C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - TCR GS3

CRL Document No. C300-BFK-C4-RGN-CRT00_ST005-51227

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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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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APPENDICES

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 (C122-OVE-Z4-RSP-CR001-00007) Materials and Workmanship Specifications. 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 3 at Tottenham Court Road Station (TCR)

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. A general location plan of the grout shafts at TCR is provided in Figure 1.1.1.

All BFK excavation (tunnelling) works within the plan extent of the compensation grouting arrays from TCR Station Grout Shaft 3 were completed by February 2014. One small grout jacking episode was implemented immediately after the completion of tunnelling which was completed in February 2014. An abridged version of this report was issued in August 2014 (C300-CCM-08749), about 6 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 3 at TCR Station and includes manual monitoring up to September 2015 when the manual monitoring within the GS3 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 the instrumentation. 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 and HSAA (Horizontal Shape Accel Arrays) in the GS3 area are included in Appendix B. Two HSAA were drilled from GS3 at an elevation about 1m above the crown of the tunnels, in lieu of inclinometers and extensometers from the ground surface. A separate report is provided for the ATS network (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 after 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.

Figure 1.1.1 General Shafts Location Plan (reproduced from C300-BFK-C-DWG-CRT00_ST005_Z-50020)

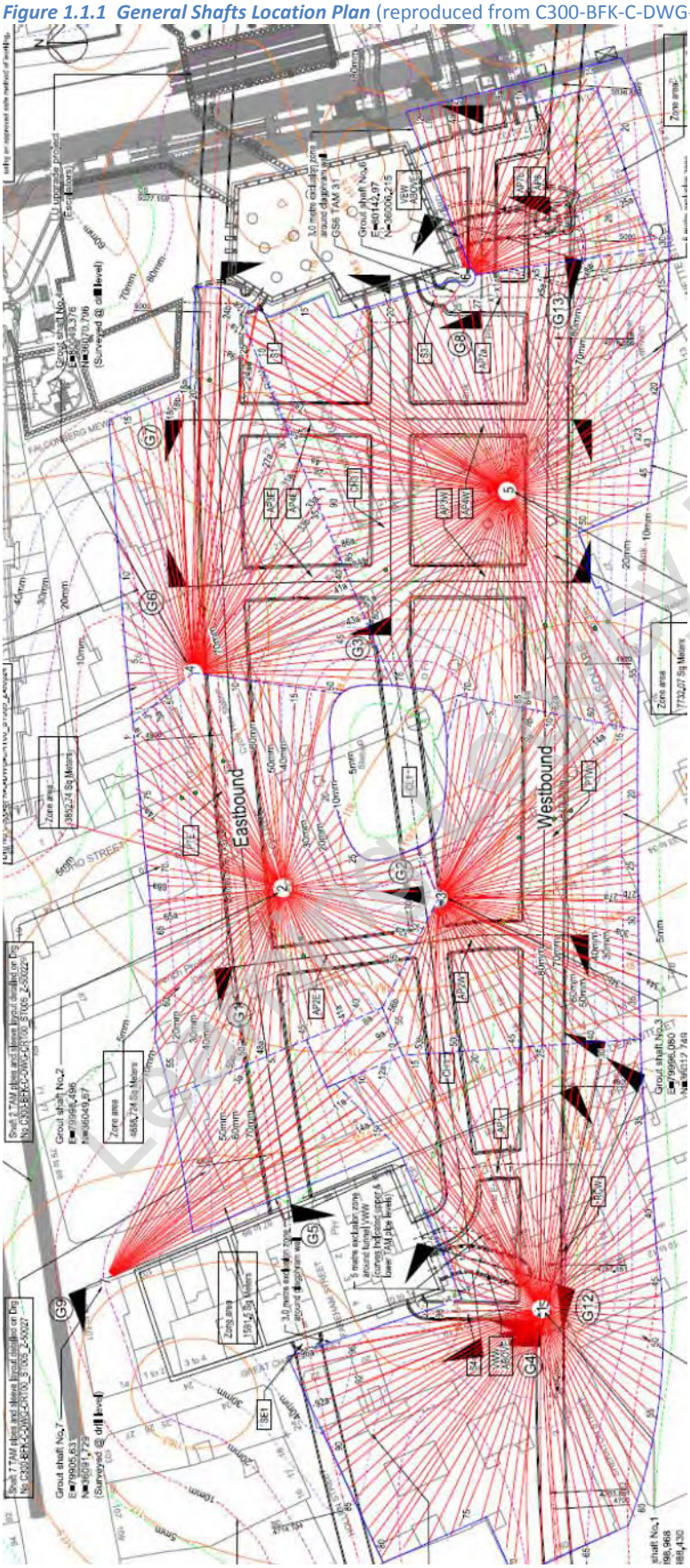

Table 1.1 Extracts from Works Information

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.

