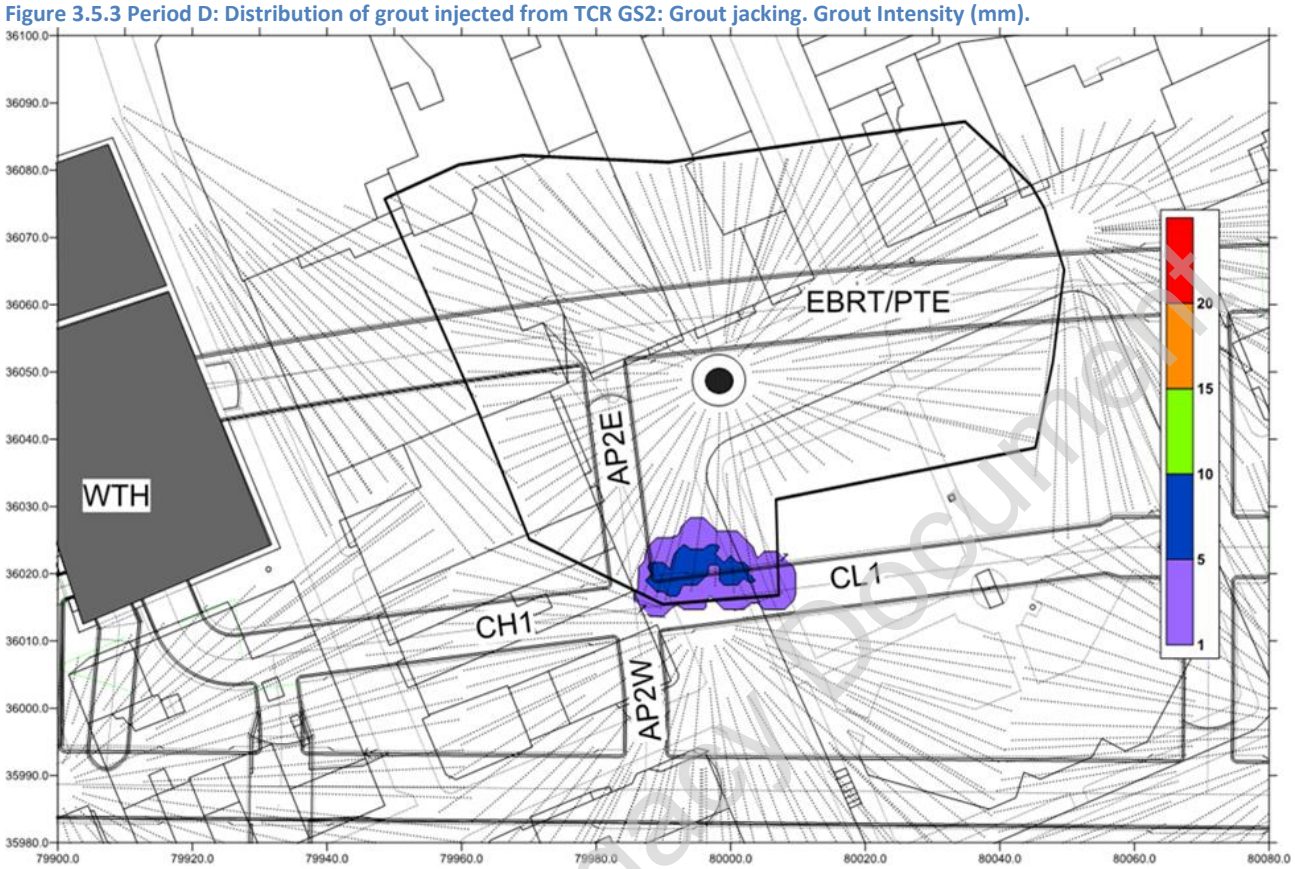


Figure 3.5.3 Period D: Distribution of grout injected from TCR GS2: Grout jacking. Grout Intensity (mm).



The predicted greenfield settlement contour from construction of the EBRT (without compensation grouting) and AP2E in Figure 3.5.1 indicates about 20mm maximum settlement at the specified volume losses (Figure 3.5.1a) where the effects from both tunnels combine. The maximum volume loss settlement for the EBRT alone is ~13mm. At the eastern and western ends of the GS2 array there was 6mm observed settlement (Figure 3.5.1b). Smaller settlement is apparent at the junction of the two tunnels in the zone of compensation grouting for AP2E. The maximum observed settlement in Period D from AP2E is 3mm compared with the volume loss value of 18mm, demonstrating the grout injected concurrently with AP2E excavation (Figure 3.5.2) was successful in controlling settlement.

Figure 3.5.1c shows that the cumulative settlement adjacent to GS3, at the southern extremity of the GS2 area, had reached 20mm following construction of CL1. An episode of grout jacking was undertaken from GS3 and GS2 to control the associated slopes (see Figure 3.5.3).

3.6. Period E: 19/09/13 – 30/04/14 No Tunnelling in GS2 area. Jack Grouting.

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

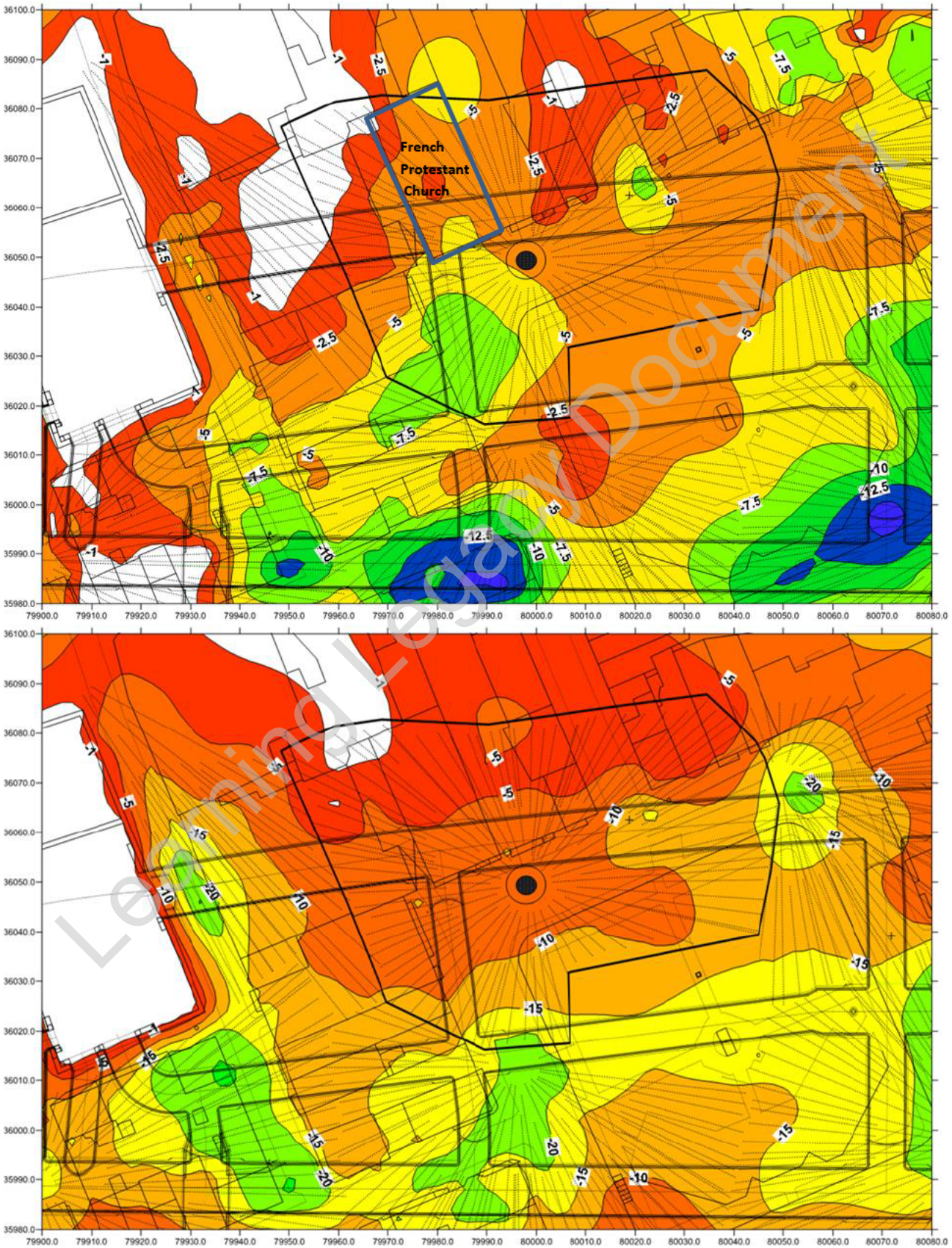
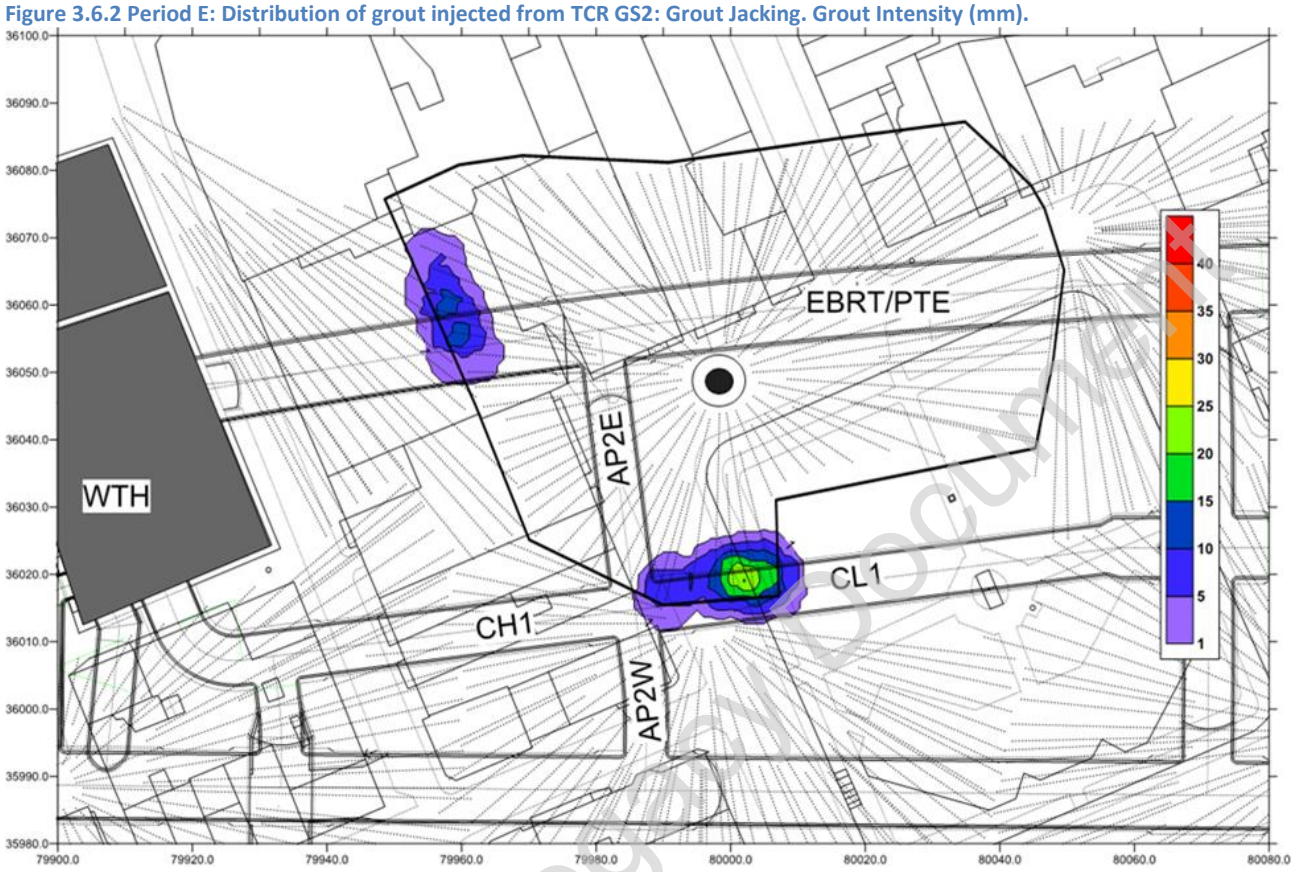


Figure 3.6.2 Period E: Distribution of grout injected from TCR GS2: Grout Jacking. Grout Intensity (mm).



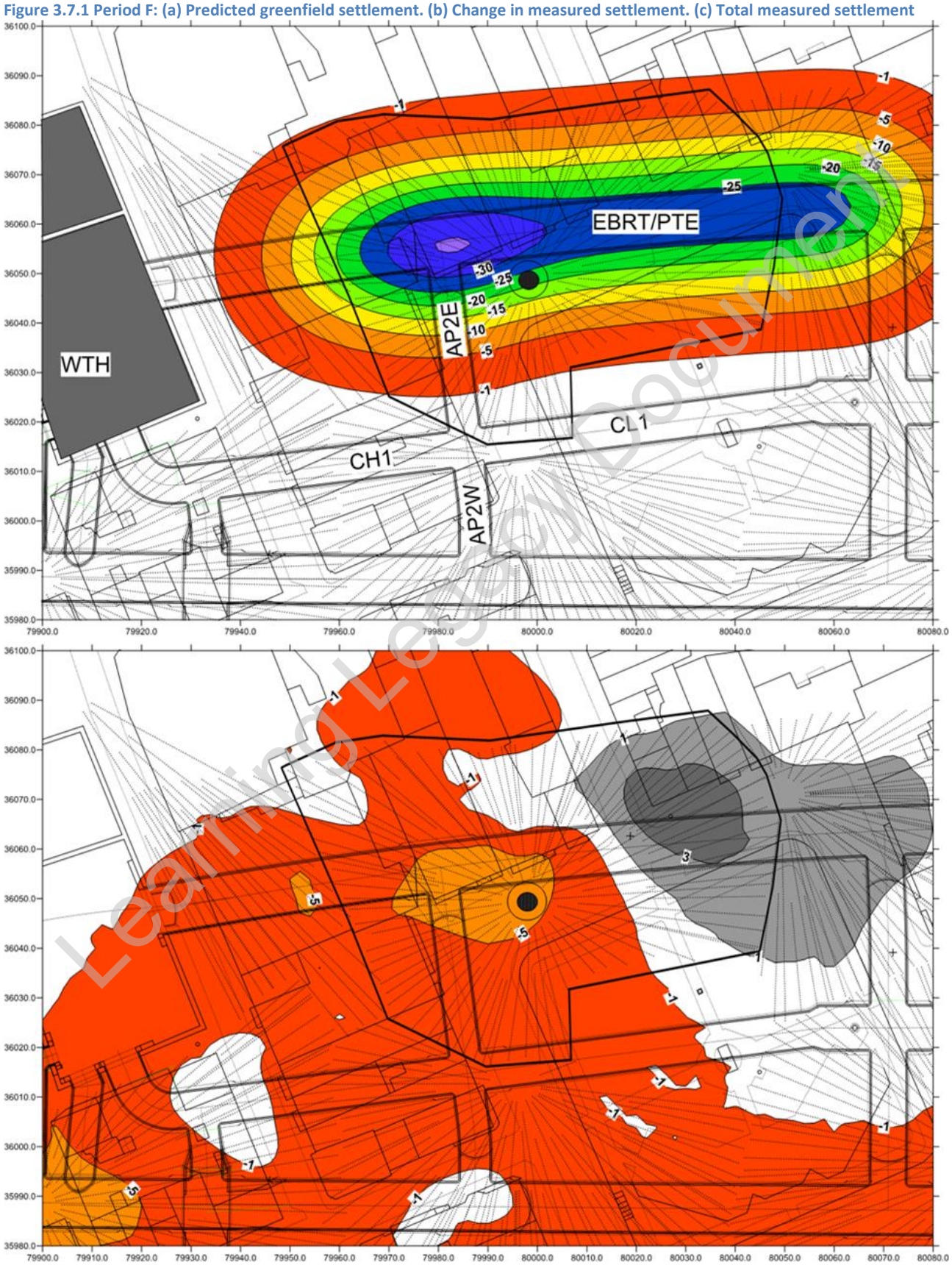
There was no tunnelling within the GS2 area within the 7 month duration of Period E, but increases in settlement of up to 10mm were recorded over AP2E and CH1Ext from post-construction settlement. Localised movements were also recorded on one PLP at the south east corner of Soho Street and on an HLC in the north-east corner of the French Protestant Church. It is noted that the kerbs at the corners of streets have proven to be particularly susceptible to damage. Also, the redevelopment of 61 Oxford Street was immediately adjacent to the rear of the Church.

The maximum total settlement remained small (~15mm) at the end of Period E (Figure 3.6.1b).

Two areas were subject to grout jacking episodes in conjunction with adjacent grout shafts (GS7 to the west and GS3 to the south) to control slopes (Figure 3.6.2).

3.7. Period F: 30/04/14 – 21/06/14 PTE, AP2E connection, Concurrent and Jack Grouting.

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



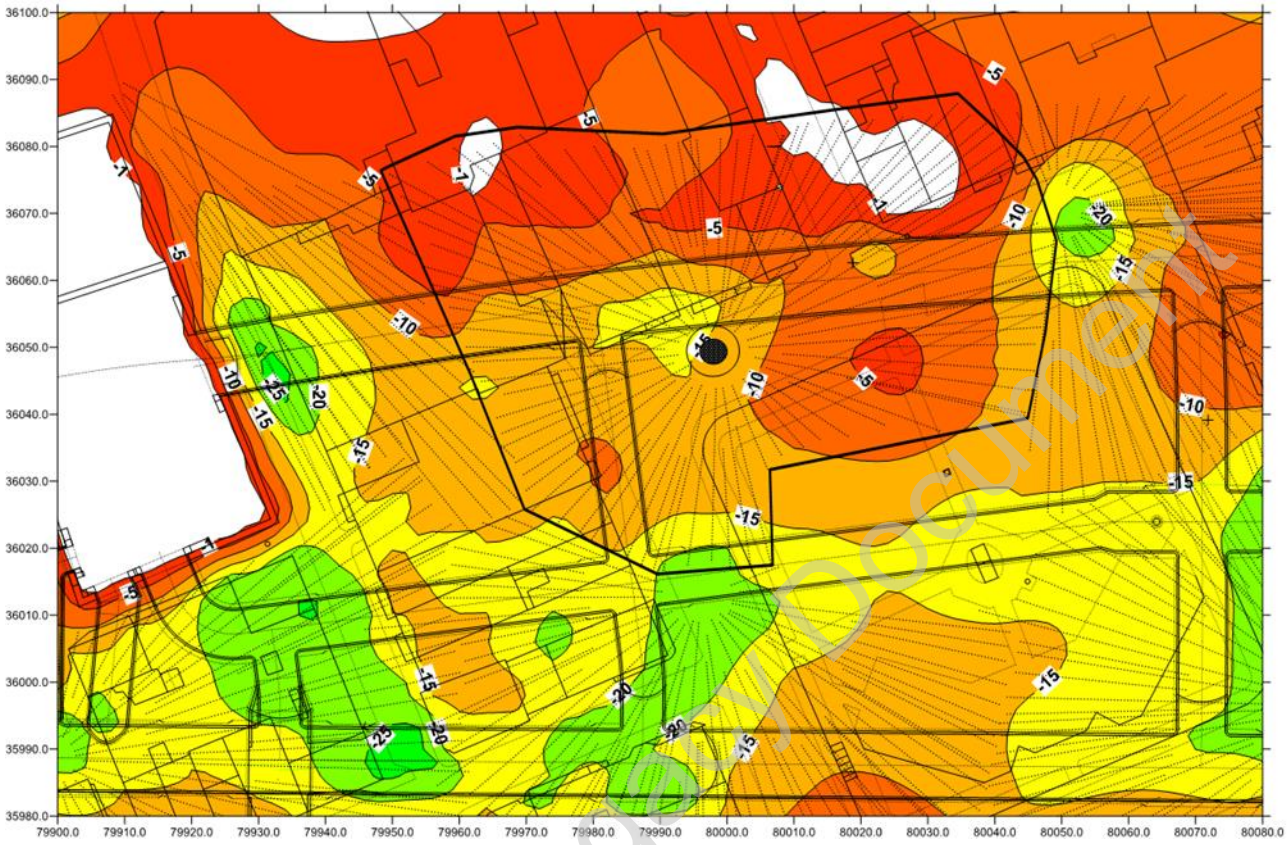


Figure 3.7.2 Period F: Distribution of grout injected from TCR GS2: Concurrent grouting. Grout Intensity (mm).