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 3 at TCR Station. Tunnel excavation commenced with CH1 in May 2013 and was completed with the junction between AP2W and PTW in February 2014. To facilitate comparison of monitoring data with construction activities 7 periods (A to G) have been assigned. Tunnelling within the plan extent of the arrays was completed in 3 of these periods (C, D & F) as shown in Table 2.1. The main construction activities in each period are summarised in Table 2.2.

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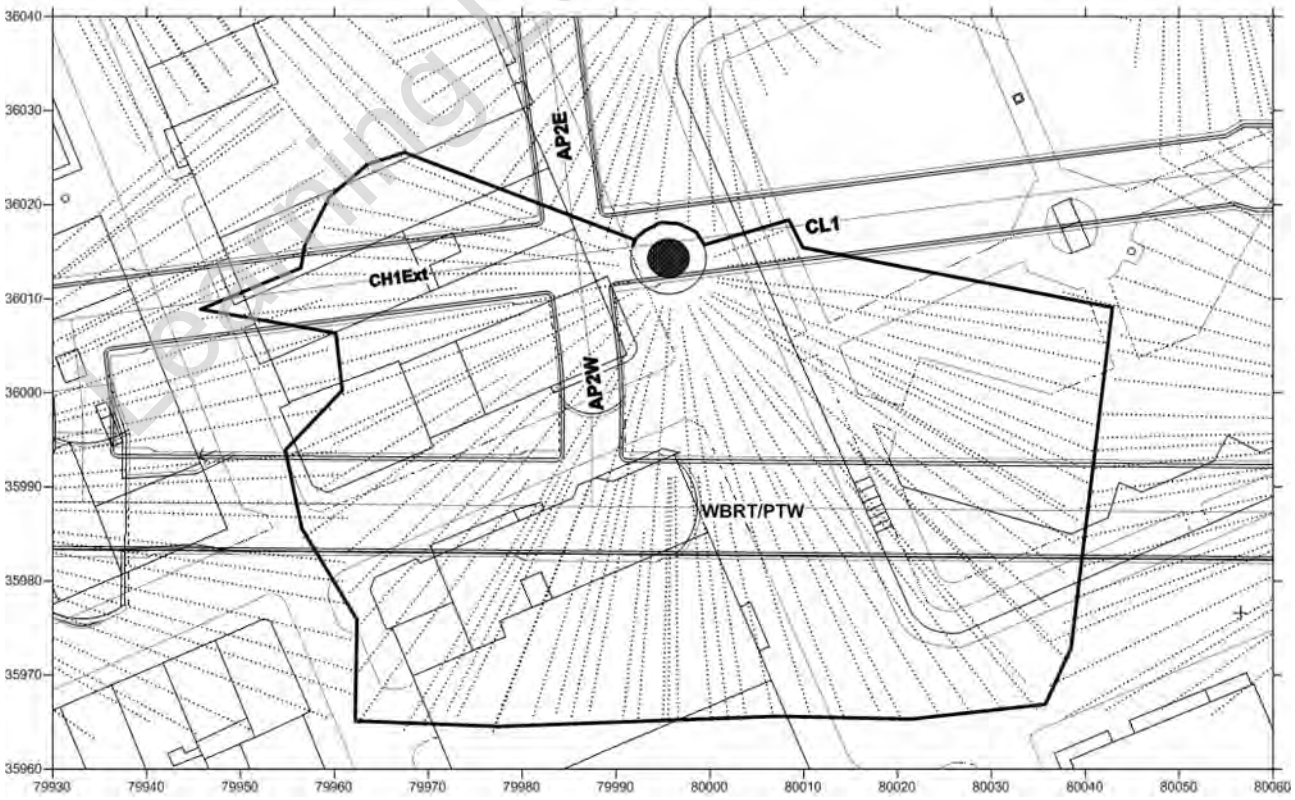
Table 2.1 Progress of C300/C410 works at TCR GS3 area.