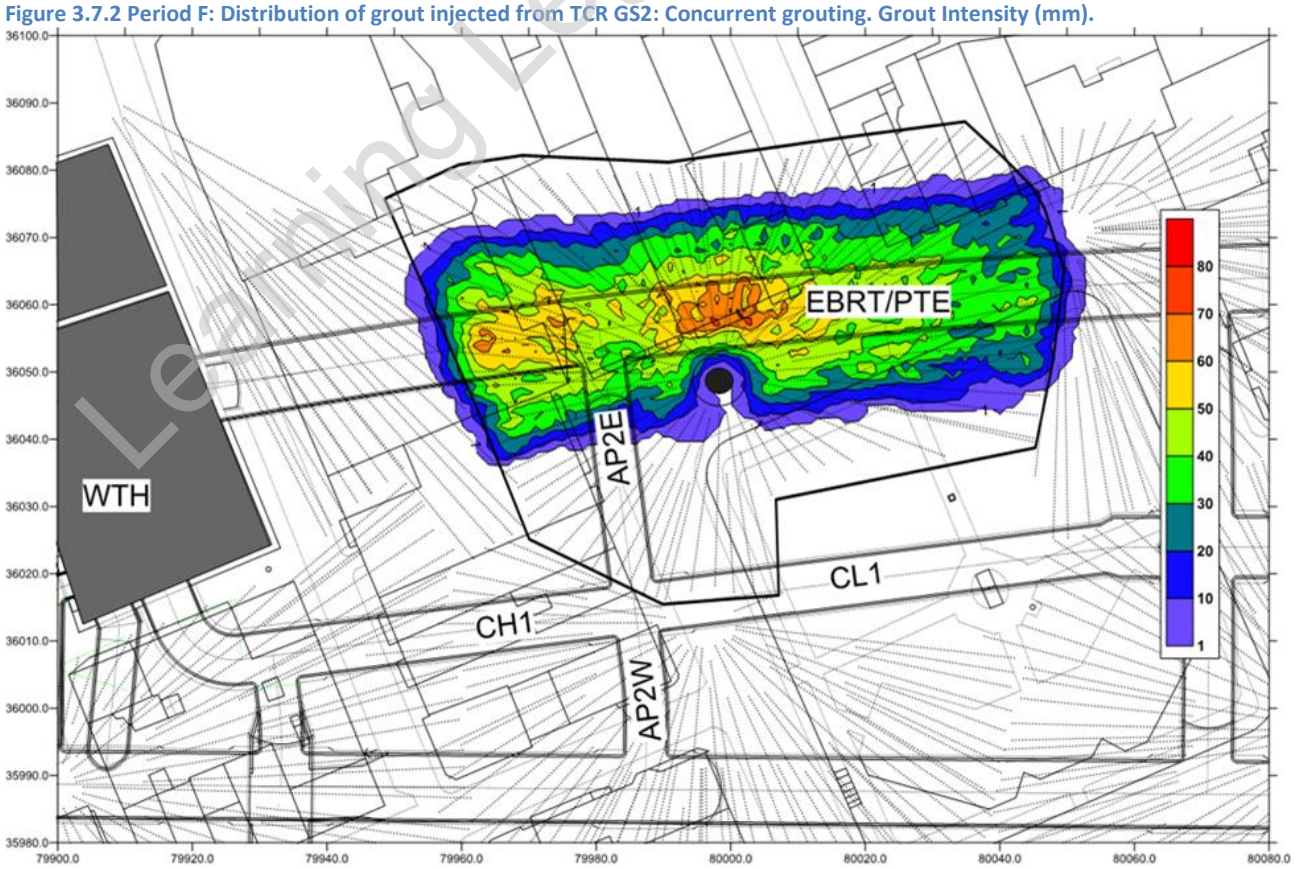
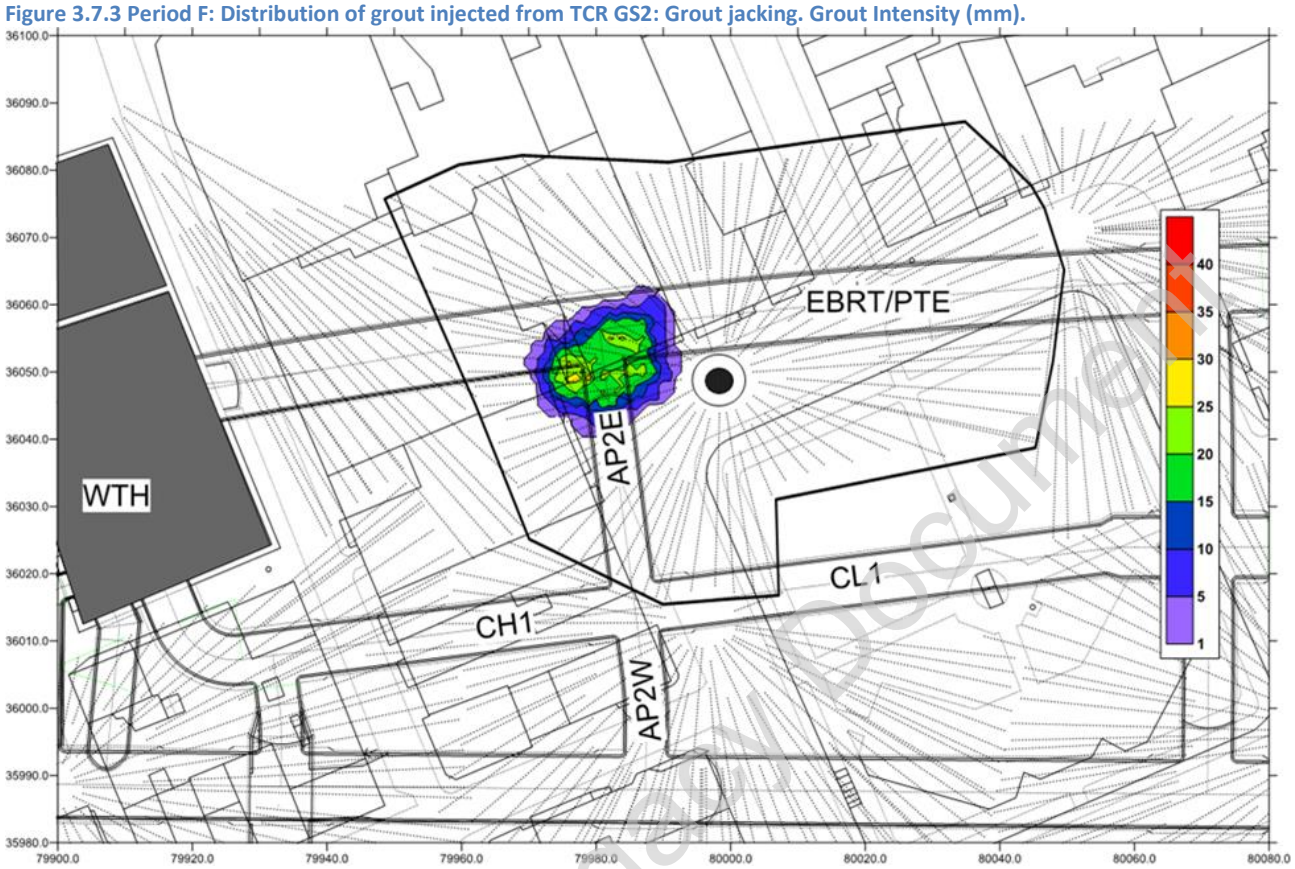


Figure 3.7.3 Period F: Distribution of grout injected from TCR GS2: Grout jacking. Grout Intensity (mm).



The Eastbound Platform Tunnel (PTE) was constructed in Period F and the connection to AP2E was completed. The volume loss settlement shown in Figure 3.7.1a shows a maximum of 35mm where the two effects combine. The observed movements (Figure 3.7.1b) range from 5mm settlement to 3mm heave as a result of the concurrent compensation grouting illustrated in Figure 3.7.2. An equivalent grout thickness of 40 to 60mm was injected over the tunnel. The total settlement contour in Figure 3.7.1c is therefore similar to that in Figure 3.6.1c prior to Period F.

Since concurrent grouting was not practicable for the short length of the AP2E connection, a grout jacking episode was undertaken as shown in Figure 3.7.3.

3.8. Period G: 21/06/14 – 25/09/15 Post Construction. Jack Grouting.

Figure 3.8.1 Period G: (a) Observed settlement in Period G; (b) Total settlement

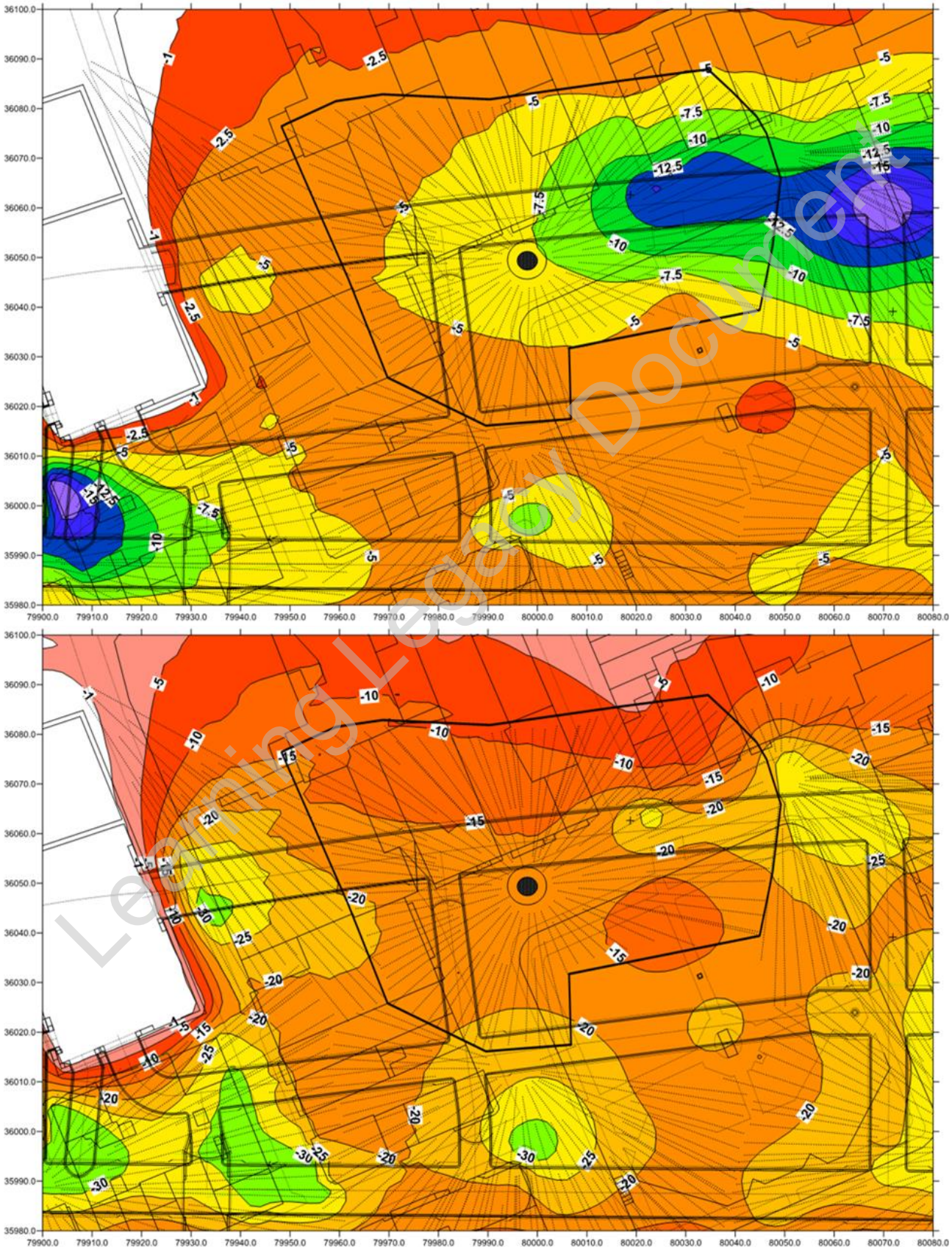
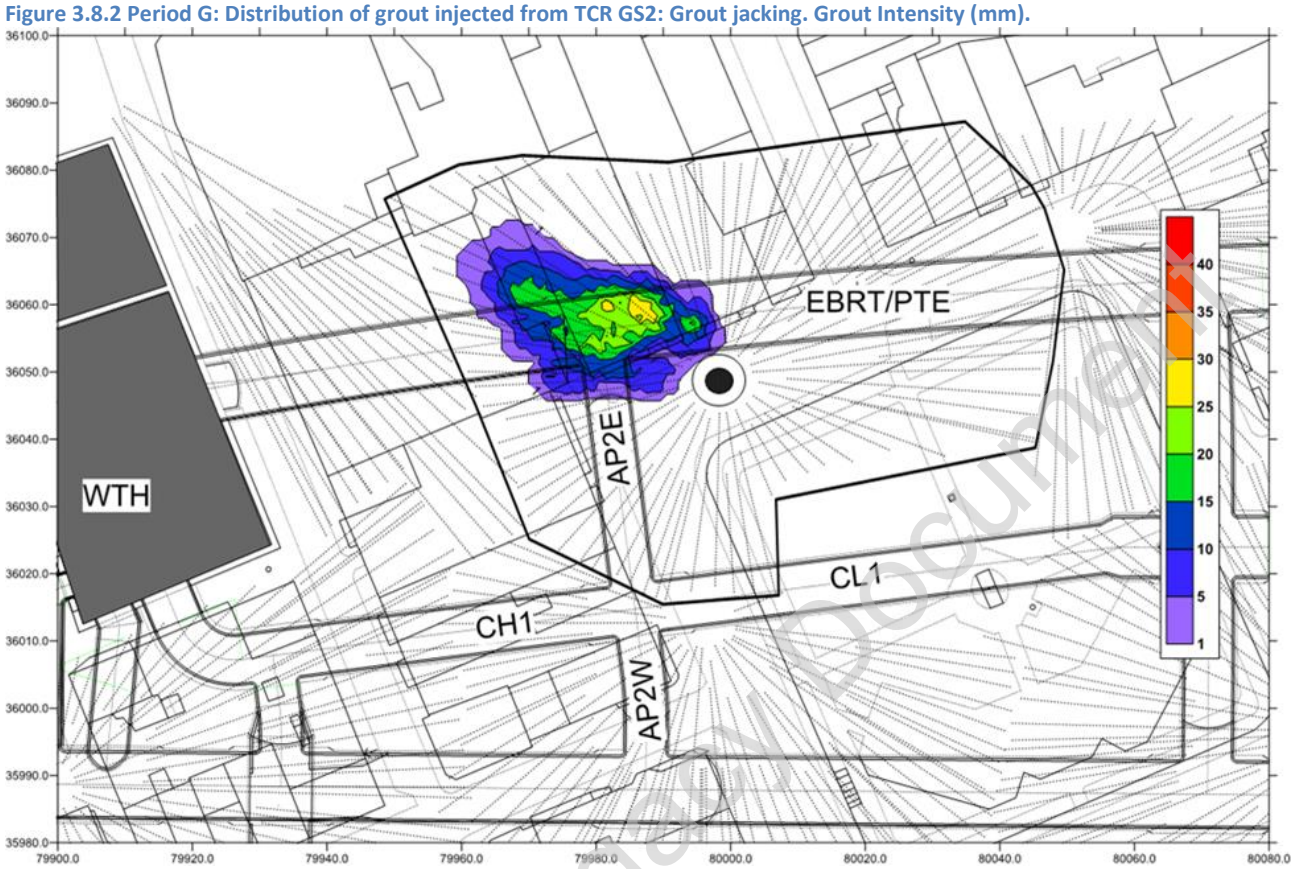


Figure 3.8.2 Period G: Distribution of grout injected from TCR GS2: Grout jacking. Grout Intensity (mm).



Post construction settlement between June 2014 and the final full survey in August / September 2015 is shown on Figure 3.8.1a. Within the GS2 area settlement increased by a maximum of 14mm with the magnitude increasing to the east of the area. The PTE was constructed from west to east and hence some of the consolidation settlement at the west of the area had occurred in Period F, prior to the completion of the tunnel throughout the GS2 area.

Total settlement had a maximum local value of 25mm but was typically 15mm to 20mm as shown in Figure 3.8.1b. Most of the settlement was due to consolidation with the majority of the volume loss settlement compensated by the concurrent grouting. Notwithstanding the inclusion of a year of post construction settlement, the final settlements remain much lower than the predicted (volume loss) values.

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 4.1.1. By inspection no deflection ratio triggers have been breached. A larger version of Figure 4.1.1. is included in Appendix C. Details are given in Table 4.1.1.

Slope triggers are as follows:

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

Table 4.1.1 Details of Amber trigger breaches on BRE & HLC

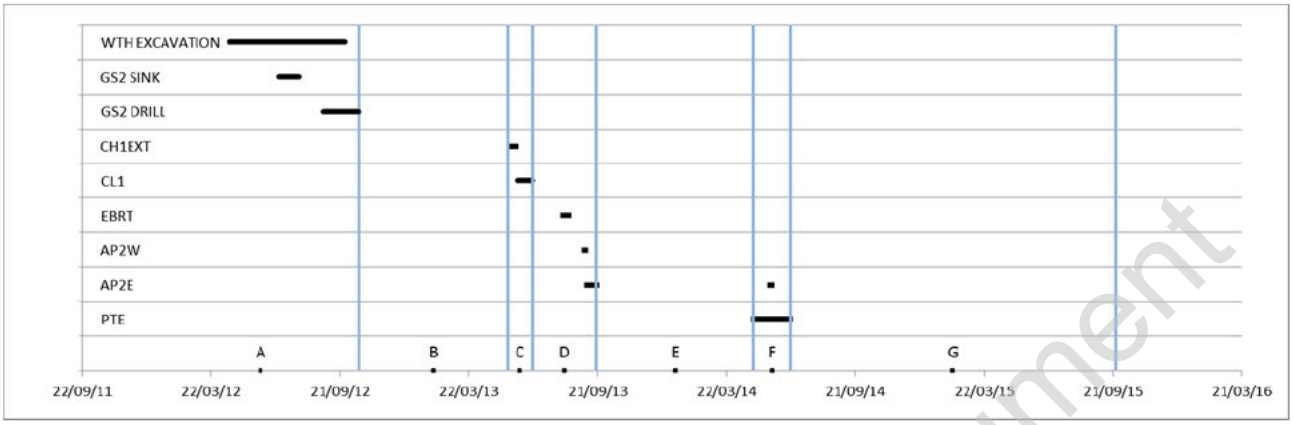
BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Soho Square - West					
C08LB079 - C08LB080	Amber	Borderline (16 readings of 149 >1.0 between 04/08/13 & 11/07/13 Mean 0.80)	04/08/13	1.09	0.98
C08LB099 - C08LB100	Amber	Max 1.01 during construction (Period F).	08/06/14	1.18	1.18

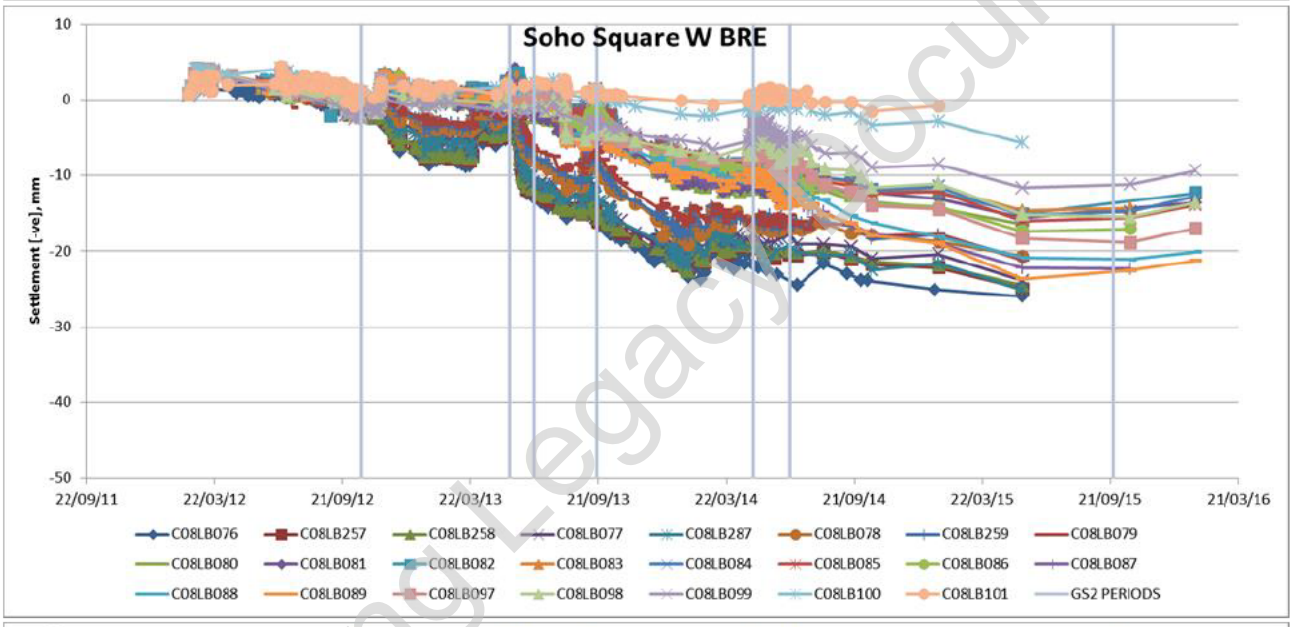
Figure 4.1.1 Locations where building slope triggers have been exceeded

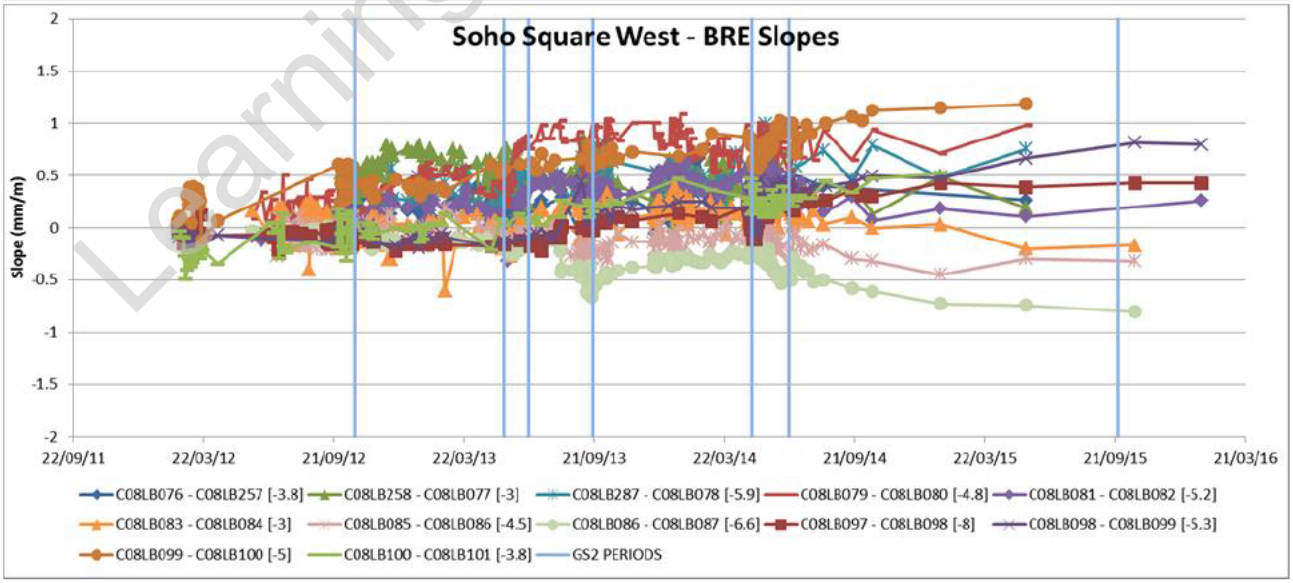
BRE monitoring data from the facades within the footprint of GS2 are presented in the following sections, namely Soho Square west, Soho Square north, French Protestant Church west party wall and the east and west facades of Soho Street. The plots presented for each comprise, as appropriate:

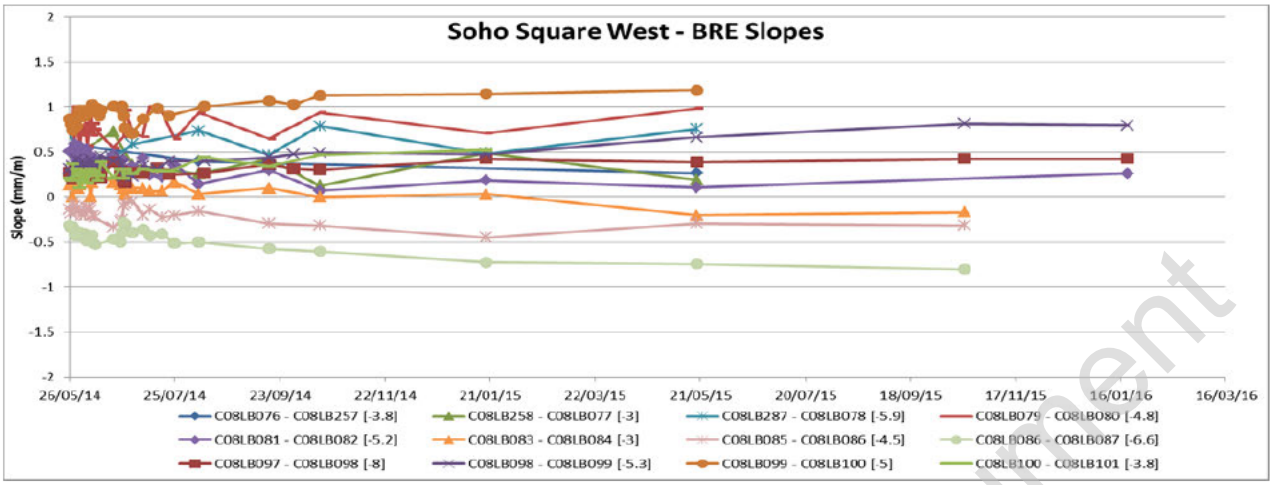
1. Summary of tunnel construction and associated construction periods;
2. Time settlement history;
3. Settlement profile plots with series as close to the end of each construction period as is available;
4. Time slope history over the full construction period [with the distances between the points in metres shown in the legend in square brackets];
5. Time slope history since the completion of tunnelling i.e. Period G.

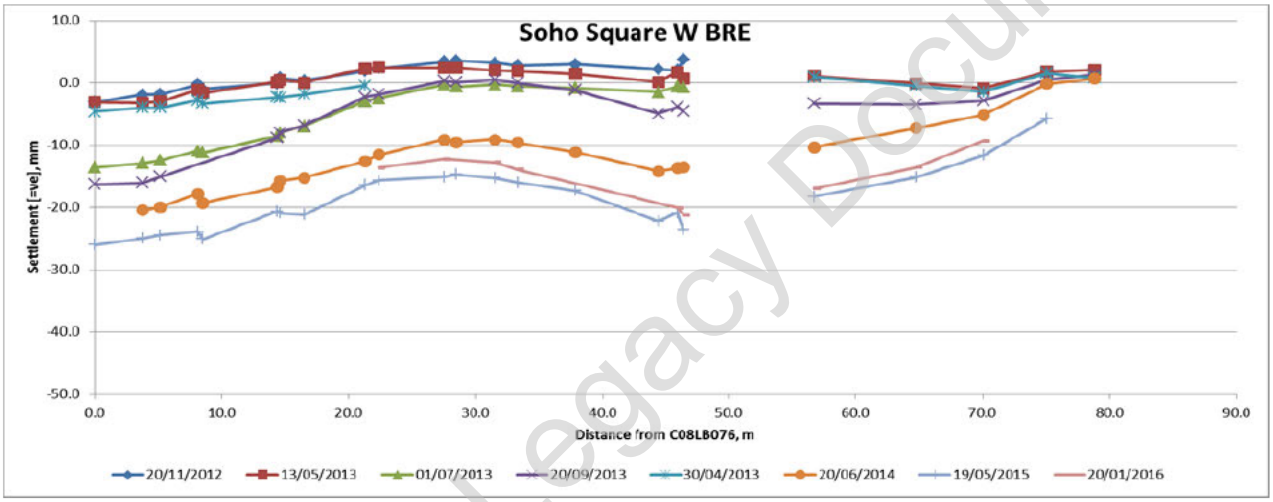
4.2. Soho Square West – north







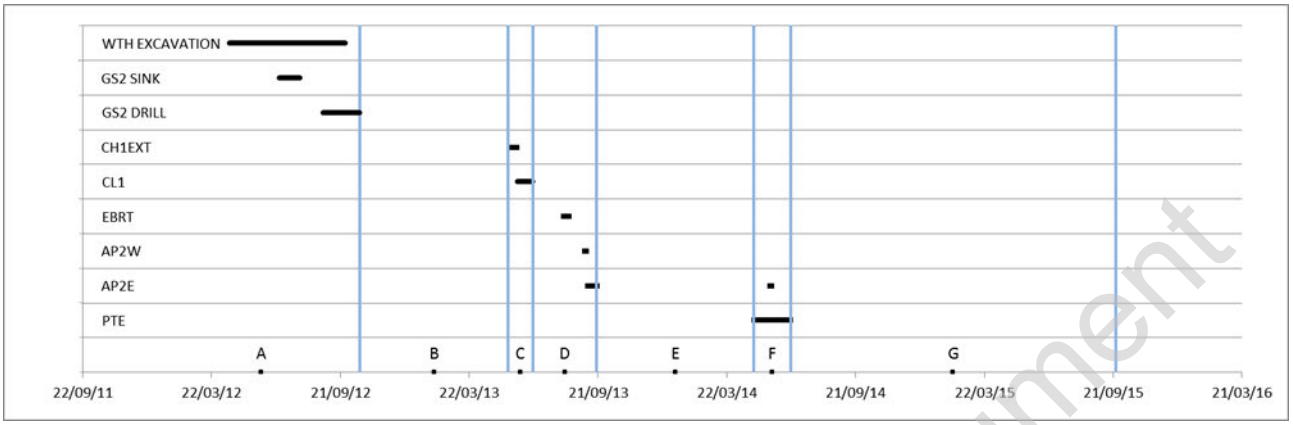


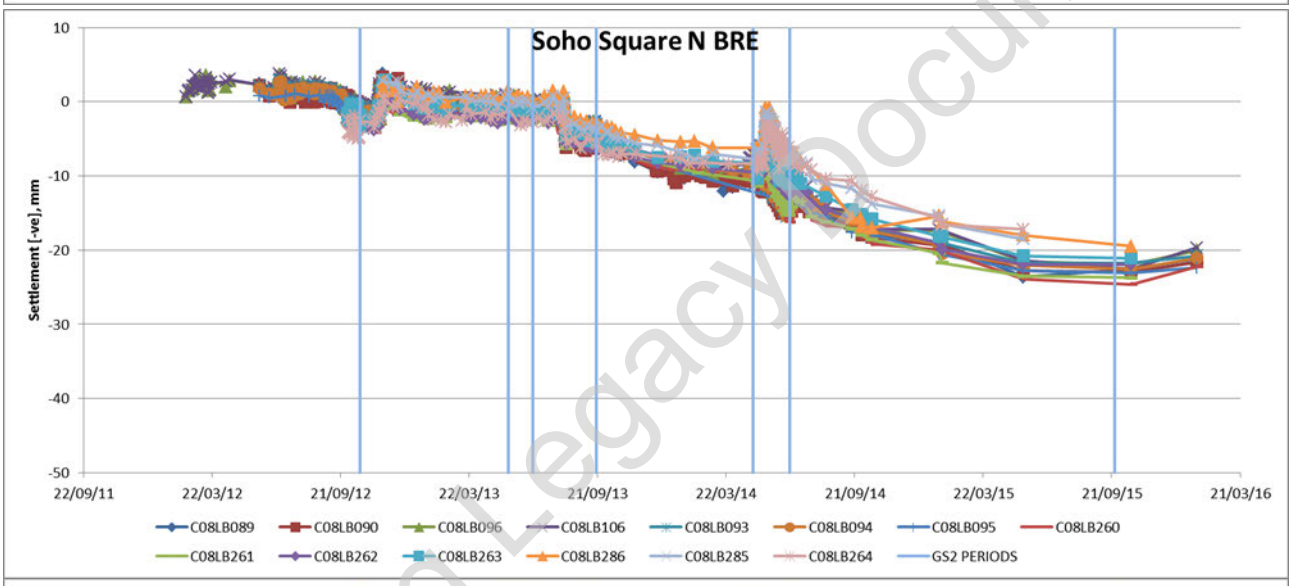


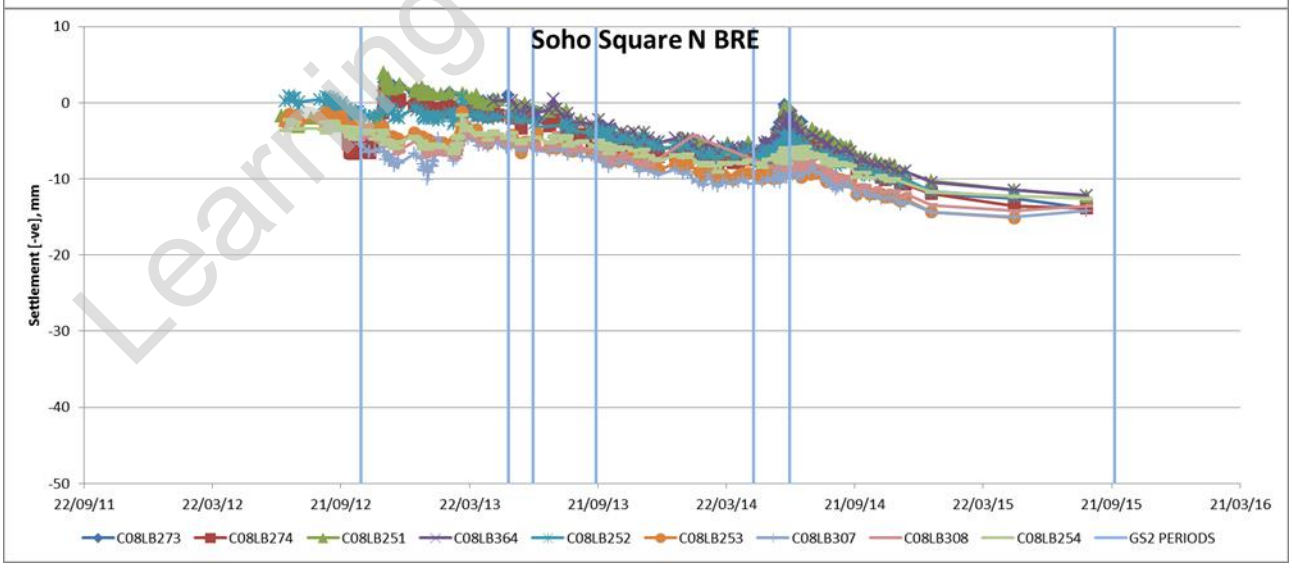
The following points are noted:

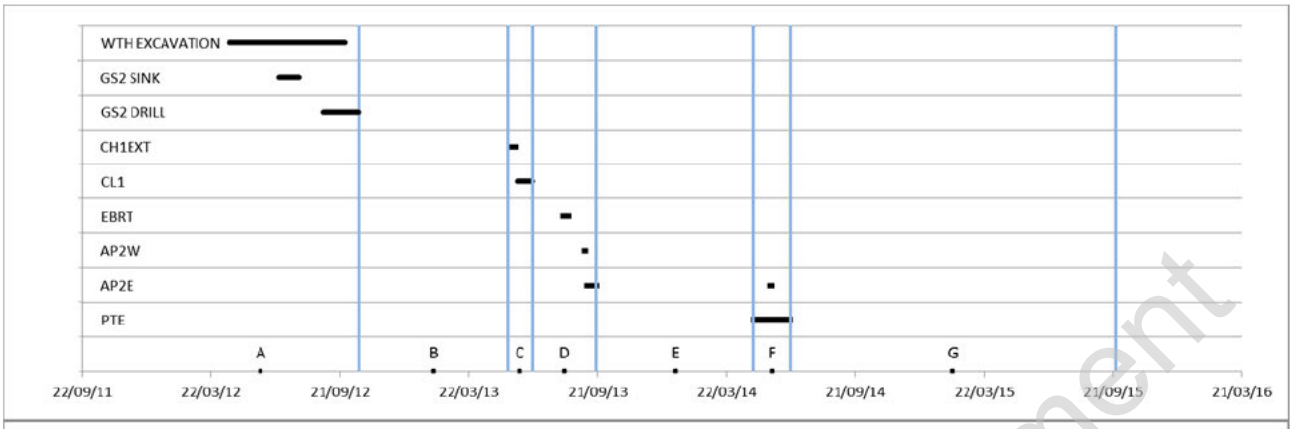
- Only part of the façade is within the TCR GS2 array (from distance 17m): data from points north of Carlisle Street are presented as shown in Figure 4.1.1.
- The only construction events where any significant settlement occurred are CL1 in Period C and PTE / AP2E in Period F. No compensation grouting was undertaken with the former or with the AP2E connection. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- Minor settlement is evident in Period A associated with Tam drilling which was reversed by pre-treatment early in Period B. The more significant settlement and heave later within Period B is on points to the south of the GS2 array and is associated with drilling and pre-treatment in the adjacent GS3 area (see C300-BFK-C4-RGN-CRT00_ST005-51227).
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between May 2015 and January 2016.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show that occasional readings between points C08LB079 and C08LB080 exceeded the Amber trigger in Periods D and E. However, given the scatter in the data, the overall trend indicates that the trigger was not exceeded. An Amber slope trigger has been exceeded between C08LB099 and C08LB100 at the very northern end of the profile: it is notable that the slope reached 0.5mm/m in Period A when maximum movements were <5mm and access to these points was only rarely available.

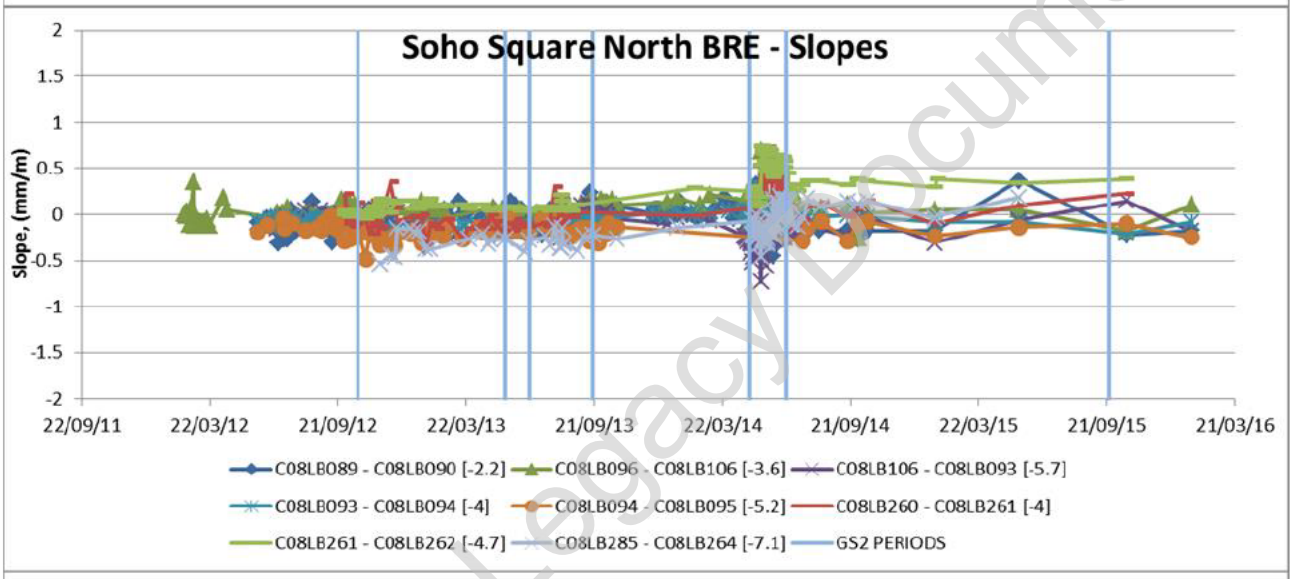
4.3. Soho Square North

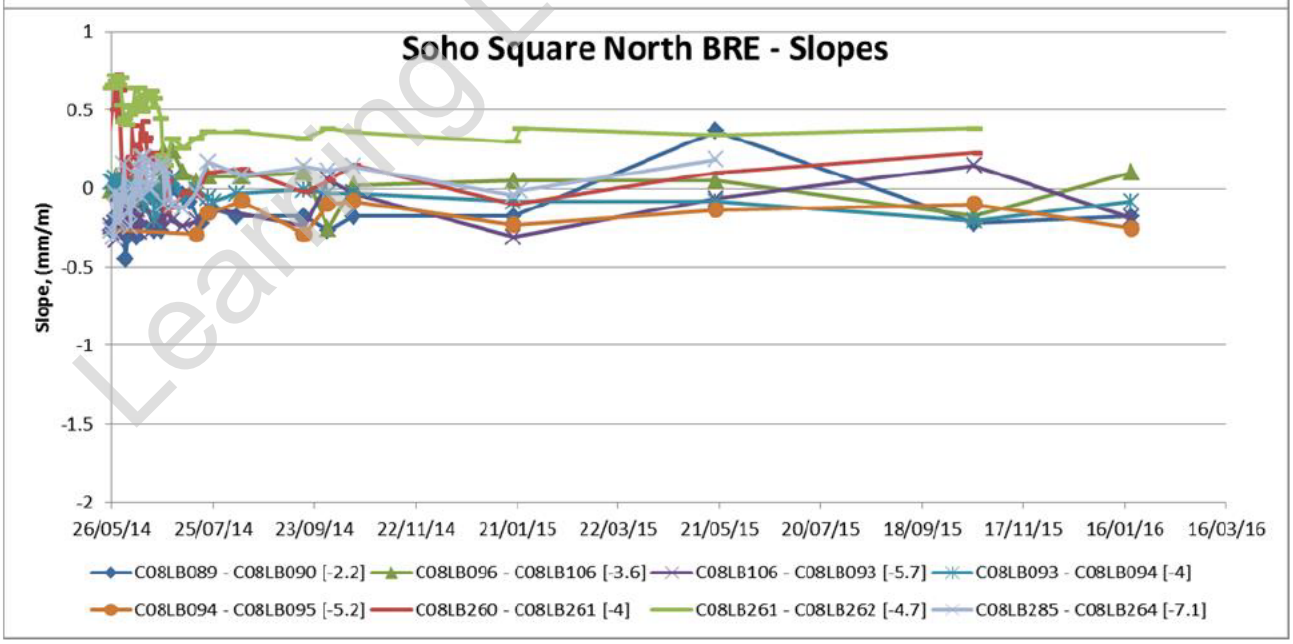


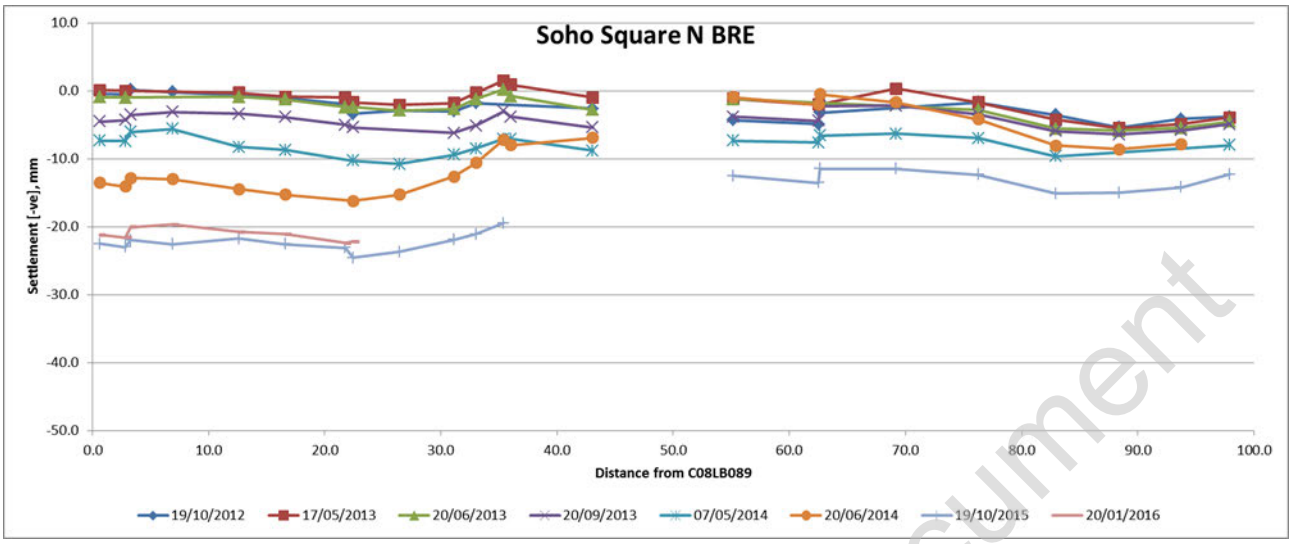








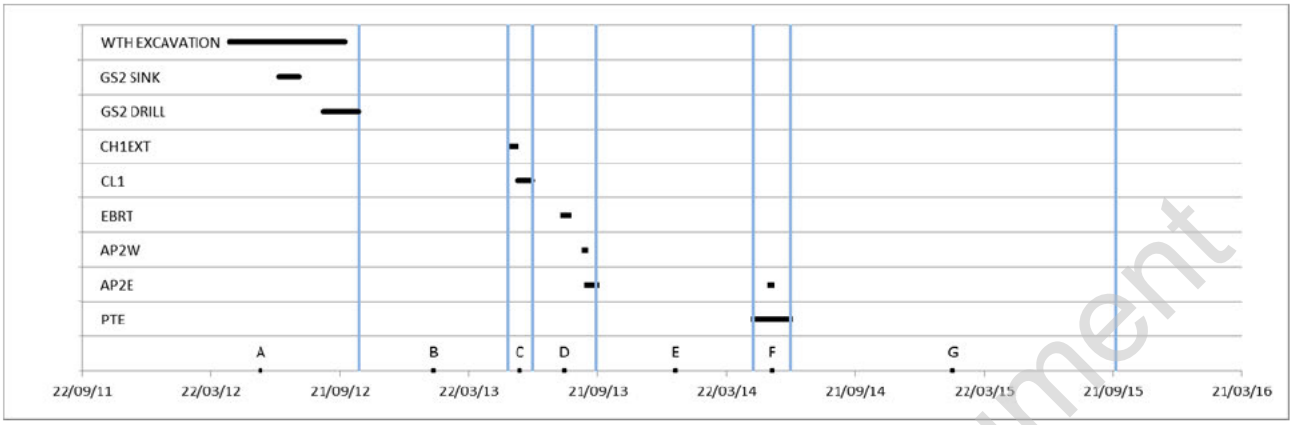


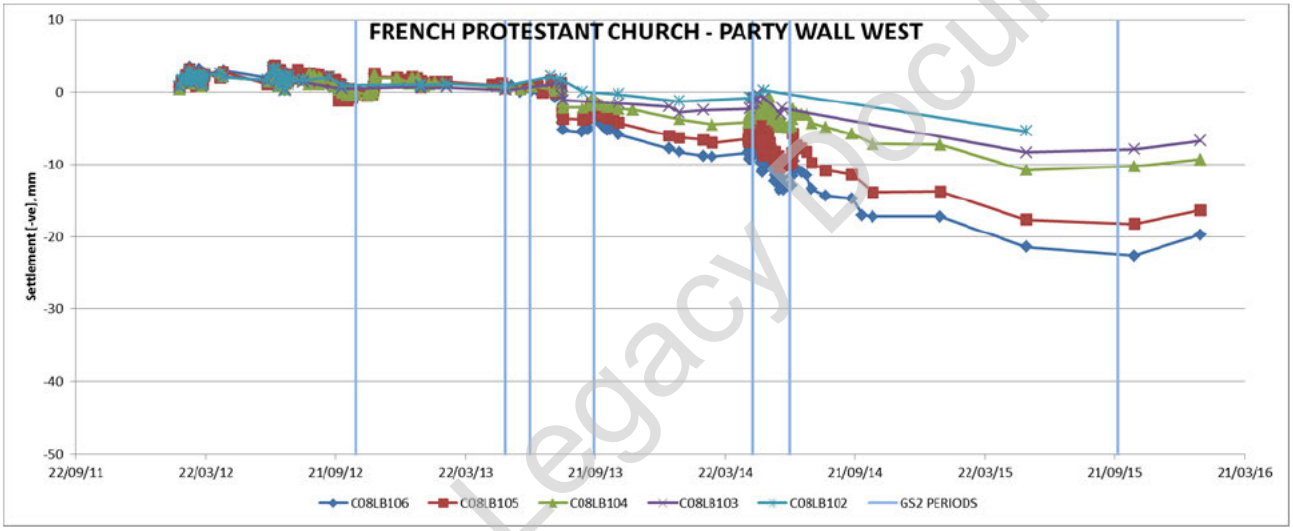


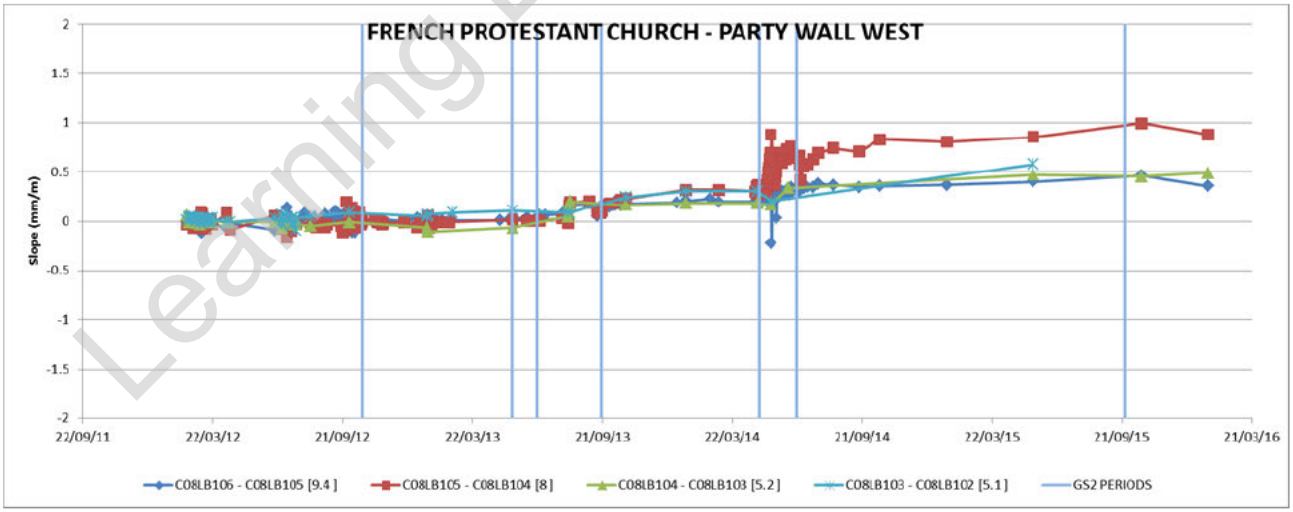
The following points are noted:

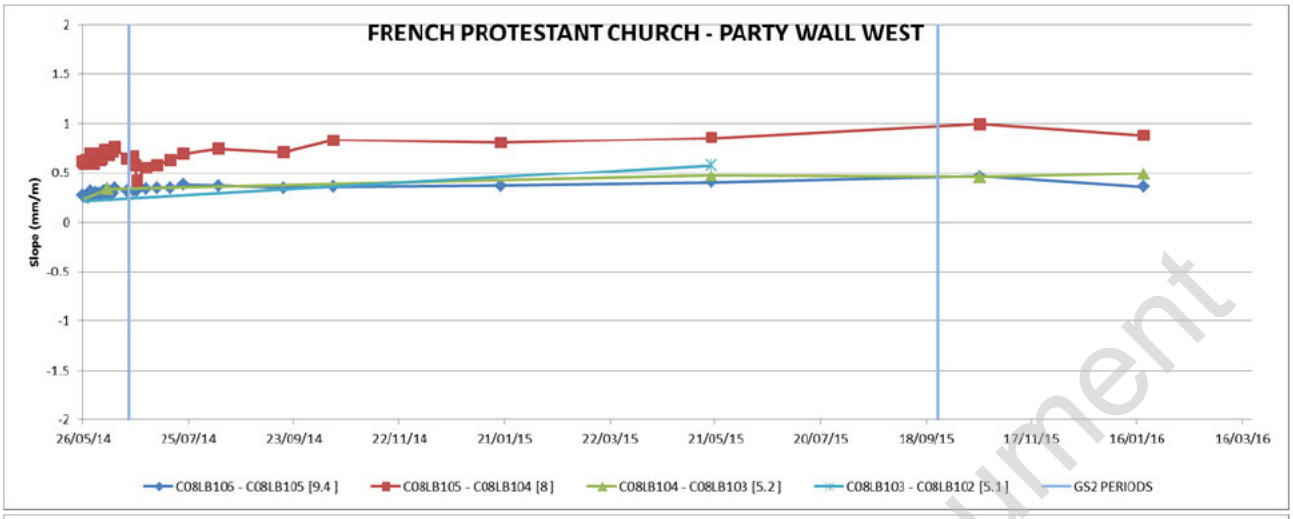
- Although part of the façade is not within the TCR GS2 array (from distance 75m): data from all points are presented as shown in Figure 4.1.1.
- The only construction event where any significant settlement occurred is the EBRT in Period D. No compensation grouting was undertaken with the running tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between May 2015 and January 2016.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show that no triggers have been exceeded and slopes have been stable since the end of construction.