PERIOD	TUNNEL	START DATE	END DATE
C	Lower Concourse Tunnel 1 Extension (CH1Ext)	10/05/2013	29/05/2013
	Central Link 1 (CL1)	30/05/2013	17/06/2013
	Westbound Running Tunnel (WBRT)	30/05/2013	09/06/2013
D	Access Passage 2 West (AP2W)	02/09/2013	05/09/2013
	Access Passage 2 East (AP2E)	07/09/2013	12/09/2013
F	Platform Tunnel Westbound (PTW)	09/12/2013	26/01/2014
	Access Passage 2 West (AP2W) connection	01/02/2014	04/02/2014

Figure 2.1.1Tunnels within extent of grout array from Grout Shaft 3



2.2. Other construction works

Works by BFK prior to the commencement of tunnelling included:

- Sinking of Grout Shaft 3
- Drilling for installation of TaMs
- Pre-treatment grouting
- Excavation of Western Ticket Hall (WTH) box

Works by Others prior to the start of tunnelling included:

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

Works by Others during tunnelling comprised:

- Refurbishment of buildings on south side of Carlisle Street

Works by Others after completion of tunnelling include:

- C422 installation of internal structure to WTH and removal of temporary props (no grouting).

2.3. Compensation Grouting

The volume of grout injected from TCR GS3 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 20m^3 injected prior to tunnelling, concurrent grouting over 120m^3 and grout jacking just over 30m^3. Concurrent grouting was undertaken with all tunnels except the WBRT, CL1 and the AP2W / PTW junction. 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. The AP2W / PTW junction is 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 (as per C300-CCM-01519 and 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 GS3 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 GS3 area.

Period	Start Date	End Date	Main Works
A	30/09/2011	25/10/2012	WTH excavation, GS3 sink & Tam Drilling
B	25/10/2012	09/05/2013	Pre-treatment (& Grout Jacking)
C	09/05/2013	18/06/2013	CH1 EXT excavation, CL1 excavation, WBRT passage, concurrent grouting
D	18/06/2013	13/09/2013	AP2W excavation, AP2E excavation, concurrent grouting, grout jacking
E	13/09/2013	08/12/2013	-
F	08/12/2013	04/03/2014	AP2W stub excavation, PTW excavation, concurrent grouting, grout jacking
G	04/03/2014	02/07/2015	-

Figure 2.3.1 Volume of grout injected from TCR GS3 by grouting type.

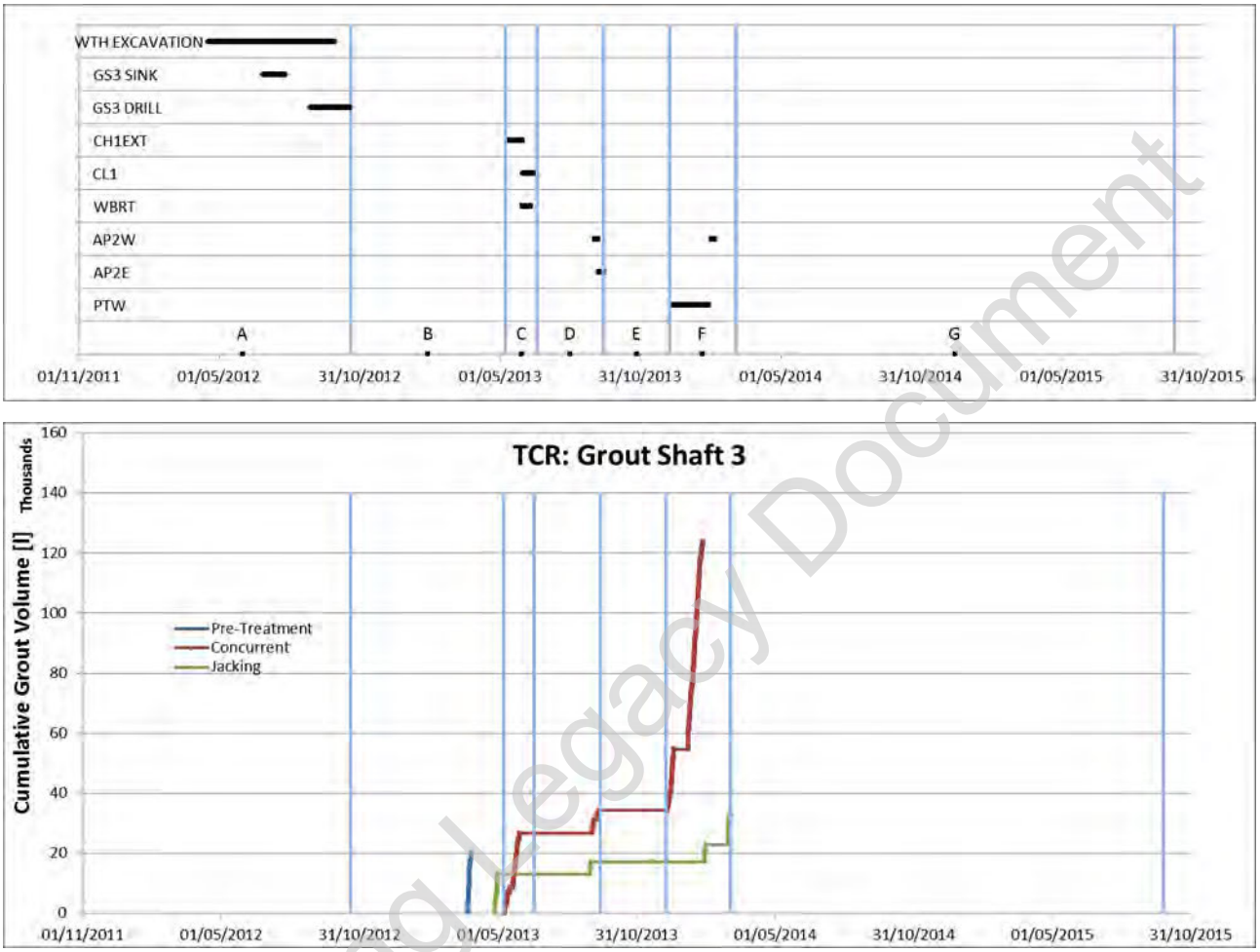


Figure 2.3.2 Distribution of grout injected from TCR GS3: Pretreatment grouting. Grout Intensity (mm).