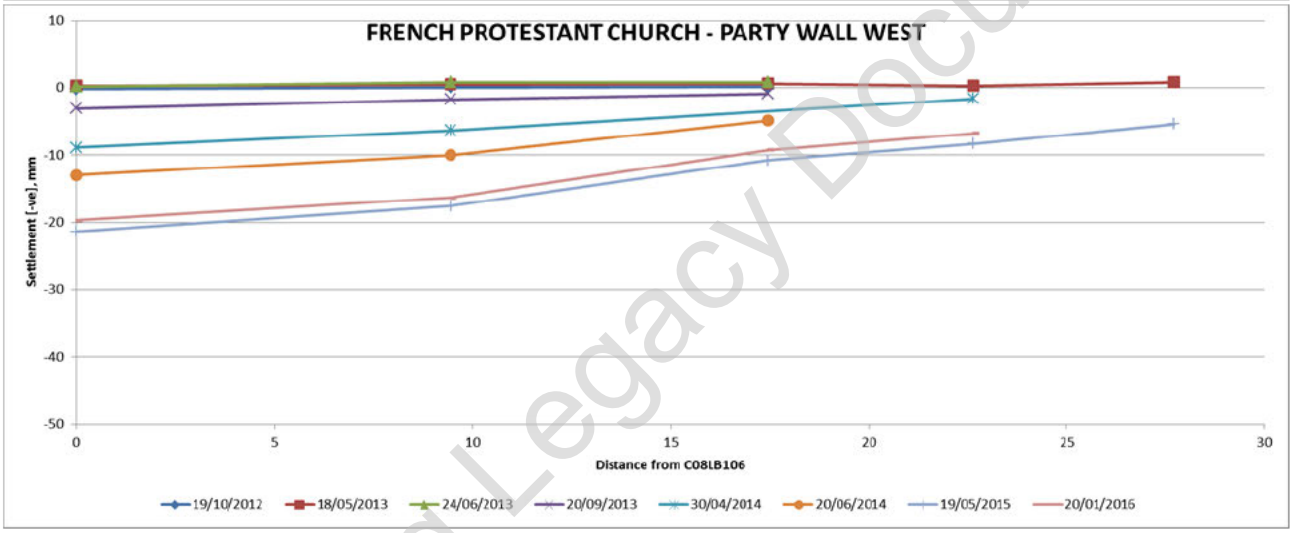
4.4. French Protestant Church – West Party Wall







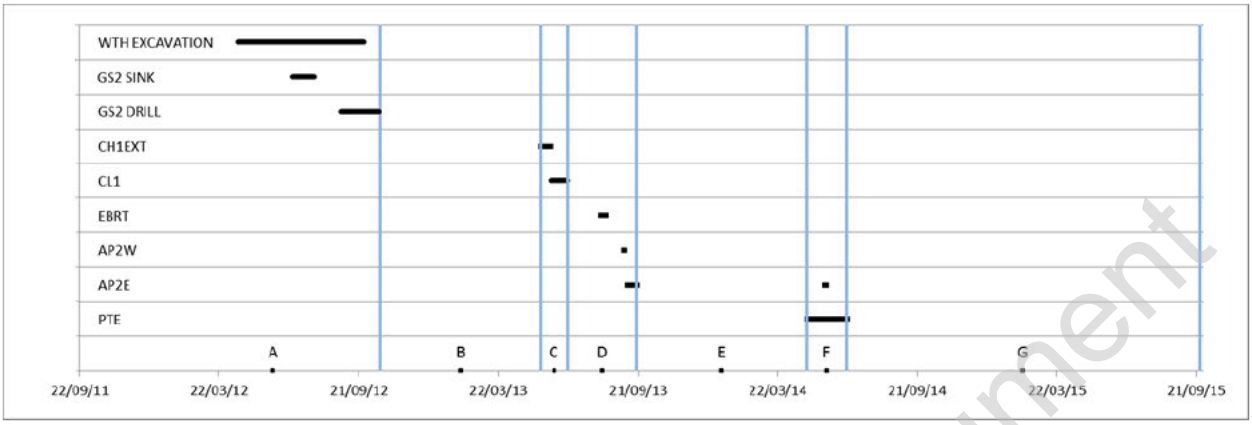


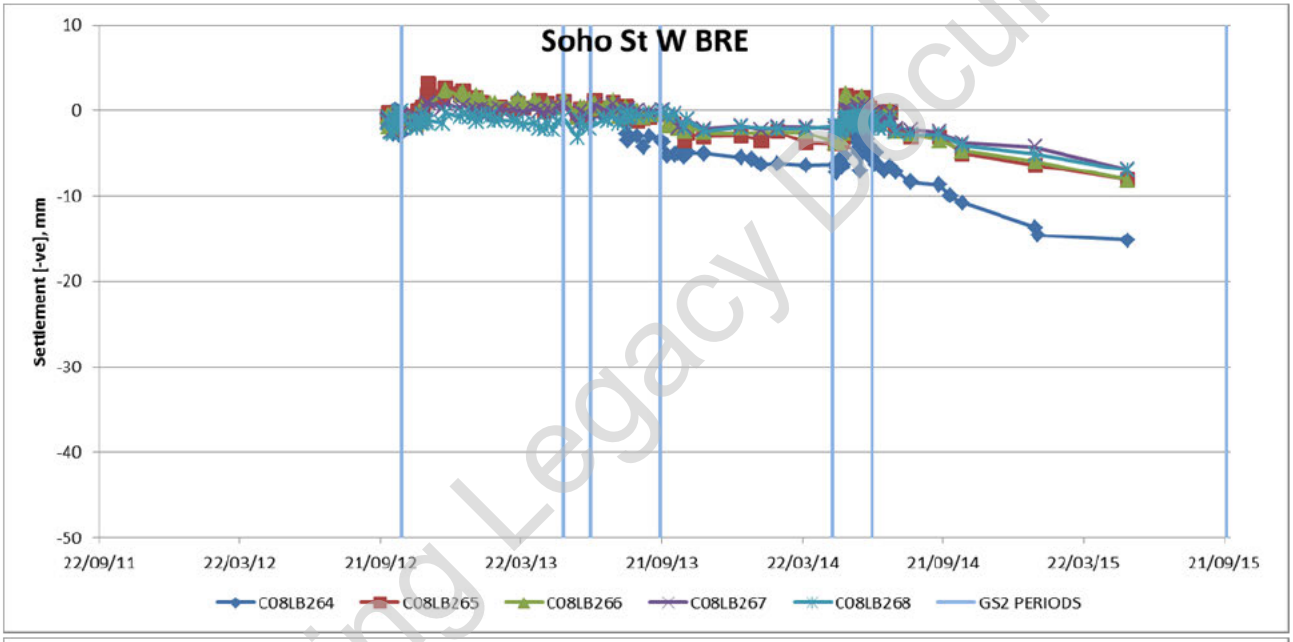


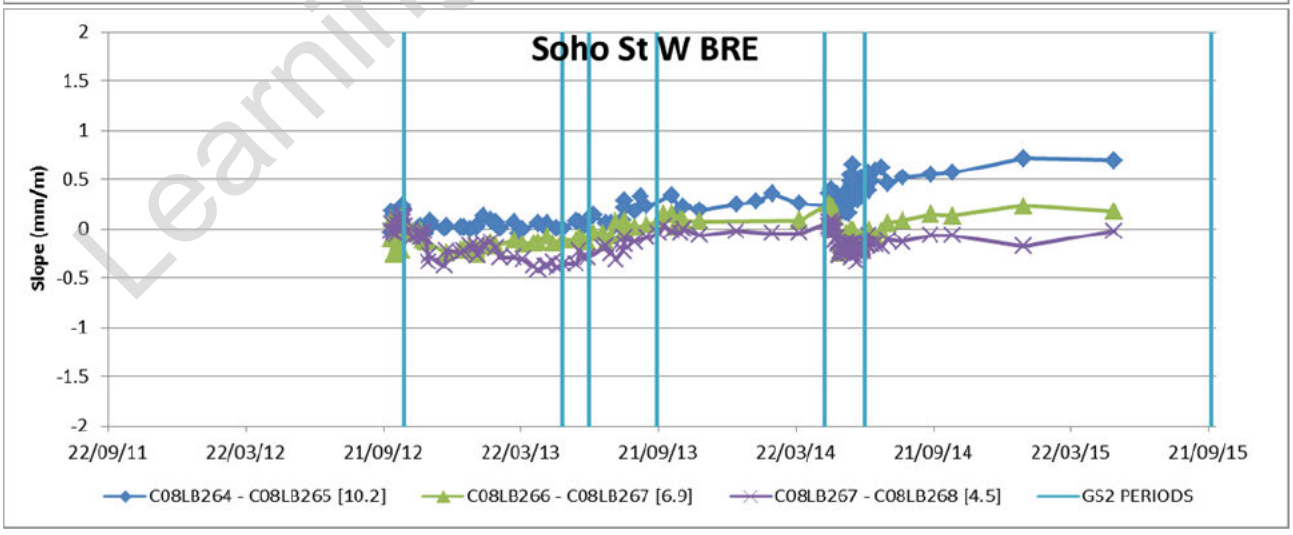
The following points are noted:

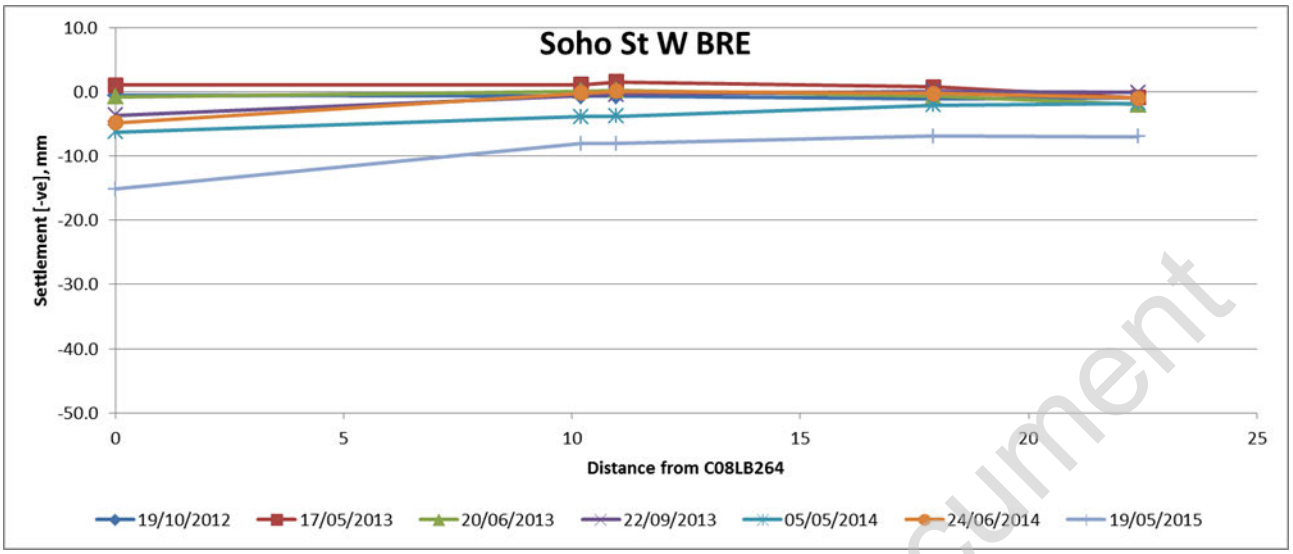
- All of the points on the west party wall of the French Protestant Church are all within the TCR GS2 array, as shown in Figure 4.1.1.
- The only construction event where any significant settlement occurred is the EBRT in Period D. No compensation grouting was undertaken with this tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between May 2015 and January 2016.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show increases associated with the PTE / AP2E connection in Period F as well as the EBRT. The slopes have increased slightly in the post construction period (Period G) but none have reached the Amber trigger level.

4.5. Soho Street West





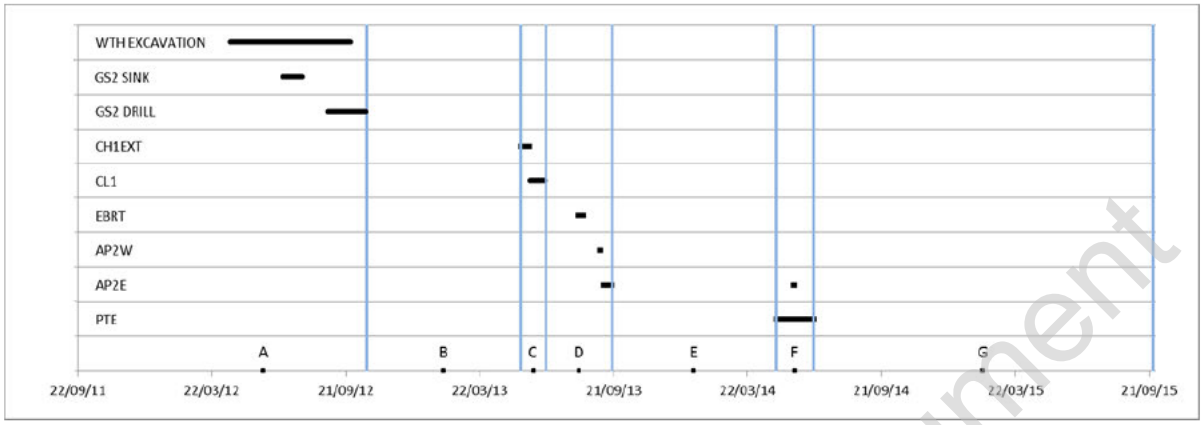


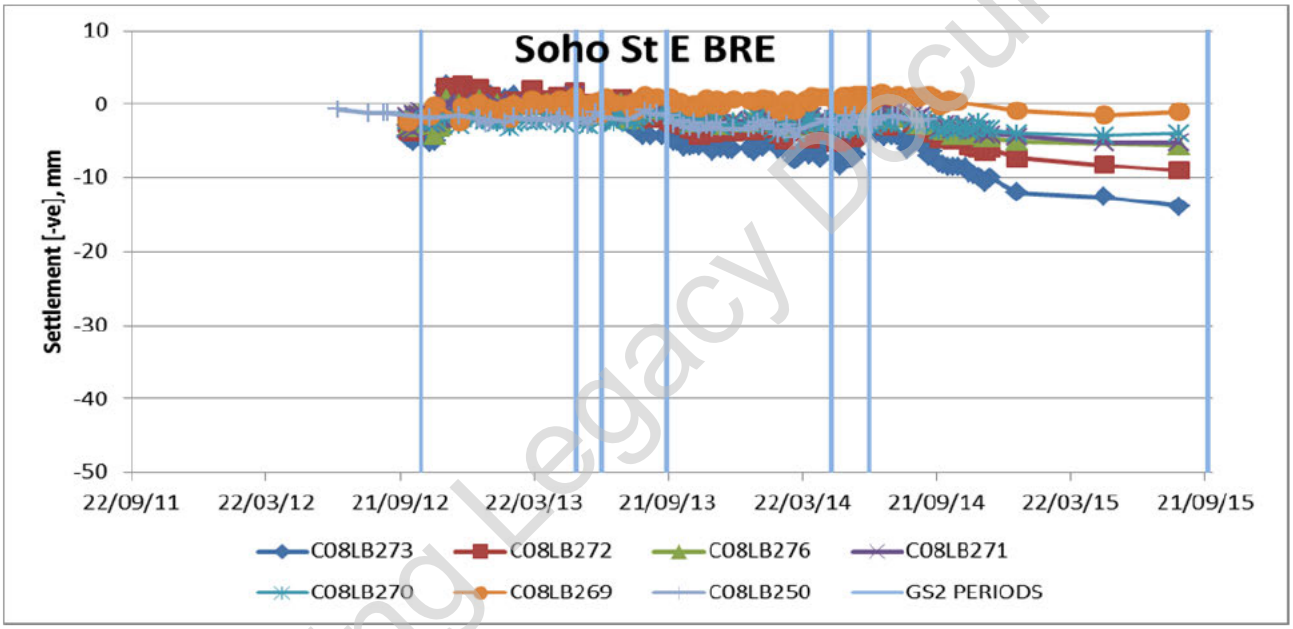


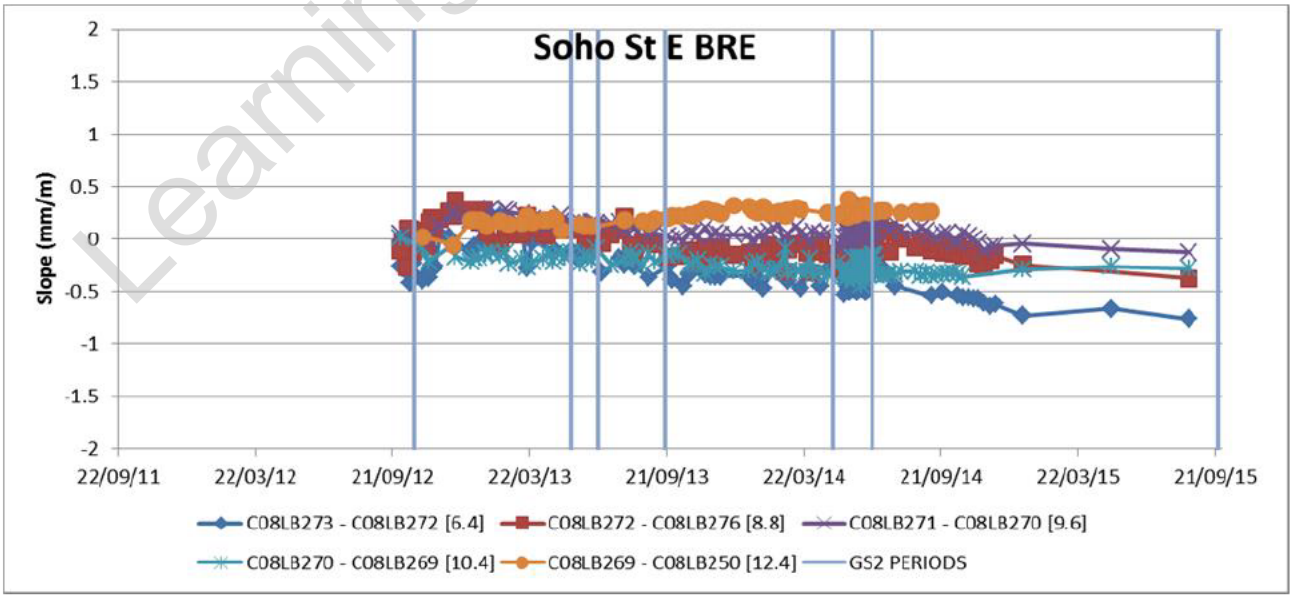
The following points are noted:

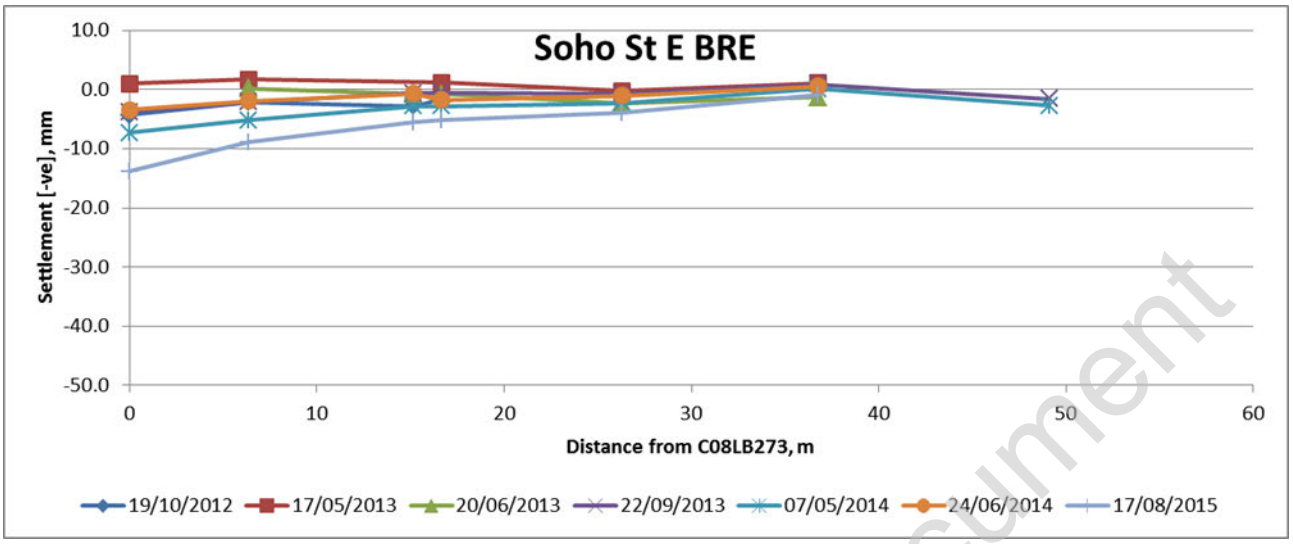
- The points on the west façade of Soho Street are within the TCR GS2 array, except for the most northerly, as shown in Figure 4.1.1. It is noted that points further north were not installed due to the re-development of this site (61 Oxford Street).
- The only construction event where any significant settlement occurred is the EBRT in Period D. No compensation grouting was undertaken with this tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances. Small (<5mm), transient heave is eveident in Period F associated with concurrent grouting for PTE.
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between the final two readings.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plot shows increases associated with the PTE / AP2E connection in Period F as well as the EBRT. The slopes have increased slightly in the post construction period (Period G) but none have reached the Amber trigger level.