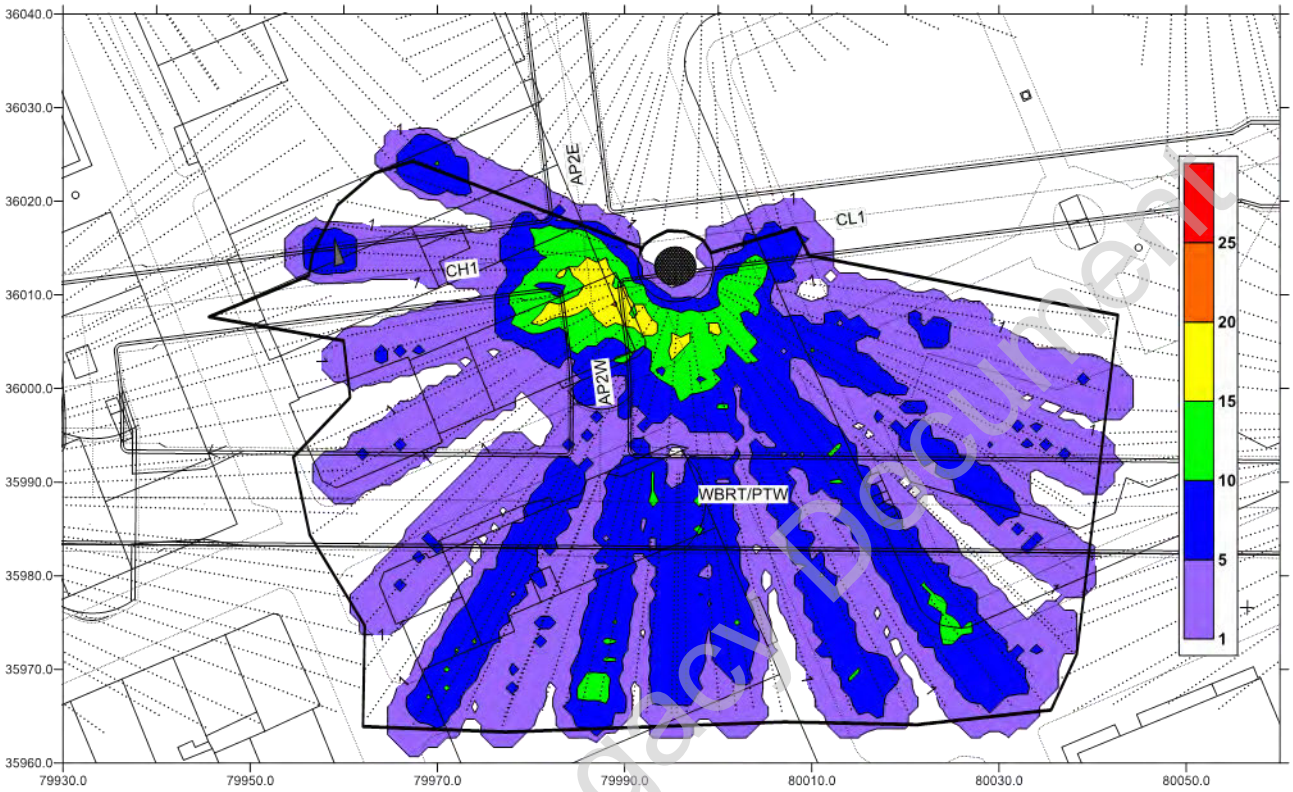


Figure 2.3.3 Distribution of grout injected from TCR GS3: Concurrent grouting. Grout Intensity (mm).