4.6. Soho Street East









The following points are noted:

- The points on the east façade of Soho Street are within the TCR GS2 array up to distance ~17m on the profile plot i.e. the most northerly 3 points are outside the array, as shown in Figure 4.1.1.
- The only construction event where any significant settlement occurred is the EBRT in Period D. No compensation grouting was undertaken with this tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between the final three readings.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plot shows no marked increases associated with individual construction event. The slopes have increased slightly in the post construction period (Period G) but none have reached the Amber trigger level.

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 5.1.1. By inspection no deflection ratio triggers have been breached. A larger version of Figure 5.1.1. is included in Appendix C. 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

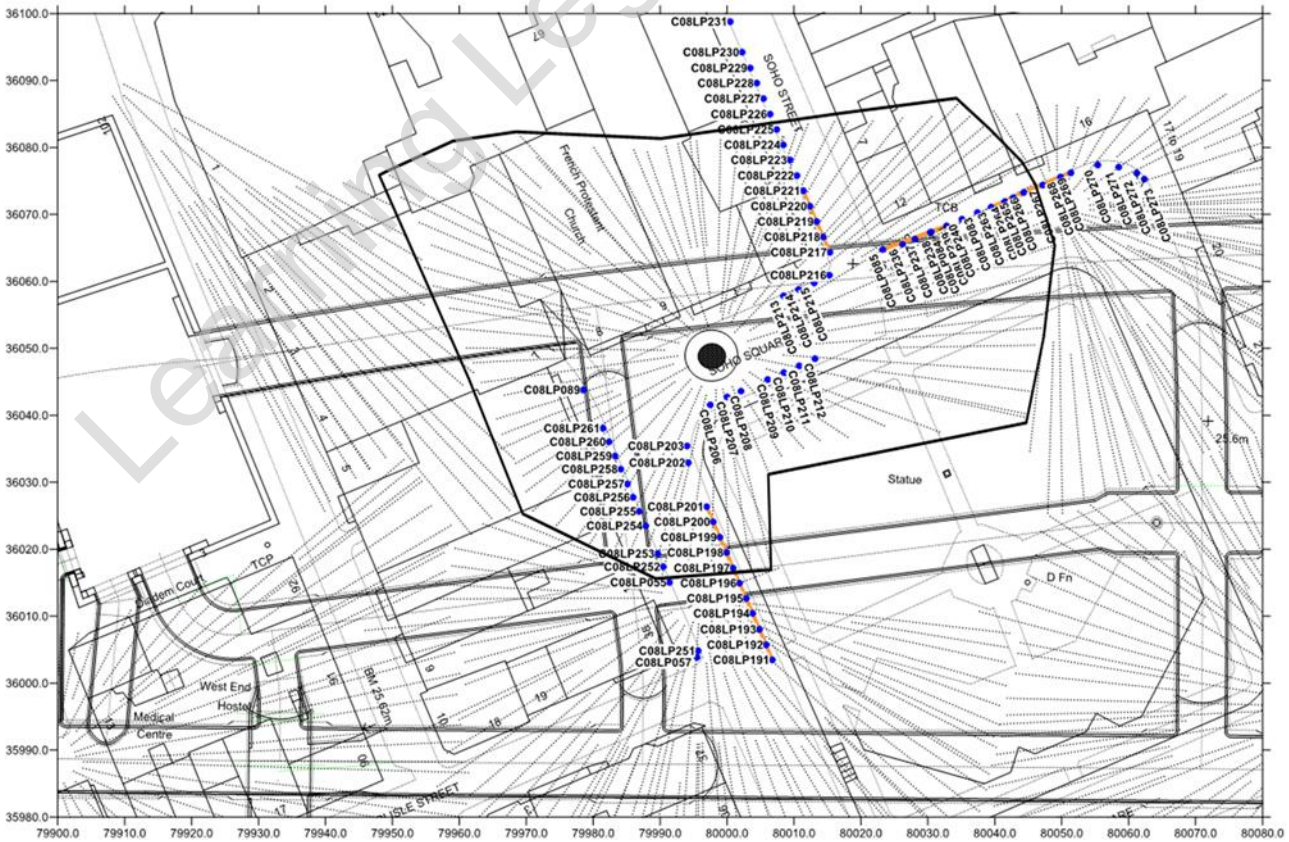
PLP monitoring data from the kerb lines within the footprint of GS 2 are presented in the following sections, namely Soho Square west outer and inner kerb lines, Soho Square north outer and inner kerb lines and Soho Street west. The plots presented for each comprise, as appropriate:

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];
5. Time slope history since the completion of tunnelling i.e. construction Period G.

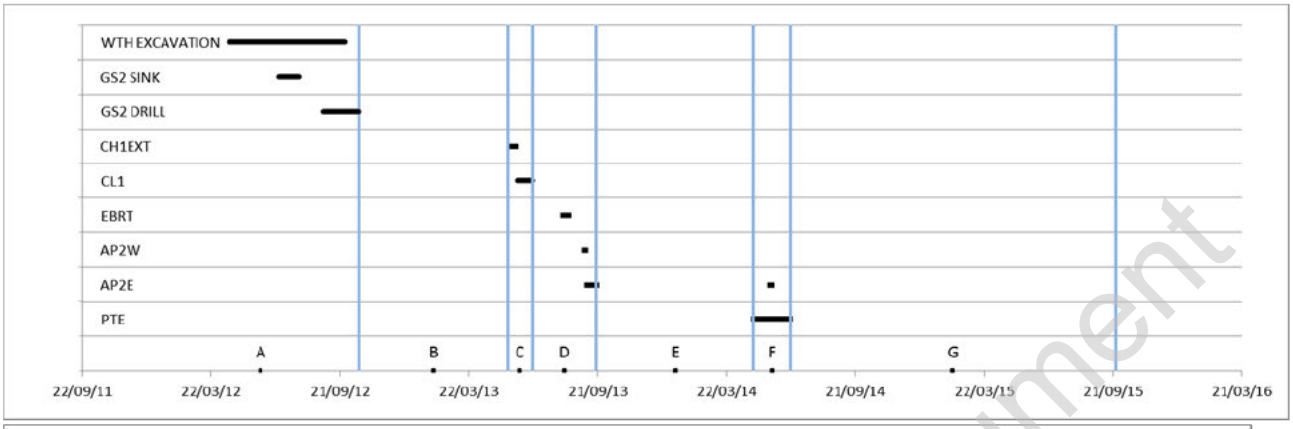
Table 5.1 Details of Amber trigger breaches on PLP

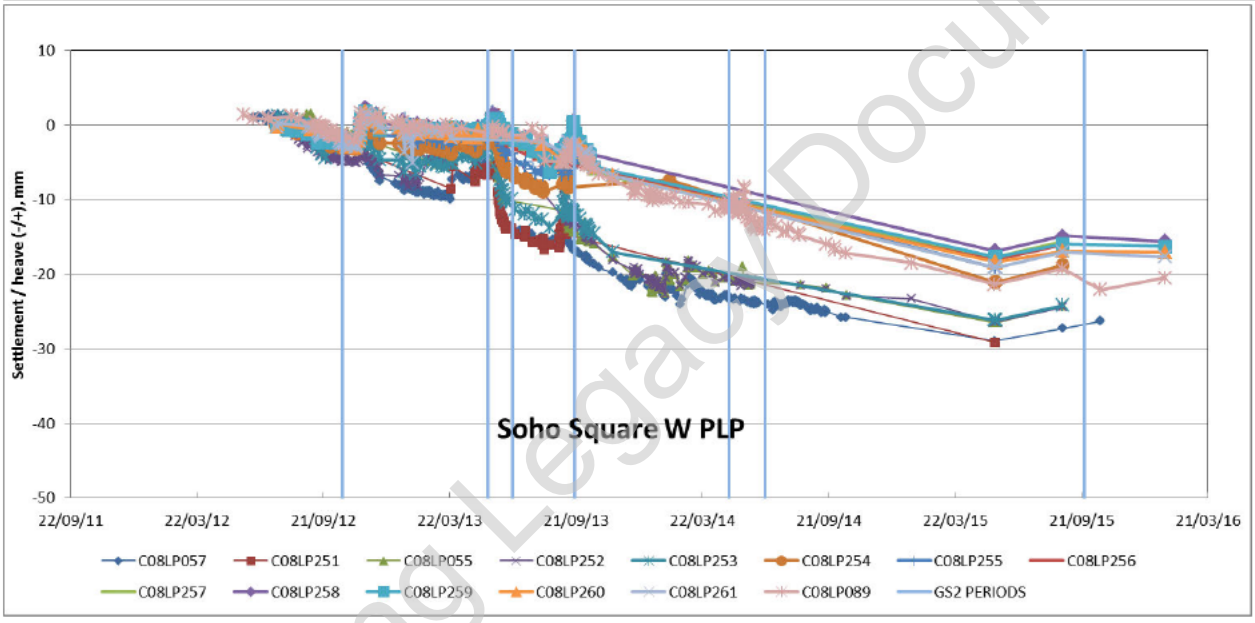
Kerb Line		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Soho Square West – inner kerb line					
C08LP192 – C08LP196	-	Single reading of 1.07mm/m (>Amber) on 23/01/14 – not validated by subsequent reading			0.55
C08LP191 – C08LP195	Amber	Transitory slope during enlargement of PTW – reduced by subsequent grout jacking (19/02/14)	12/01/14	1.34	0.87
C08LP197 - C08LP201	Amber	Amber exceeded during CL1 excavation without concurrent grouting. Reduced by grout jacking episodes	05/06/13	1.23	0.85
C08LP196 - C08LP200	Amber		07/06/13	1.06	0.88
Soho Square North – outer kerb line					
C08LP268 - C08LP263	Amber	Trigger exceeded prior to tunnelling – contribution from adjustments to account for TCRSU monitoring data.	22/11/12	1.25	0.86
C08LP269 - C08LP264	Amber	Slope close to trigger throughout tunnelling - contribution from adjustments to account for TCRSU monitoring data.	09/06/14	1.05	0.80
C08LP239 - C08LP085	Amber	Increase in slope during Period E (no tunnelling). Transitory increase during PTE. Continued increase post construction. Point stability in doubt.	08/06/14	1.12	1.12
Soho Street West					
C08LP217 - C08LP221	Amber	Increase in slope during Period E (no tunnelling). Transitory increase during PTE. Continued increase post construction. Point stability in doubt.	19/01/15	1.27	1.27

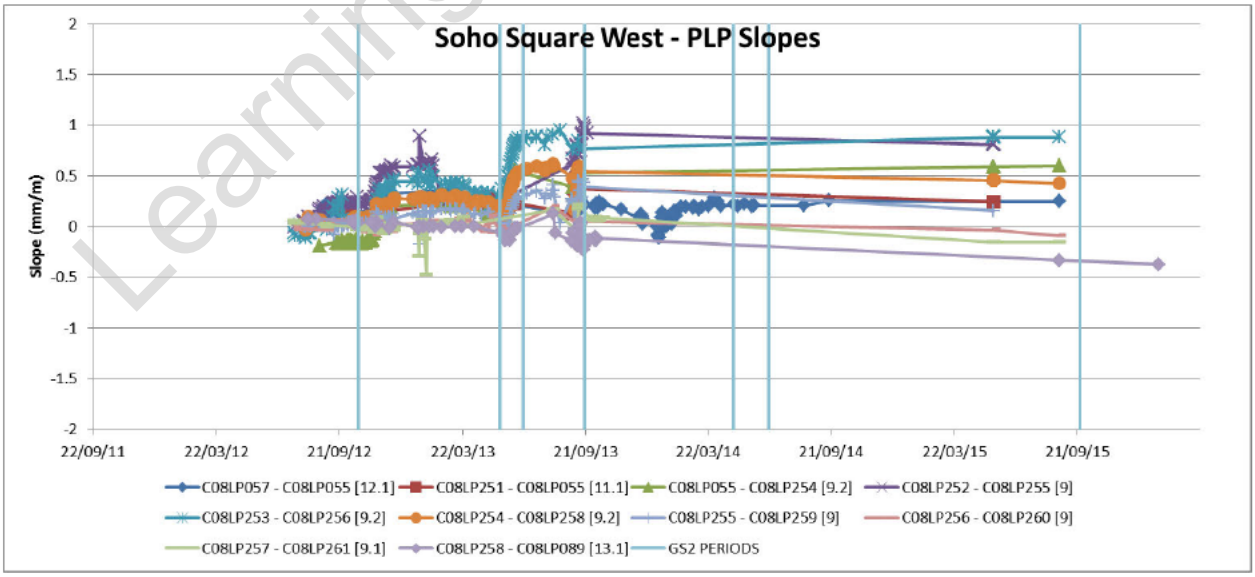
Figure 5.1.1 Location of ground monitoring points and Amber triggers

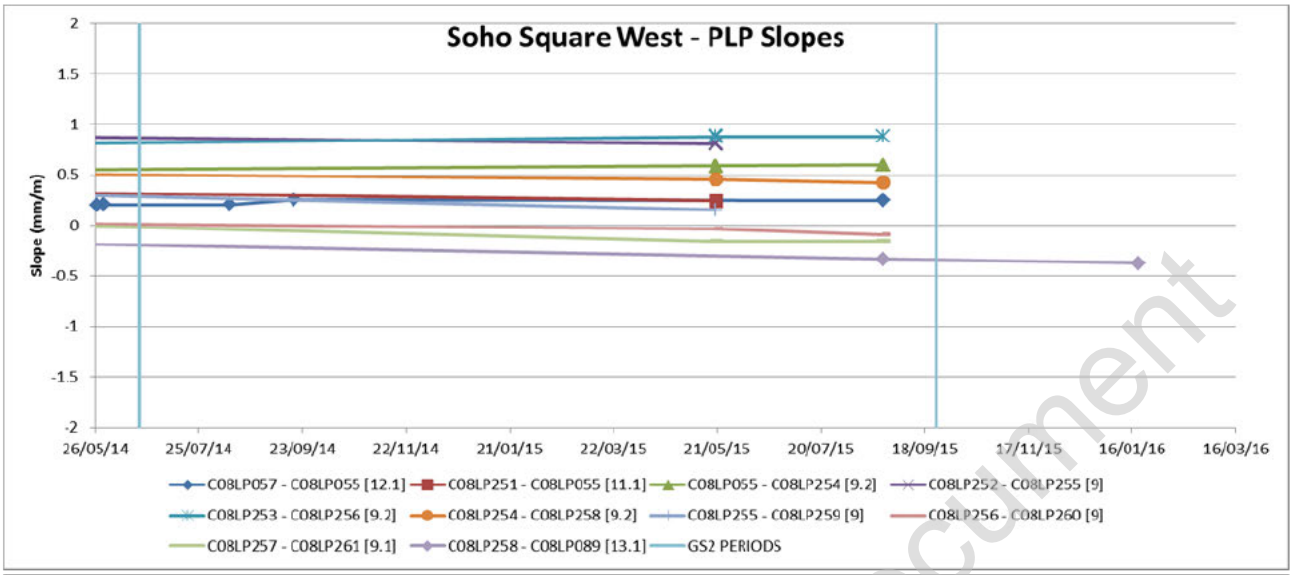


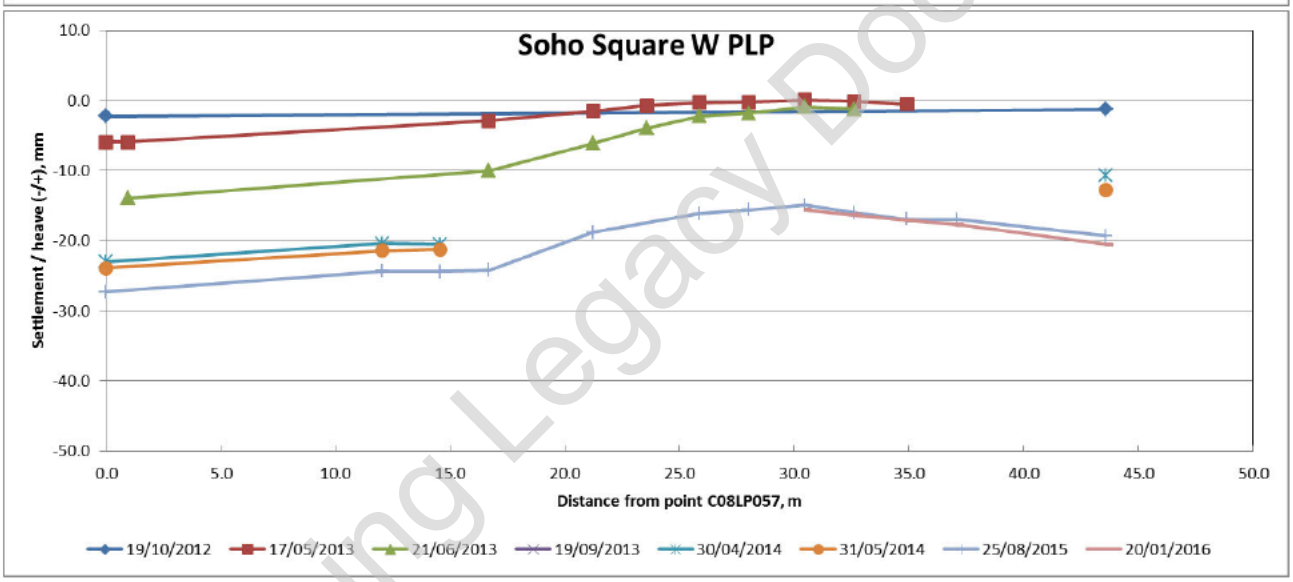
5.2. Soho Square West – outer









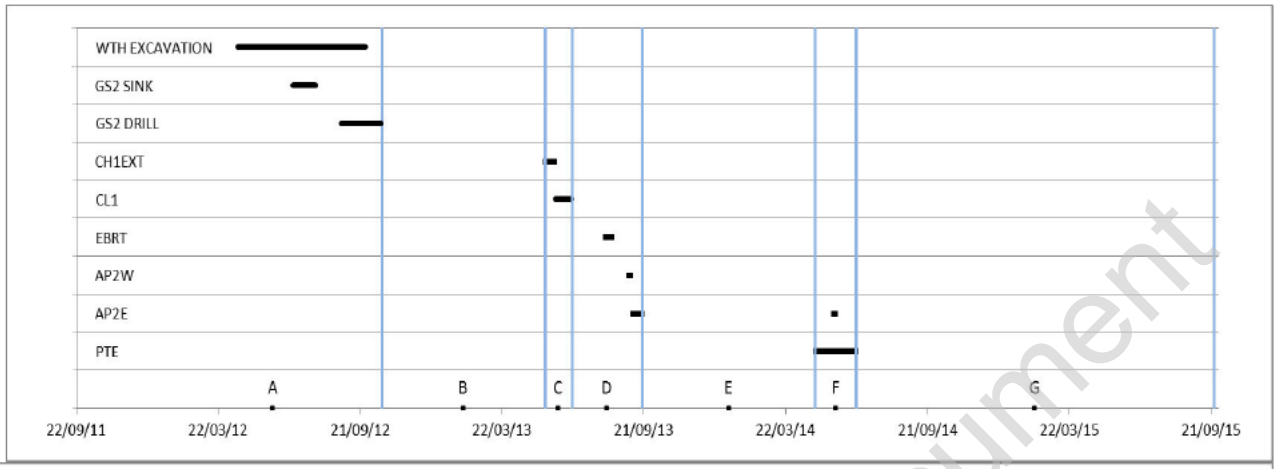


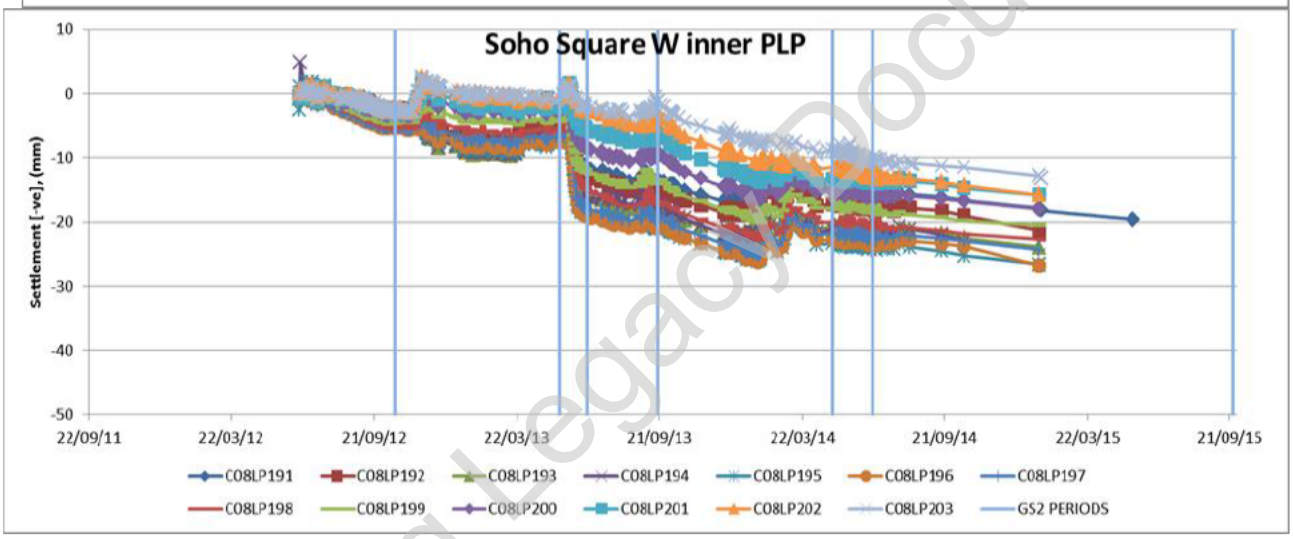
The following points are noted:

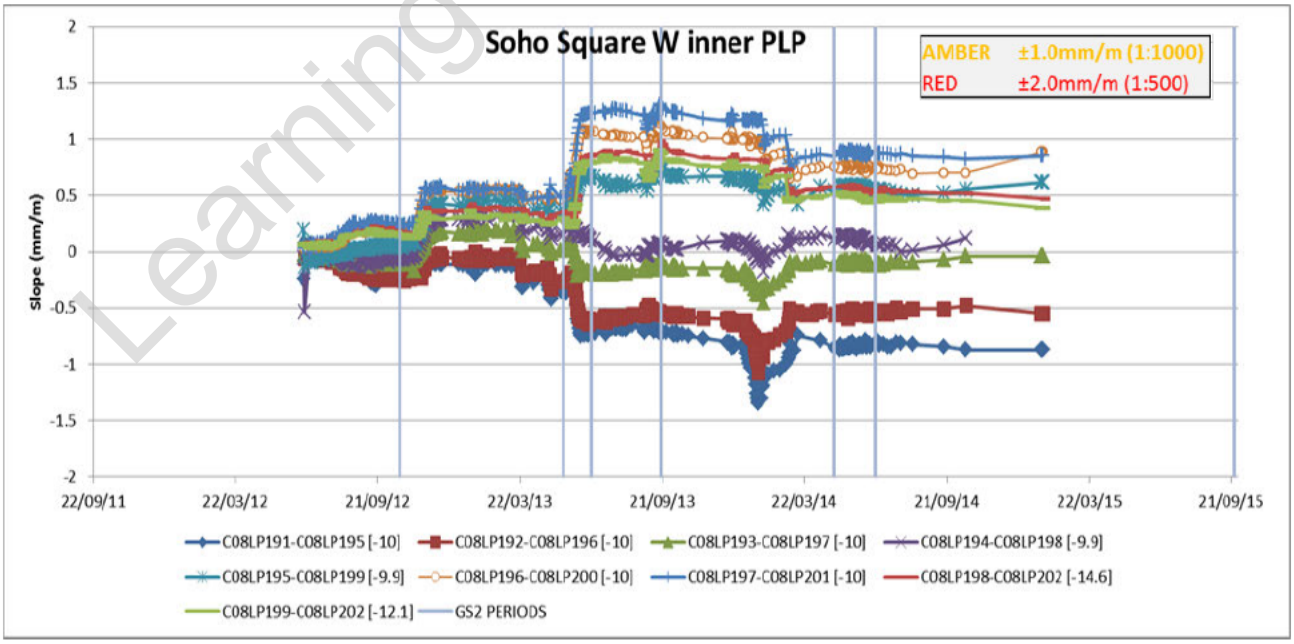
- Only part of the profile is within the TCR GS2 array (from distance 13m): data from points north of Carlisle Street are presented, as shown in Figure 5.1.1
- The only construction event where any significant settlement occurred is CL1 in Period C. No compensation grouting was undertaken with CL1. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- Minor settlement is evident in Period A associated with Tam drilling which was reversed by pre-treatment early in Period B. The more significant settlement and heave later within Period B is on points to the south of the GS2 array and is associated with drilling and pre-treatment in the adjacent GS3 area (see C300-BFK-C4-RGN-CRT00_ST005-51227).
- The rate of post construction settlement appeared to be approximately constant up to May 2015 in Period G but subsequent readings showed no significant change between May 2015 and September 2015 / January 2016.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.