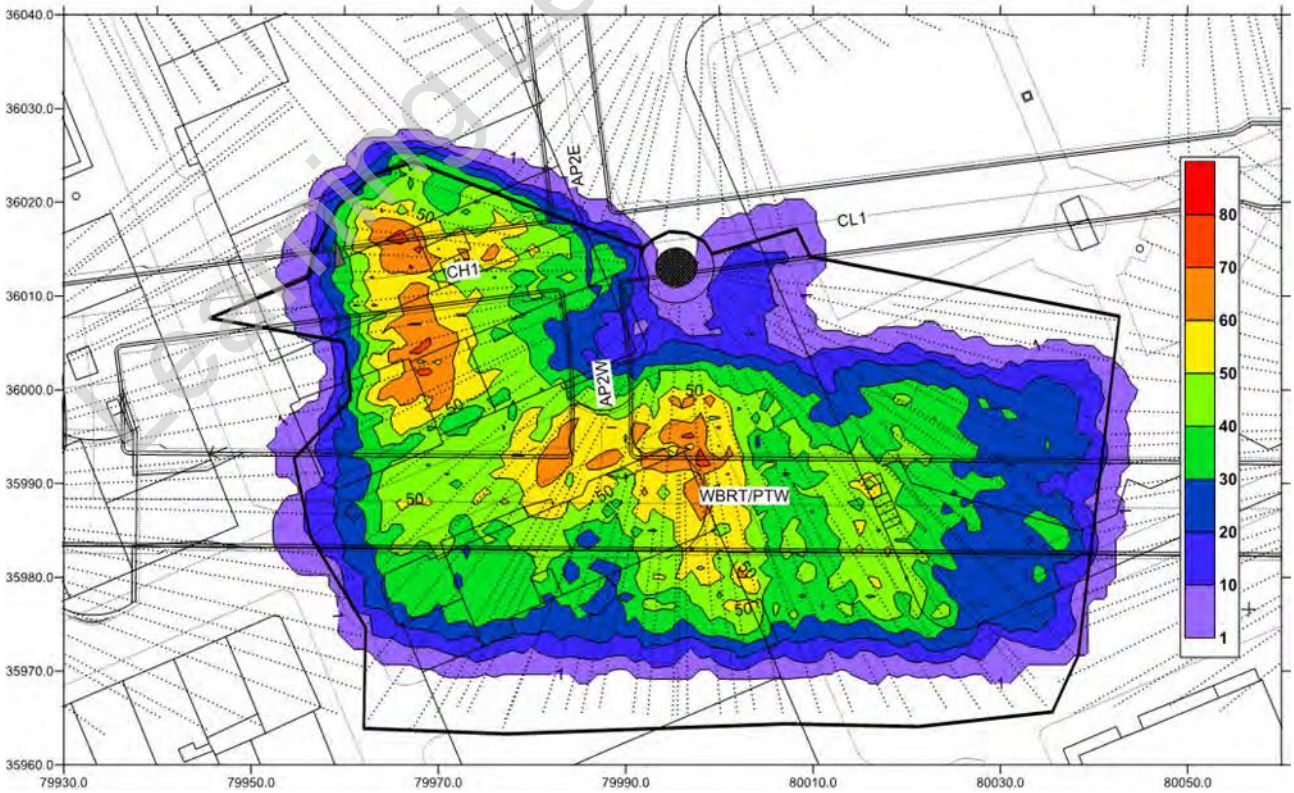


Figure 2.3.4 Distribution of grout injected from TCR GS3: Jack grouting. Grout Intensity (mm).