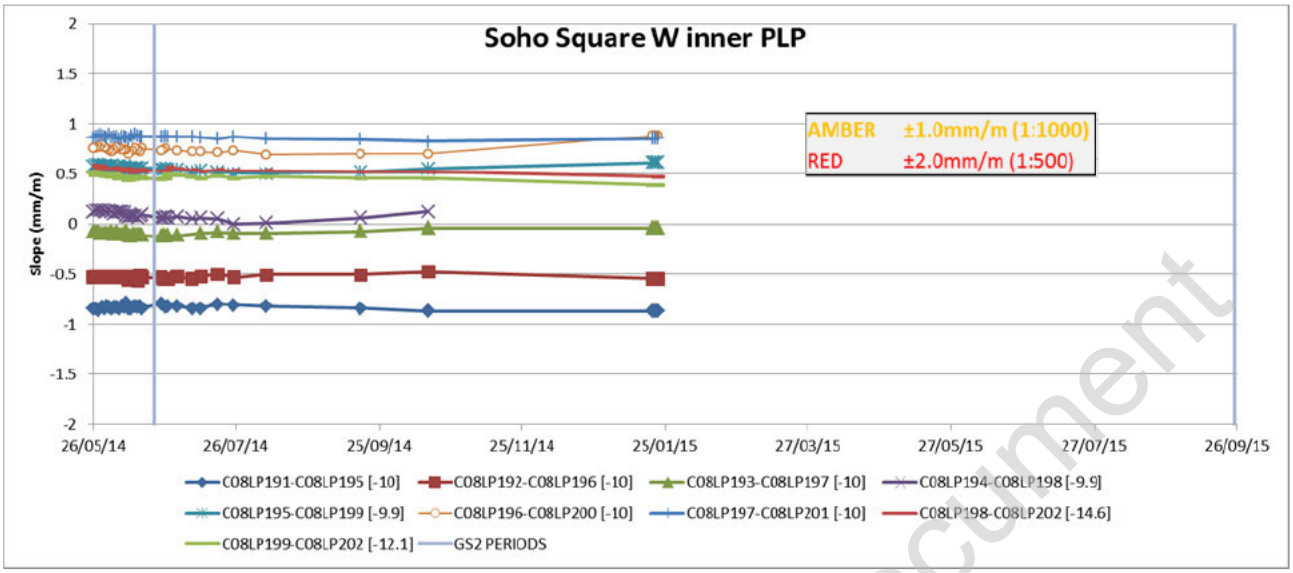
- The slope data plots show that no Amber slope trigger levels (1mm/m) have been exceeded and that the slopes are essentially constant.

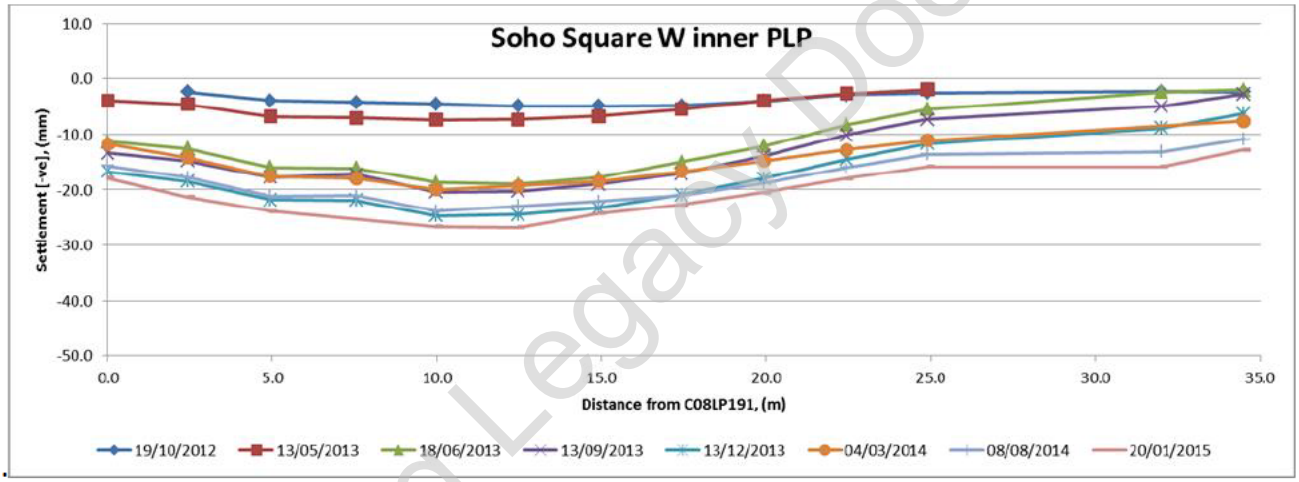
5.3. Soho Square West – inner









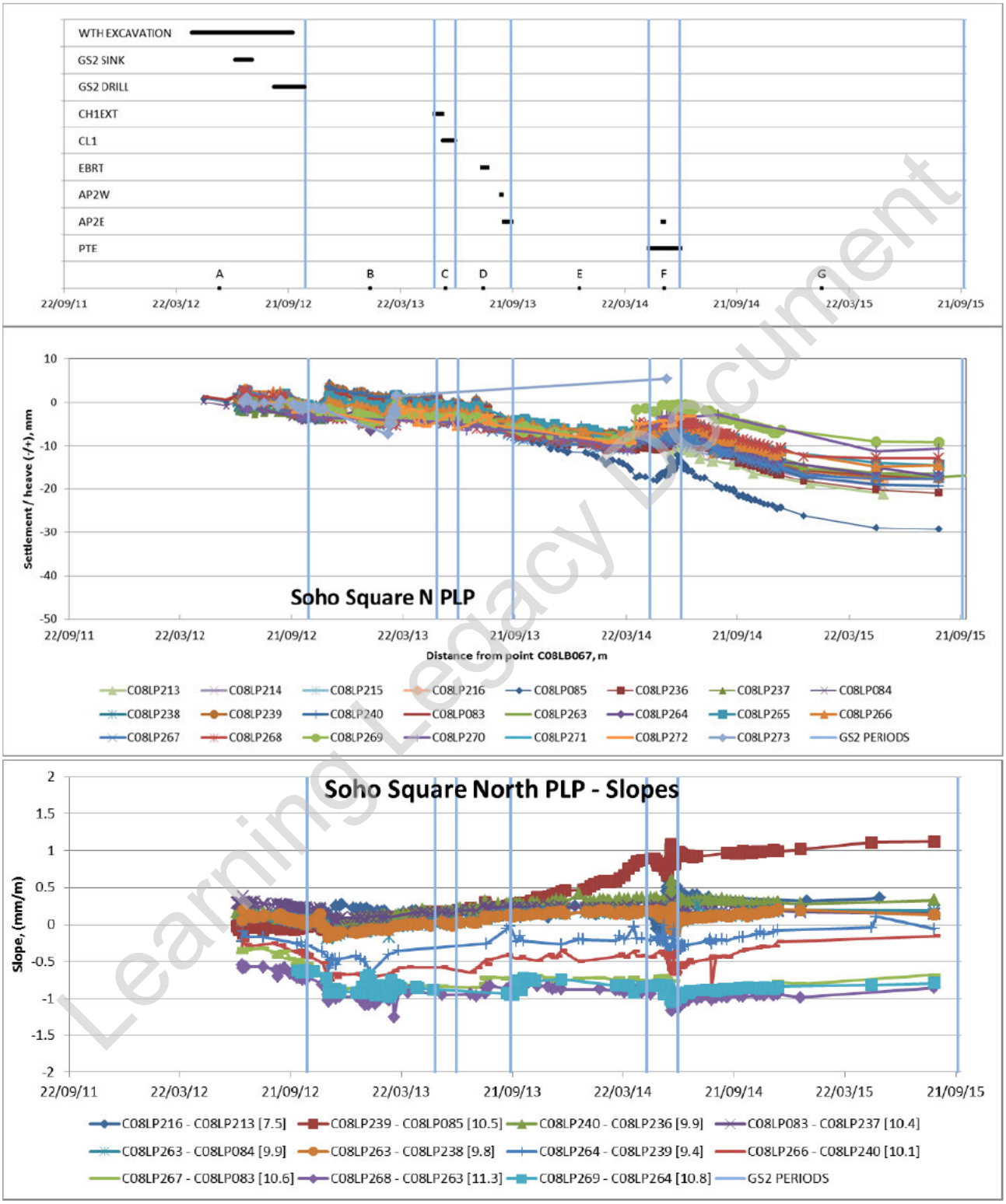


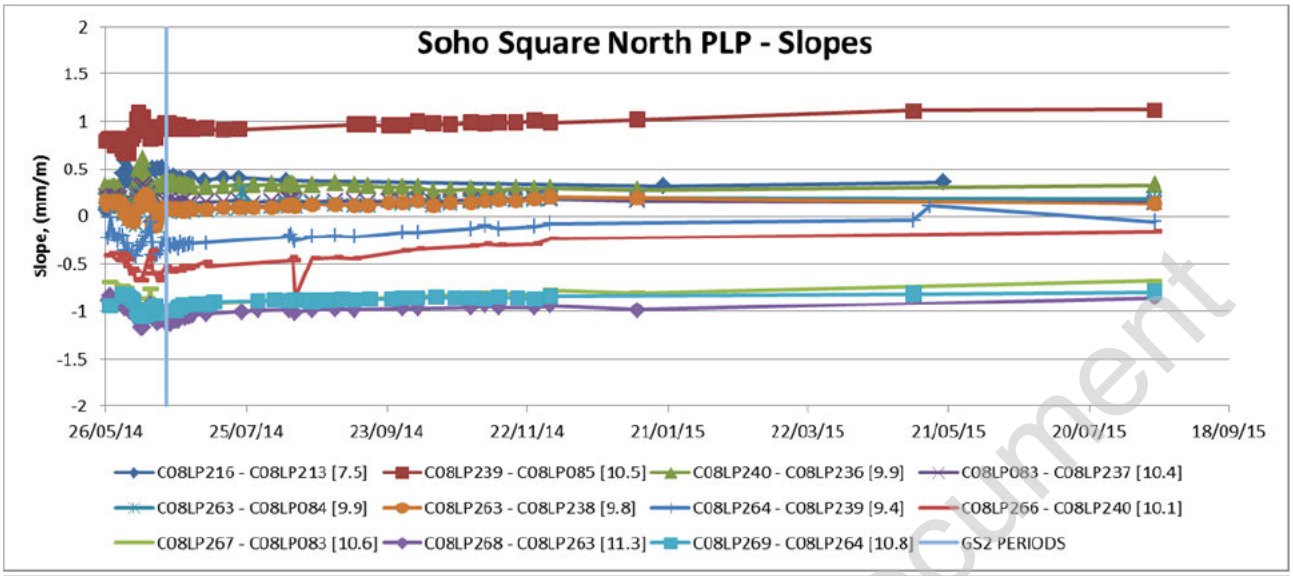
The following points are noted:

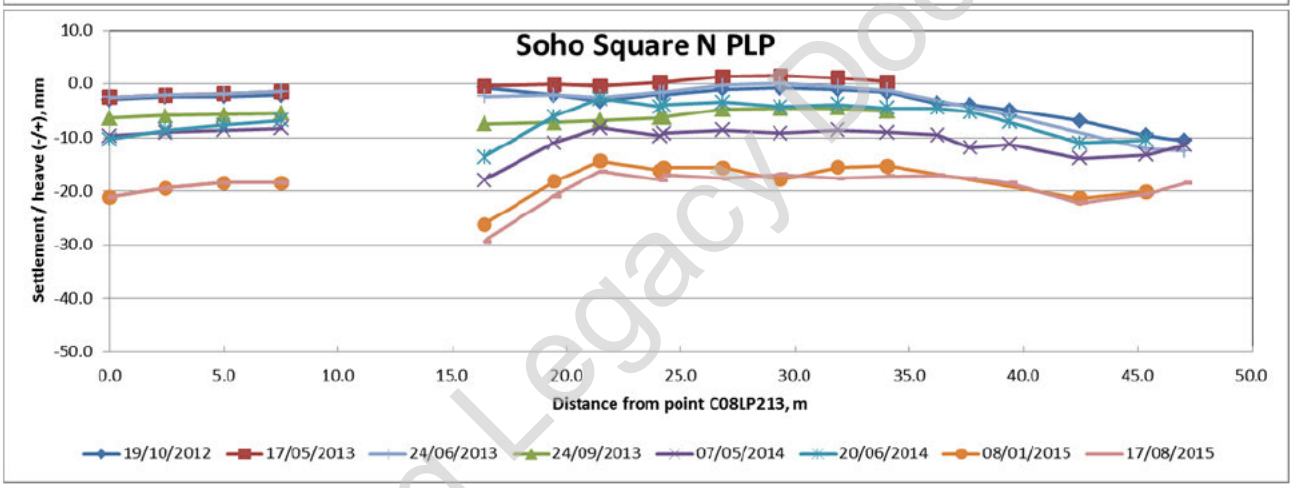
- Only part of the profile is within the TCR GS2 array (from distance 15m): however, data from all points are presented as shown in Figure 5.1.1.
- The only construction event where any significant settlement occurred is CL1 in Period C. No compensation grouting was undertaken with CL1. Where concurrent compensation grouting has been implemented (CH1Ext in Period C, AP2E and AP2W in Period D and PTE in Period F) movement has been controlled within small tolerances.
- The effect of pretreatment in Period B and a number of grout jacking episodes in Periods D and E are evident by the sharp reductions in settlement.
- The rate of post construction settlement remained approximately constant in Period G until the final reading in January 2015.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show that individual 10m Amber slope trigger levels were exceeded in Period C as a result of the construction of CL1 without concurrent compensation grouting. The slope between points C08LP197 and C08LP201 reached 1.23mm/m and that between C08LP196 and C08LP200 reached 1.06mm/m before gradually reducing.

- Further Amber triggers occurred temporarily in Period E within the adjacent GS3 area as a result of the construction of PTW and the junction with AP2W (the latter without concurrent compensation grouting). The slope between points C08LP192 and C08LP196 reached 1.07mm/m for a single reading on 23/01/14 and that between C08LP191 and C08LP195 exceeded Amber between 12/01/14 and 19/02/14, reaching a maximum of 1.34mm/m. All of these slopes were reduced to below the Amber trigger value by grout jacking episodes. No Deflection Ratio triggers were breached.

5.4. Soho Square North – outer





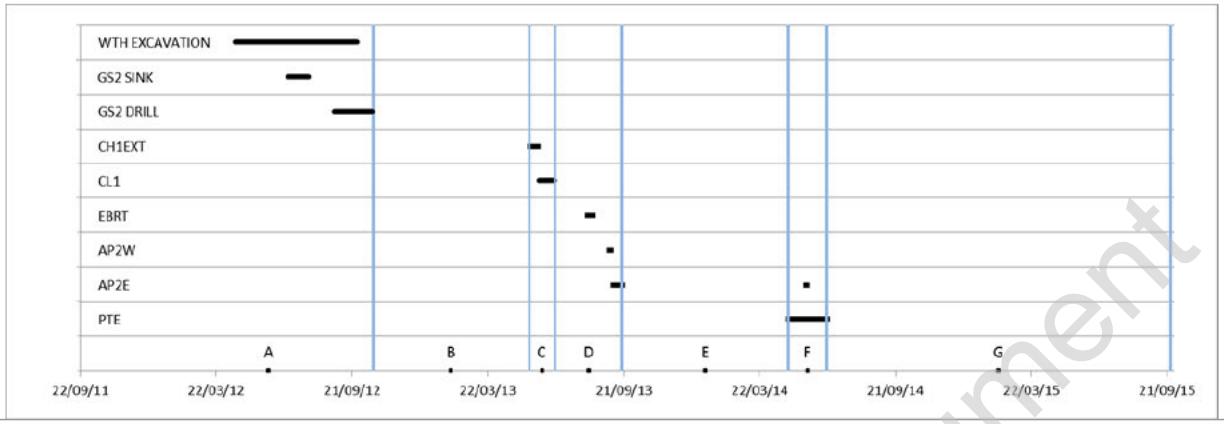


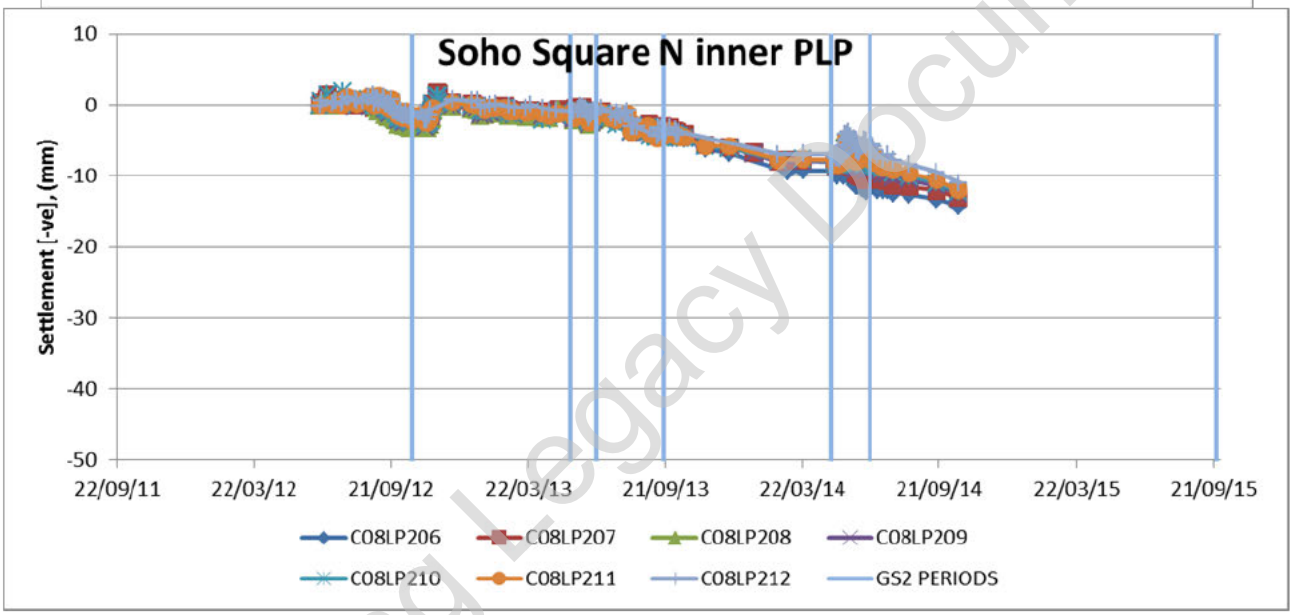
The following points are noted:

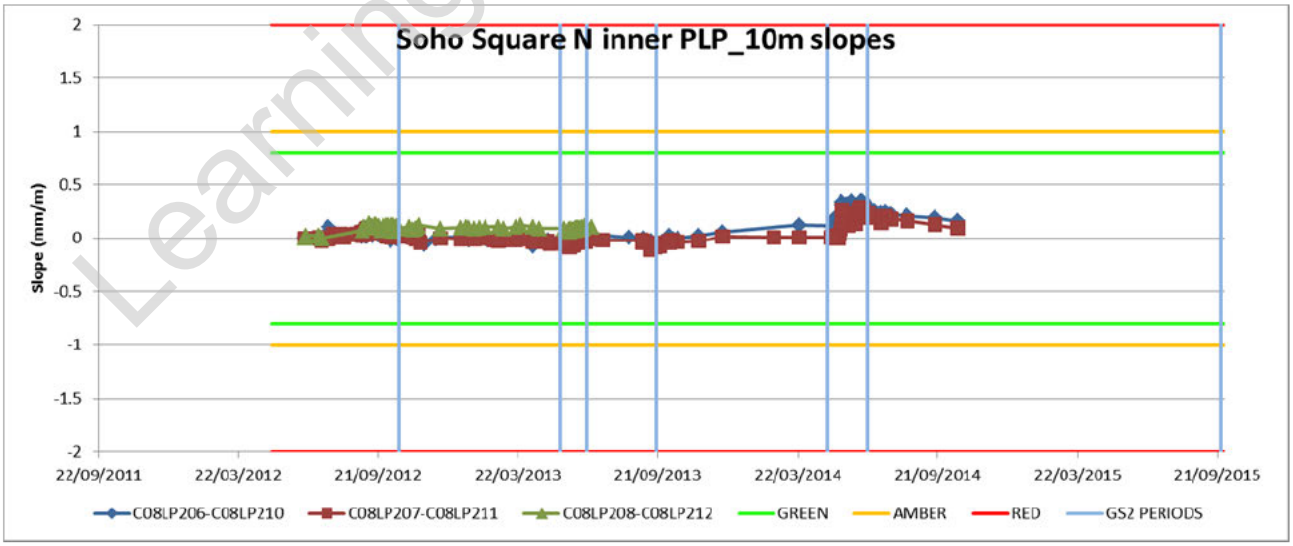
- Although part of the profile is not within the TCR GS2 array (up to distance 43m): data from points all points are presented as shown in Figure 5.1.1
- The only construction event where any significant settlement occurred is the EBRT in Period D. No compensation grouting was undertaken with the running tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- The rate of post construction settlement has continuously reduced in Period G and no significant change is shown between May 2015 and September 2015.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show that individual 10m Amber slope triggers have been exceeded between C08LP268 / C08LP263 and C08LP269 / C08LP264. These two are located at the eastern boundary of the GS2 array and extend within the 3m exclusion zone around GS4, thus it was not practical to generate significant uplift on these points. It is also noted that these triggers occurred prior to the commencement of any tunnelling work in the vicinity i.e. in Period B.

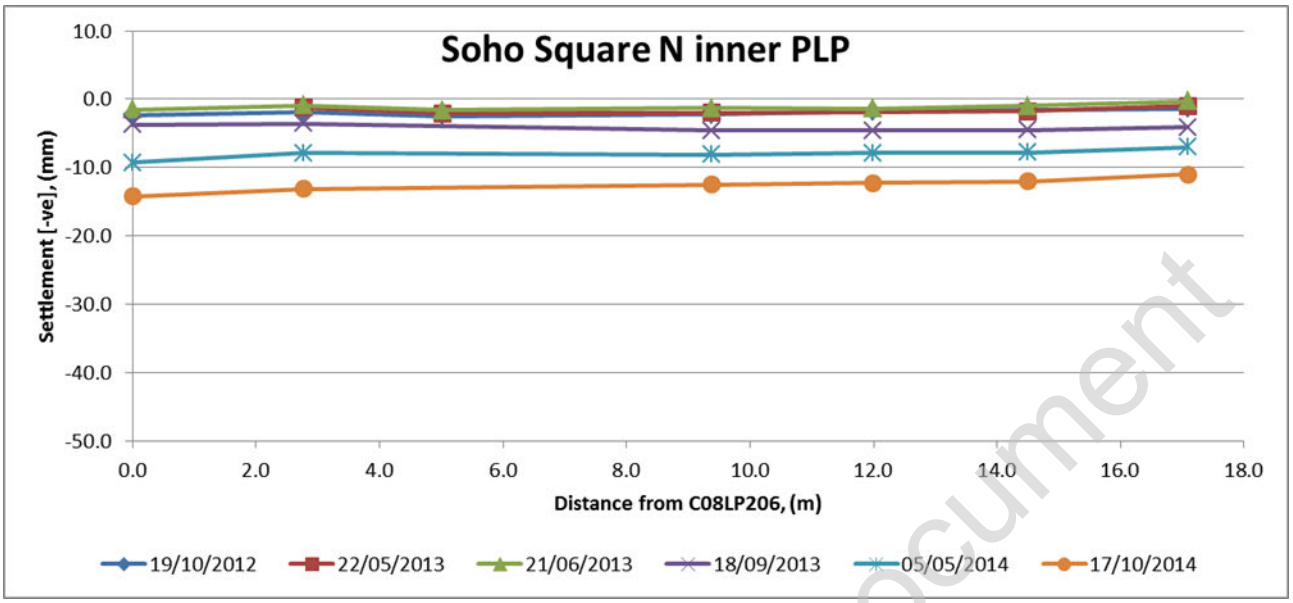
- A further slope trigger breach occurred in Period F between points C08LP239 / C08LP085. The slope had been increasing throughout Period E when no works were in progress. The concurrent grouting for PTE in Period F generated a small uplift which reduced the slope slightly initially but subsequent settlement caused it to increase. The slope has continued to increase post construction but appears to have stabilized at a value of about 1.1mm/m. It is noted that the increase in slope is primarily due to an increase rate of settlement on point C08LP085 located at the corner of Soho Square and Soho Street.
- In general, slopes have been stable since the end of construction.

5.5. Soho Square North – inner





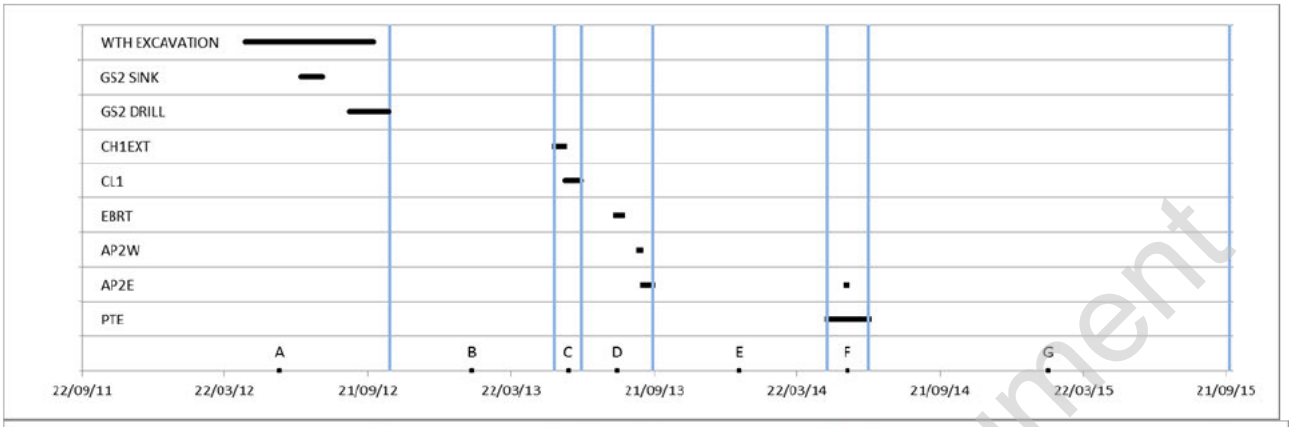


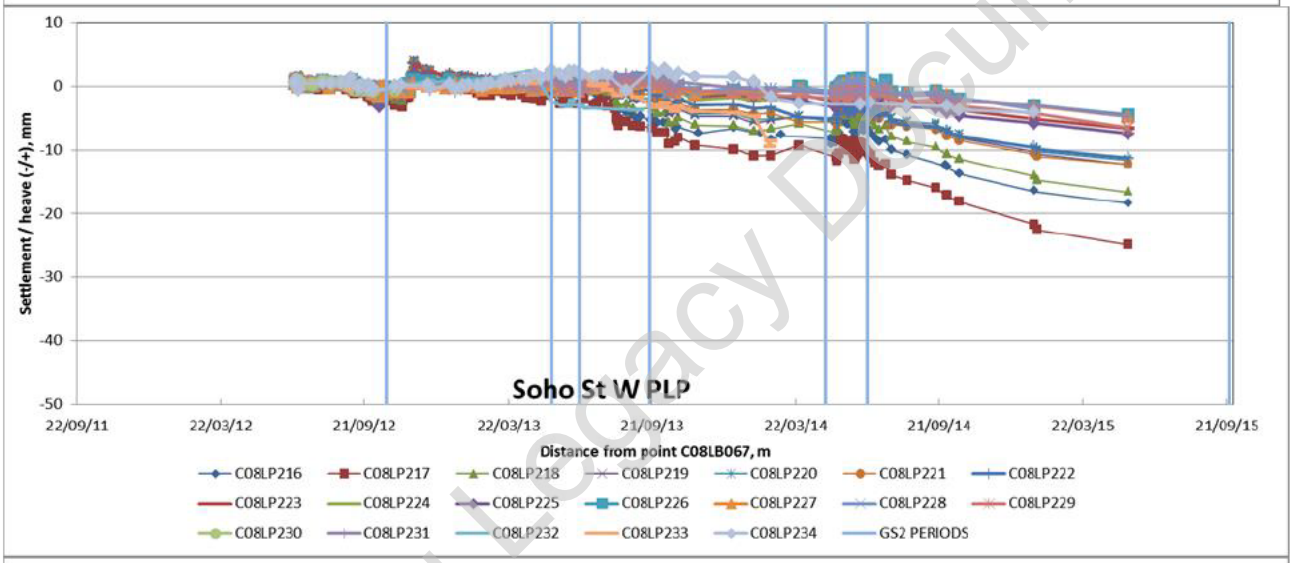


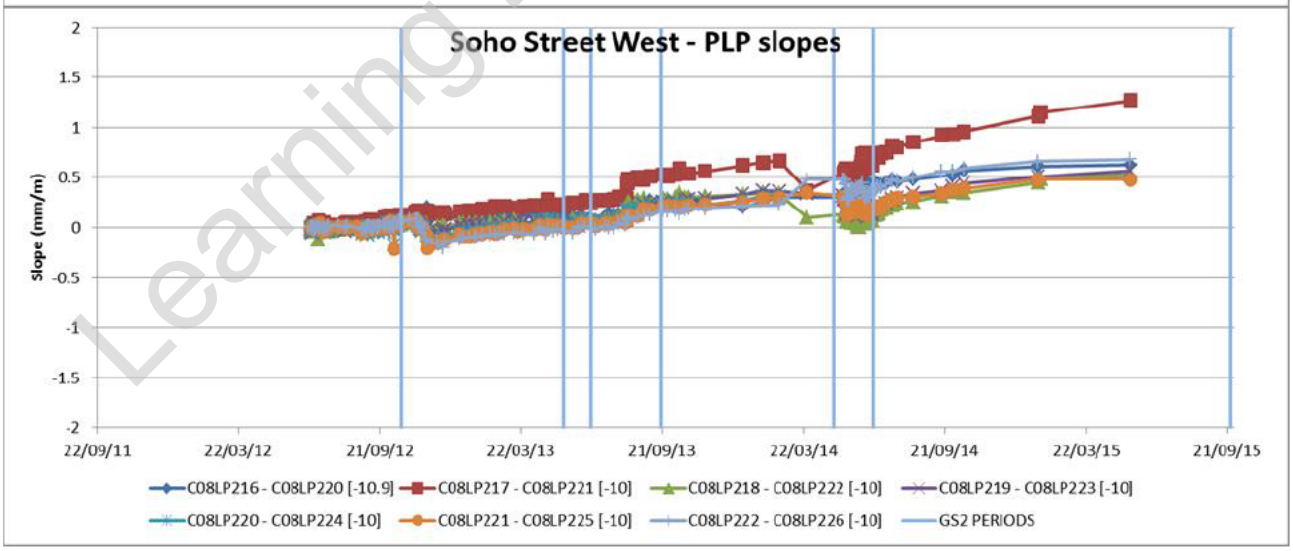
The following points are noted:

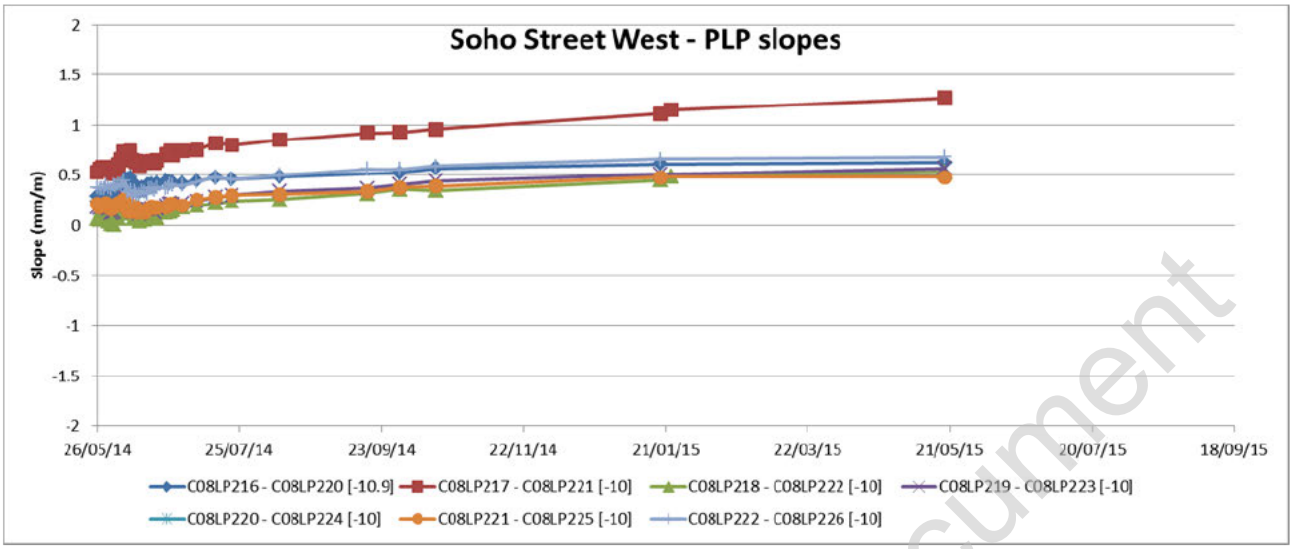
- All of the points in this profile are within the TCR GS2 array, as shown in Figure 5.1.1.
- The only tunnel construction event where any significant movement can be discerned is the PTE in Period F. Compensation grouting was undertaken with the tunnel and some settlement and heave were generated, although overall movement was controlled within small tolerances.
- The rate of post construction settlement remained approximately constant in Period G until the final reading in October 2014.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plots show that no triggers have been exceeded and slopes have been reducing since the end of construction.

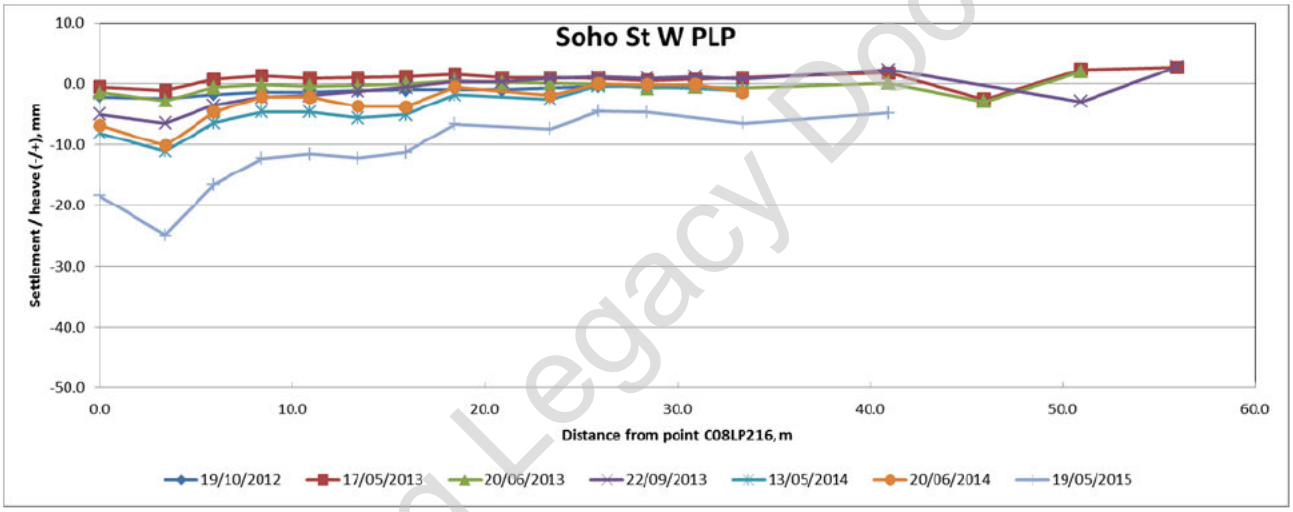
5.6. Soho Street West











The following points are noted:

- The points on the west kerb line of Soho Street are within the TCR GS2 array up to a distance of about 24m, as shown in Figure 5.1.1. It is noted that points further north were potentially affected by the re-development of this site (61 Oxford Street).
- The only construction event where any significant settlement occurred is the EBRT and PTE in Period D. No compensation grouting was undertaken with this tunnel. Where concurrent compensation grouting has been implemented movement has been controlled within small tolerances.
- The rate of post construction settlement has continuously reduced in Period G but had not stabilised by the final reading in May 2015.
- The profile plot confirms that the consolidation settlement is relatively uniform over a wide area resulting in little change in slopes.
- The slope data plot shows increases associated with PTE / AP2E connection in Period F as well as the EBRT. The slopes have increased slightly in the post construction period (Period G) and one has reached the Amber trigger level (C08LP217 – C08LP221) and continued to increase reaching a value of 1.3mm/m. It is noted that this is a result of an increased rate of settlement on point C08LP217 which is located on the corner of Soho Square and Soho Street.

6. DISCUSSION

The preceding presentation of settlement monitoring data has identified a limited number of locations where the Amber slope trigger has been exceeded. It is arguable whether any of these slope triggers also are breaches of the Compensation Grouting Performance Criteria (CGPC) for a number of reasons discussed in Sections 4 and 5, namely: the data is of doubtful validity; concurrent compensation grouting was not deemed necessary; a significant proportion of the differential movement was extant prior to BFK works; or the trigger was exceeded after the completion of tunnelling. The data also show that, in some locations the slopes continue to increase, albeit generally at a slow and decreasing rate.

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 achieved, however, a number of particular issues have become apparent as the works have progressed:

- The grout shaft location is far from ideal being close the PTE and buildings on the north side of Soho Square;
- Grout jacking to reverse settlements although necessary to comply with the CGPR is not always the optimal course of action: the reversal of movements of structure is not a linear elastic situation, there is the potential for significant damage to occur even if the recorded settlements are negligible. BFK has always considered that the *raison d'etre* of the Specification is to minimise damage notwithstanding the contractual implication of exceeding Performance Criteria;
- Although slope triggers have been exceeded, these were intended to be a simple method of ensuring the deflection ratio did not exceed the value associated with Negligible damage (the Amber trigger): this value has not been exceeded;
- Tunnelling was completed in June 2014: the increase in movements has been reviewed on a daily, weekly and then monthly basis at SRG and CTC meetings and BFK proposed in October 2014 that no further grouting to reduce movements was justified and that, therefore, the grout shaft could be de-commissioned. CRL accepted the proposal (C300-PMC-09581)and the grout shaft was subsequently de-commissioned.

7. CONCLUSION

It was concluded that no further grouting from TCR GS2 would be required based on an abridged version of this report submitted in October 2014: Grout Shaft 2 was subsequently decommissioned.

The key factor which lead to this conclusion was that, in the 3 months after the completion of tunnelling and compensation grouting, ongoing post construction settlements were kept under continual review at daily, weekly and then 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 GS2 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 governed by the stress conditions at the time of injection which are 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:

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

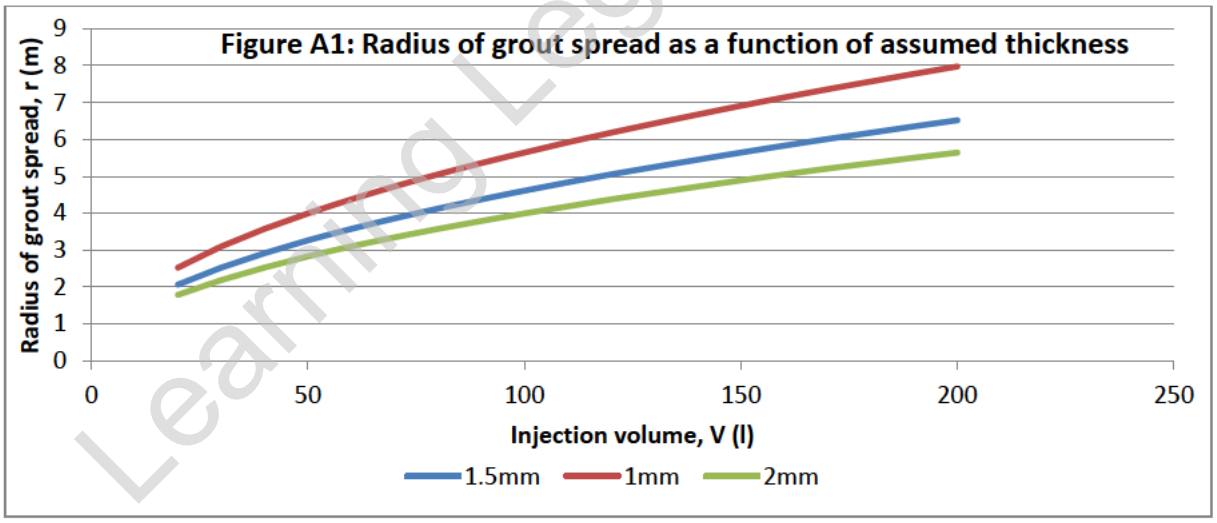


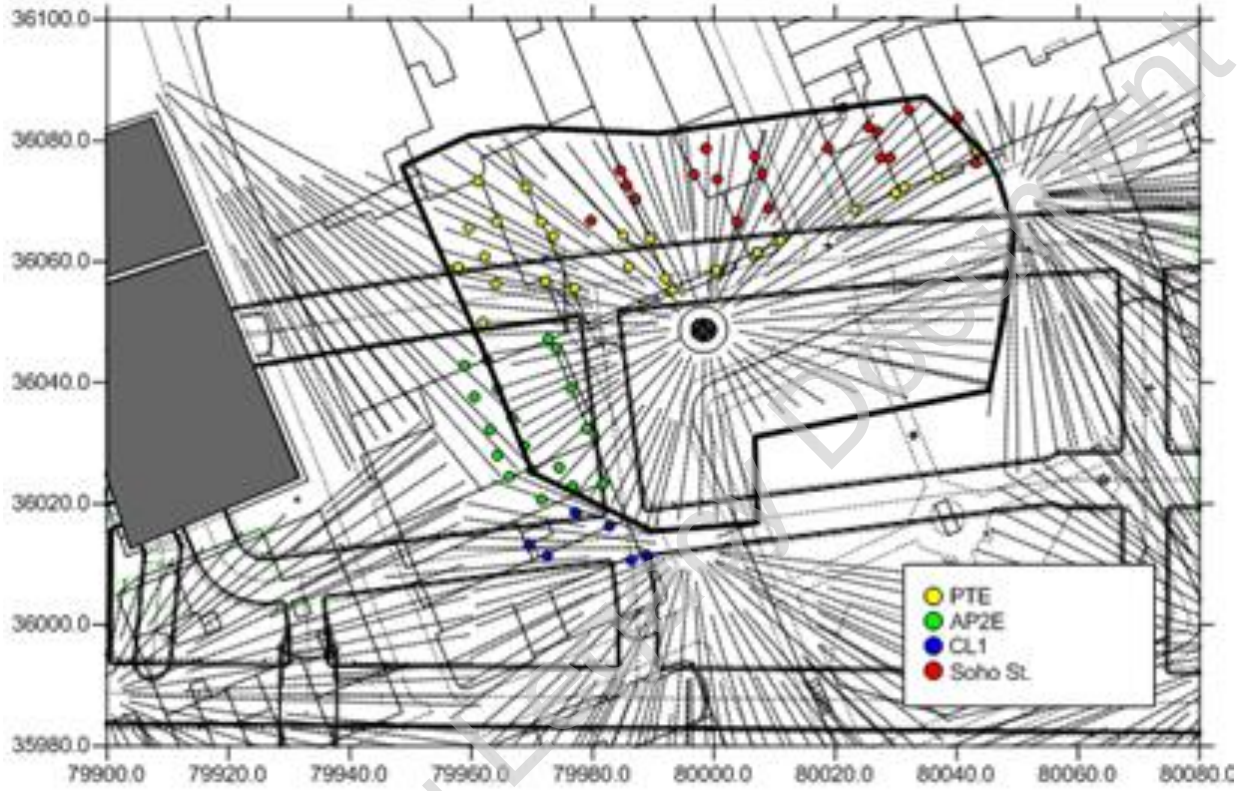
Figure A1: Radius of grout spread as a function of assumed thickness

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.

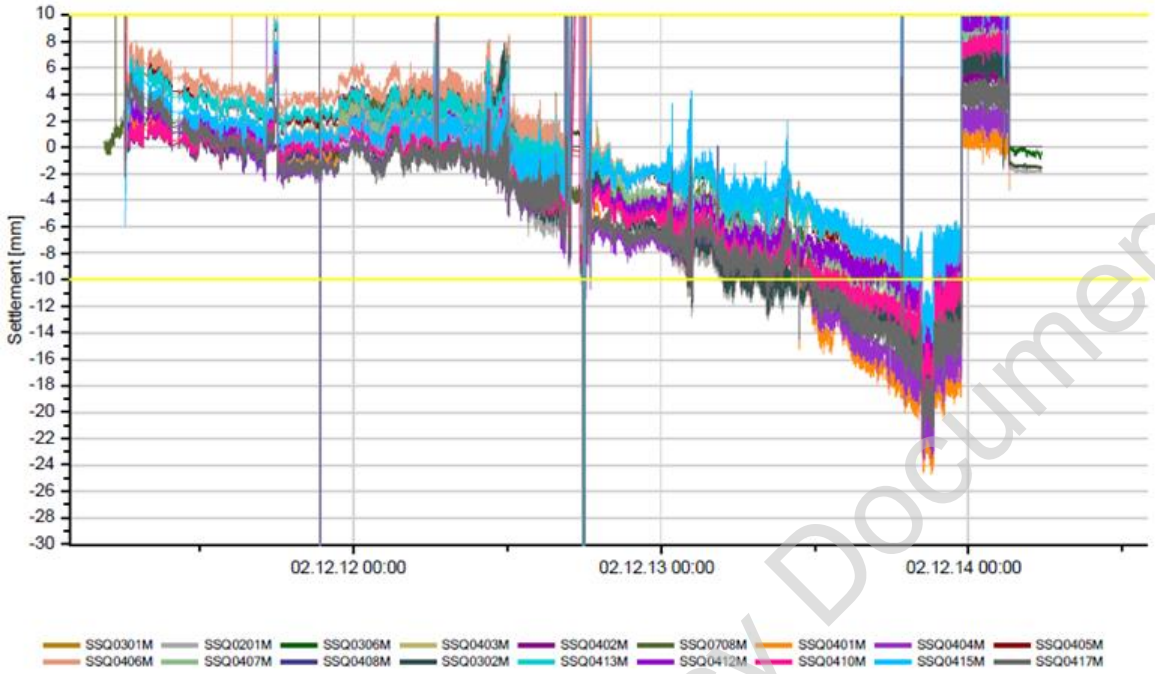
Appendix B

Data from HLCs, Shape Accel Arrays installed from GS2 and GS3 and Crack Meter in 7 Soho Square

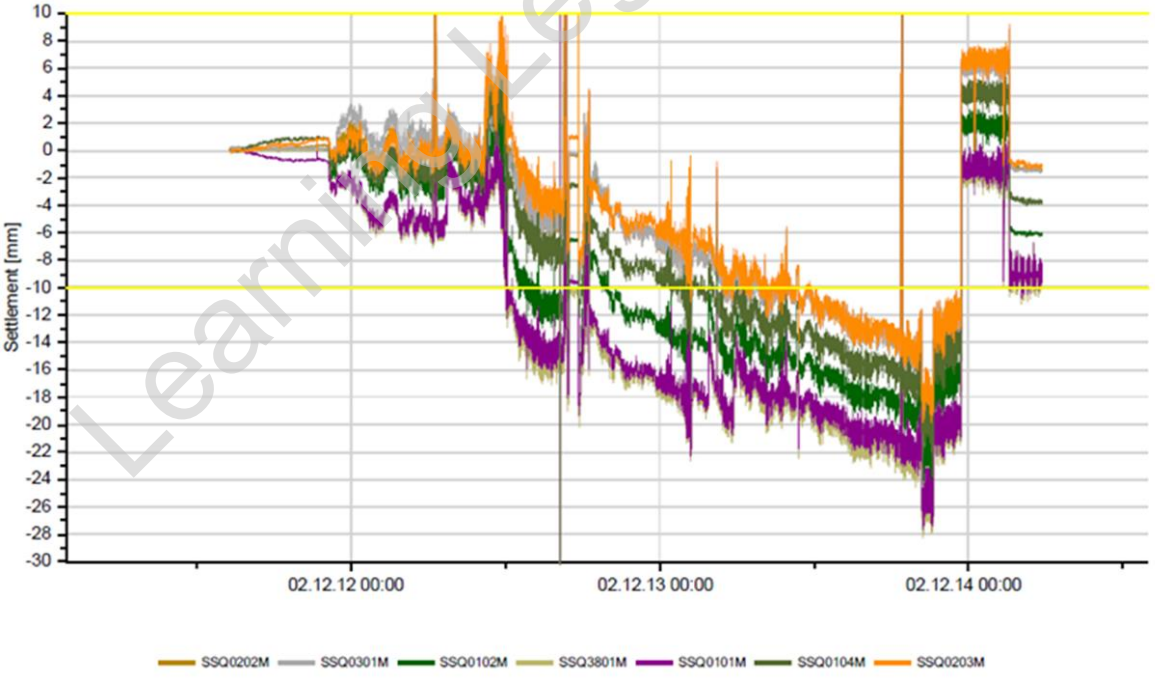


HLC were primarily used for control of compensation grouting giving data at 15 minute intervals. The system was left operational after the completion of the tunnelling to provide information on post –construction movements. Scatter observed in HLC data during December 2014 and February 2015 was due to the cessation of maintenance since this monitoring data following the completion of excavation works in February 2014 and the de-commissioning of the grout shaft from August 2014.

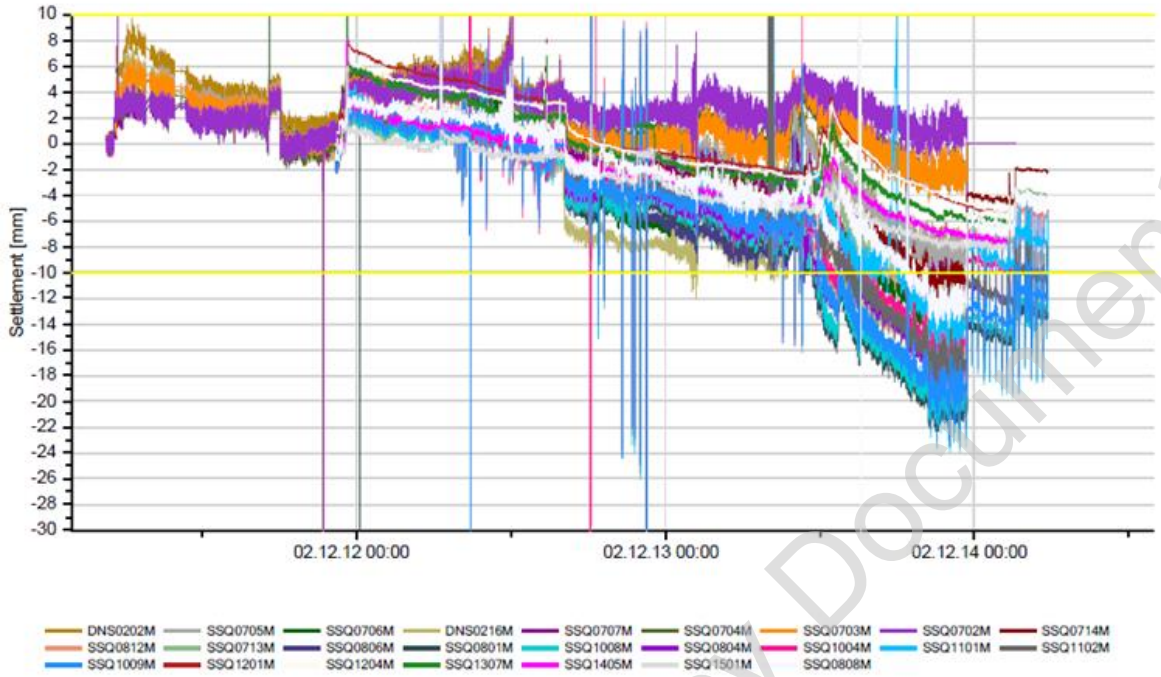
AP2E



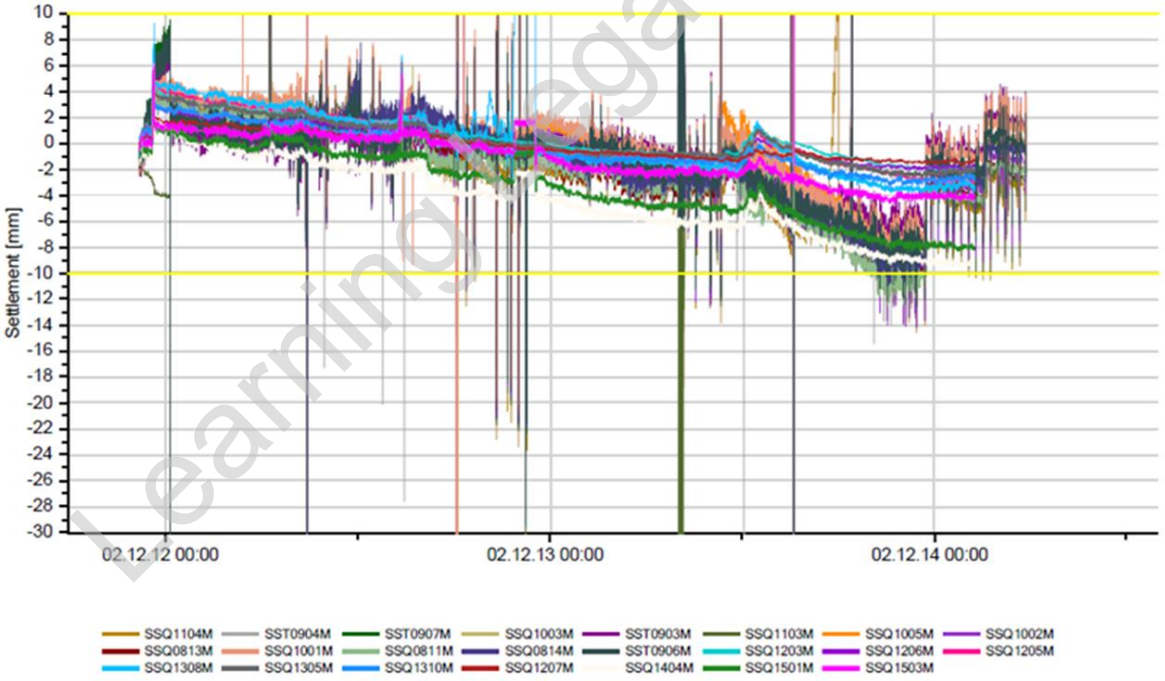
CL1

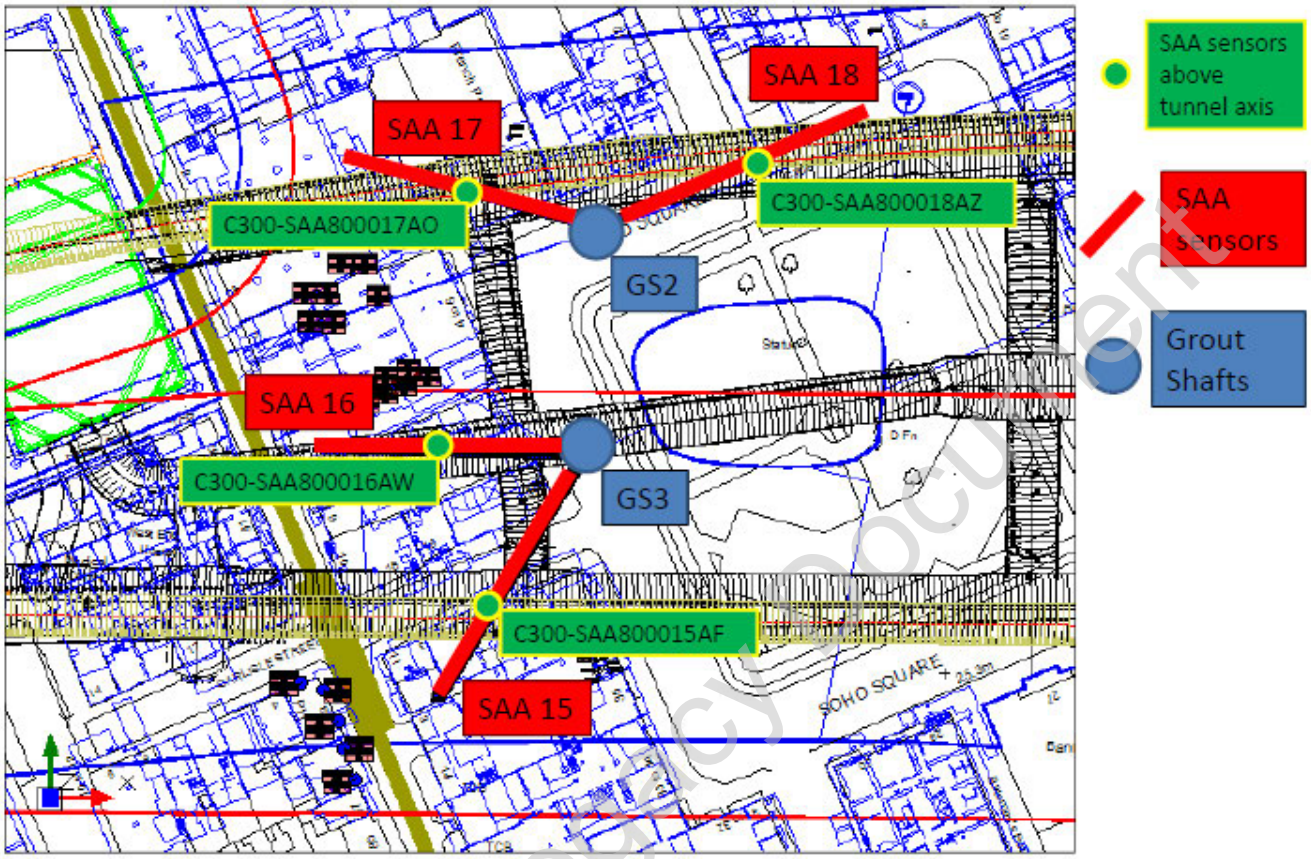


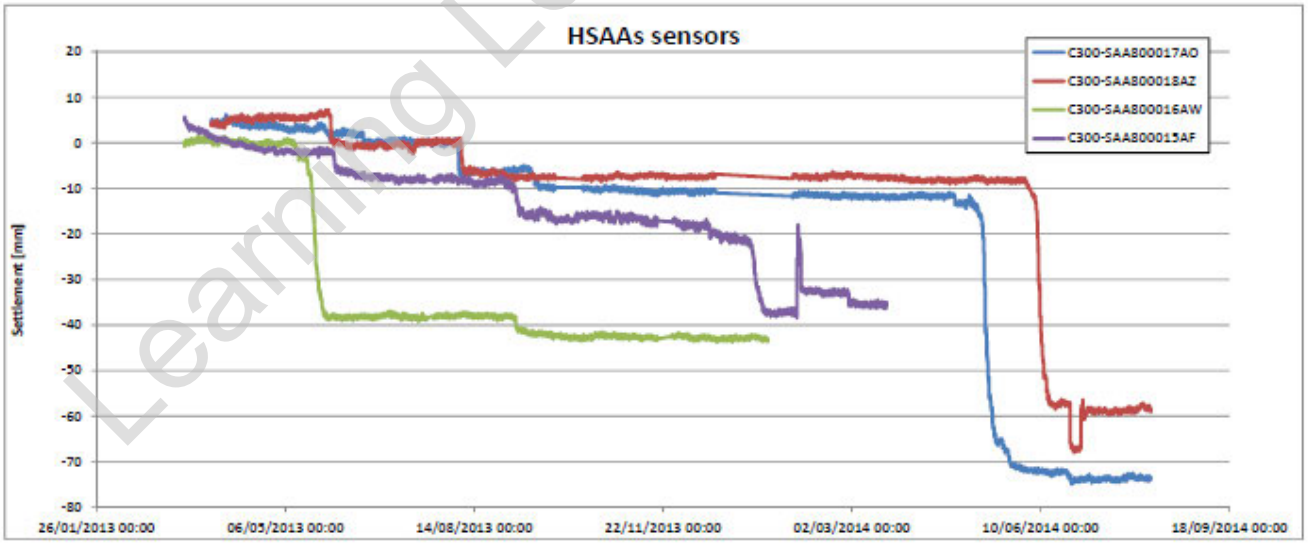
PTE

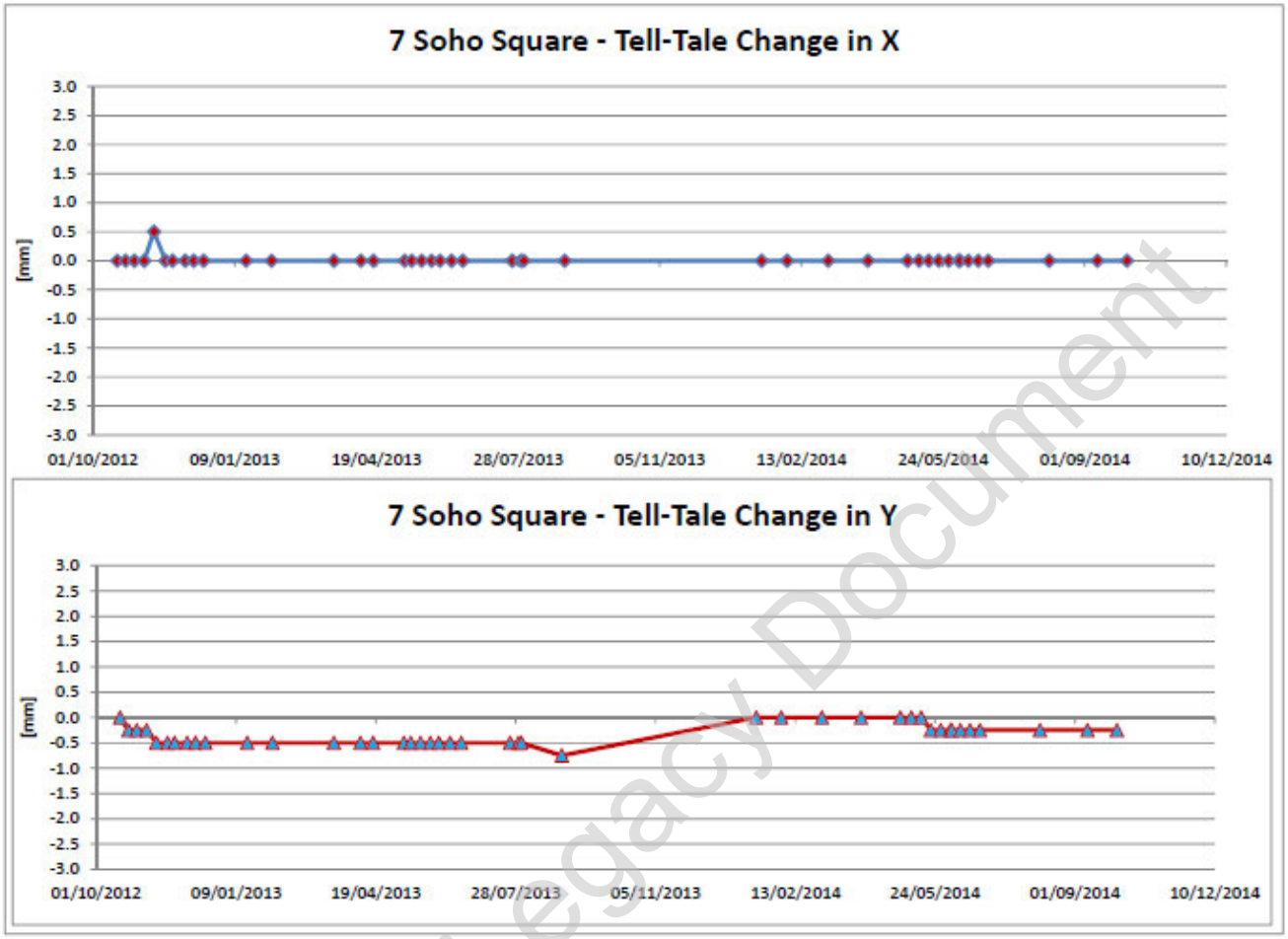


Soho St.



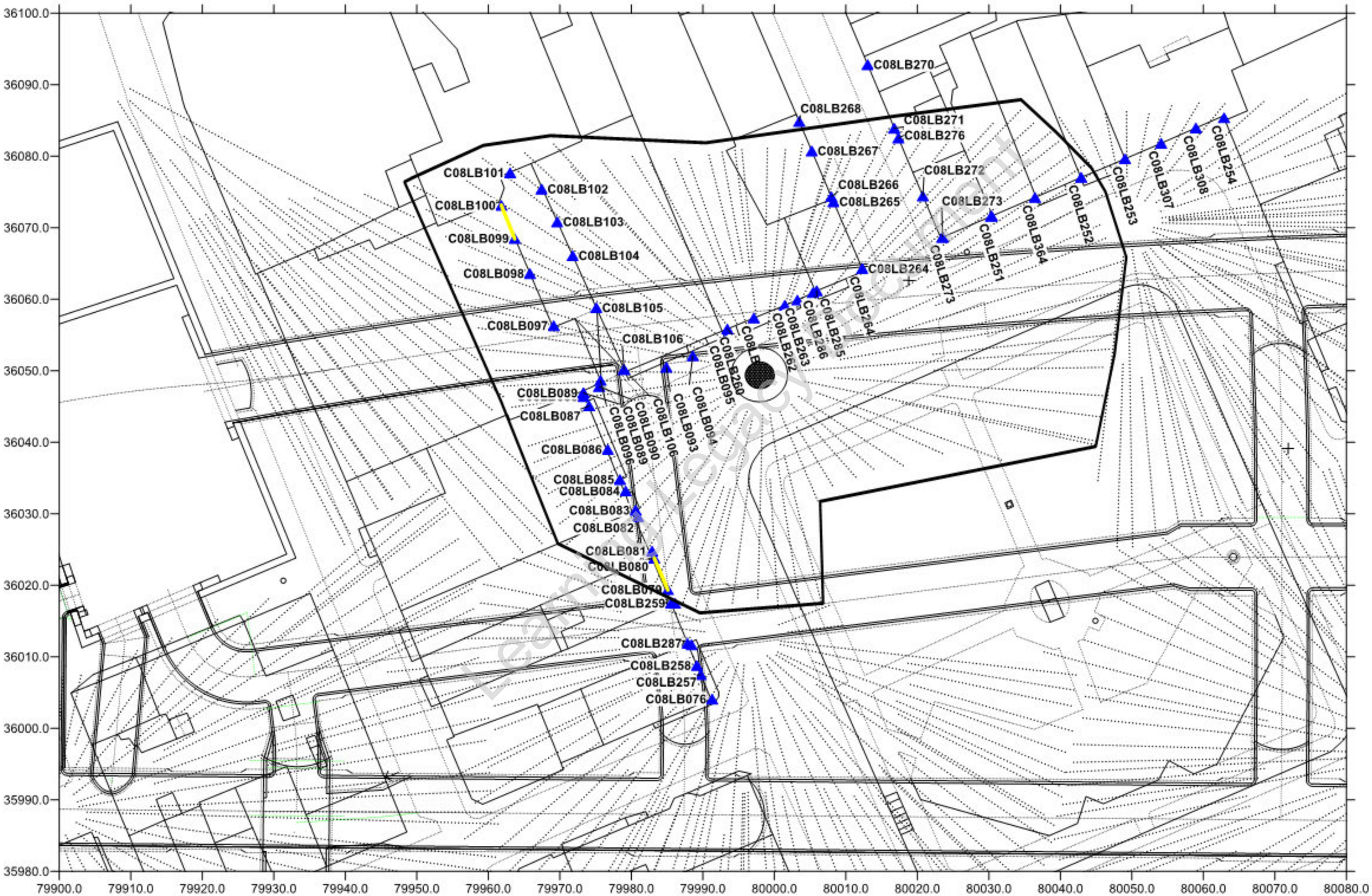






Appendix C

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


C08LB270
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C08LB271
C08LB276
C08LB267
C08LB272
C08LB266
C08LB265
C08LB273
C08LB101
C08LB102
C08LB100
C08LB103
C08LB099
C08LB104
C08LB098
C08LB264
C08LB105
C08LB097
C08LB106
C08LB089
C08LB087
C08LB086
C08LB085
C08LB084
C08LB083
C08LB082
C08LB081
C08LB080
C08LB079
C08LB259
C08LB287
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79970.0
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80030.0
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80050.0
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