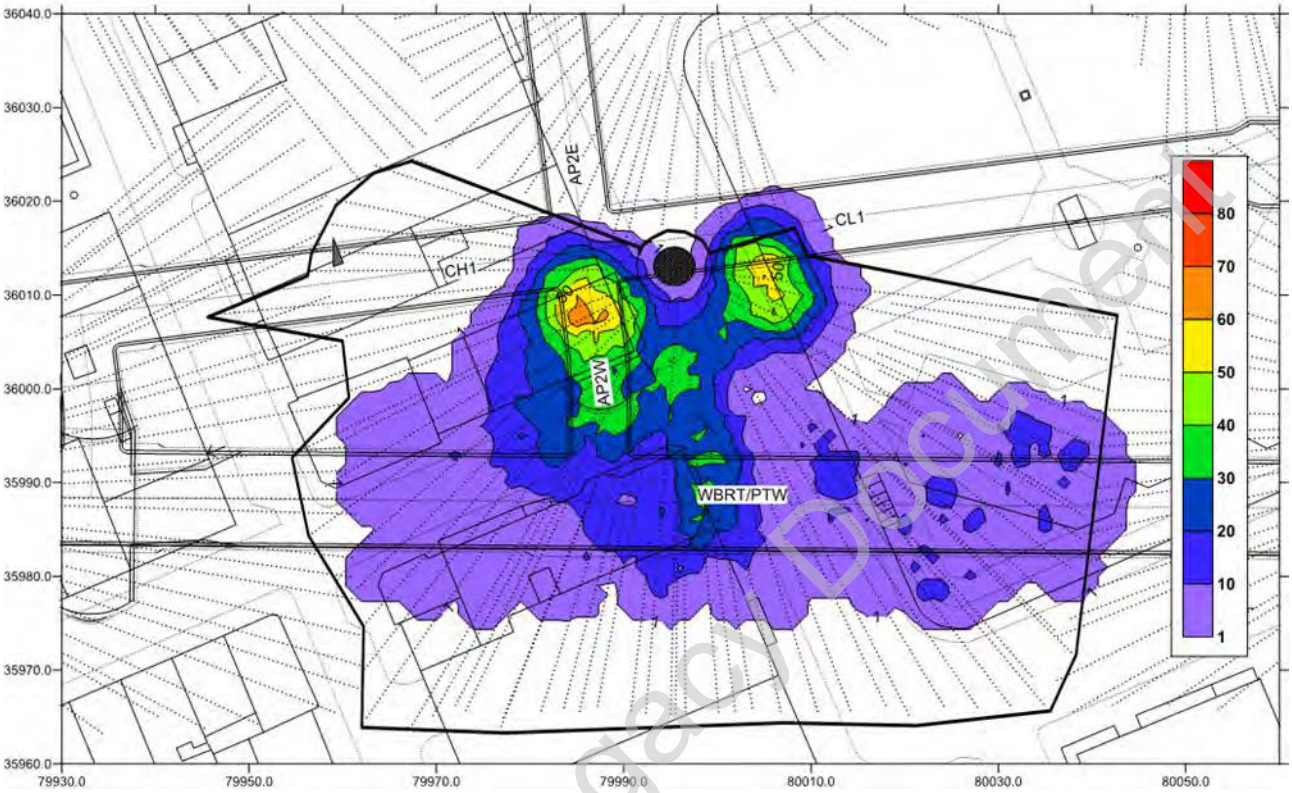
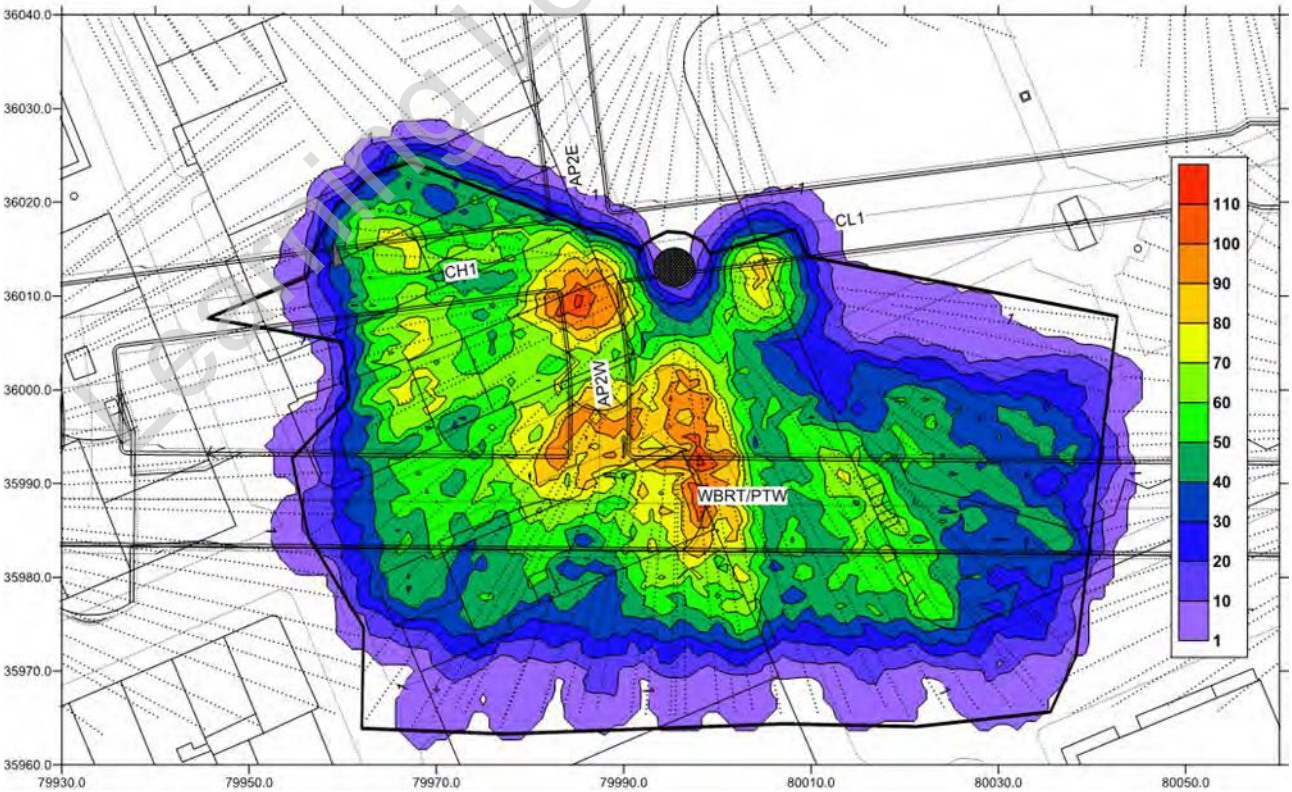


Figure 2.3.5 Distribution of grout injected from TCR GS3: All grouting. Grout Intensity (mm).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. SETTLEMENT OVERVIEW

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

The following points are noted:

- Settlements are generally significantly 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 settlement contour is 20mm compared to 50mm on the prediction;
    - The spacing of the contours implies that actual slopes are much less than the volume loss prediction
    - the extent of the zone of settlement is similar to that predicted with any differences in the locations of the 1mm contour attributable to the tolerances on the survey data.

Figure 3.1.1 Predicted greenfield settlement contours (supplied by C122)

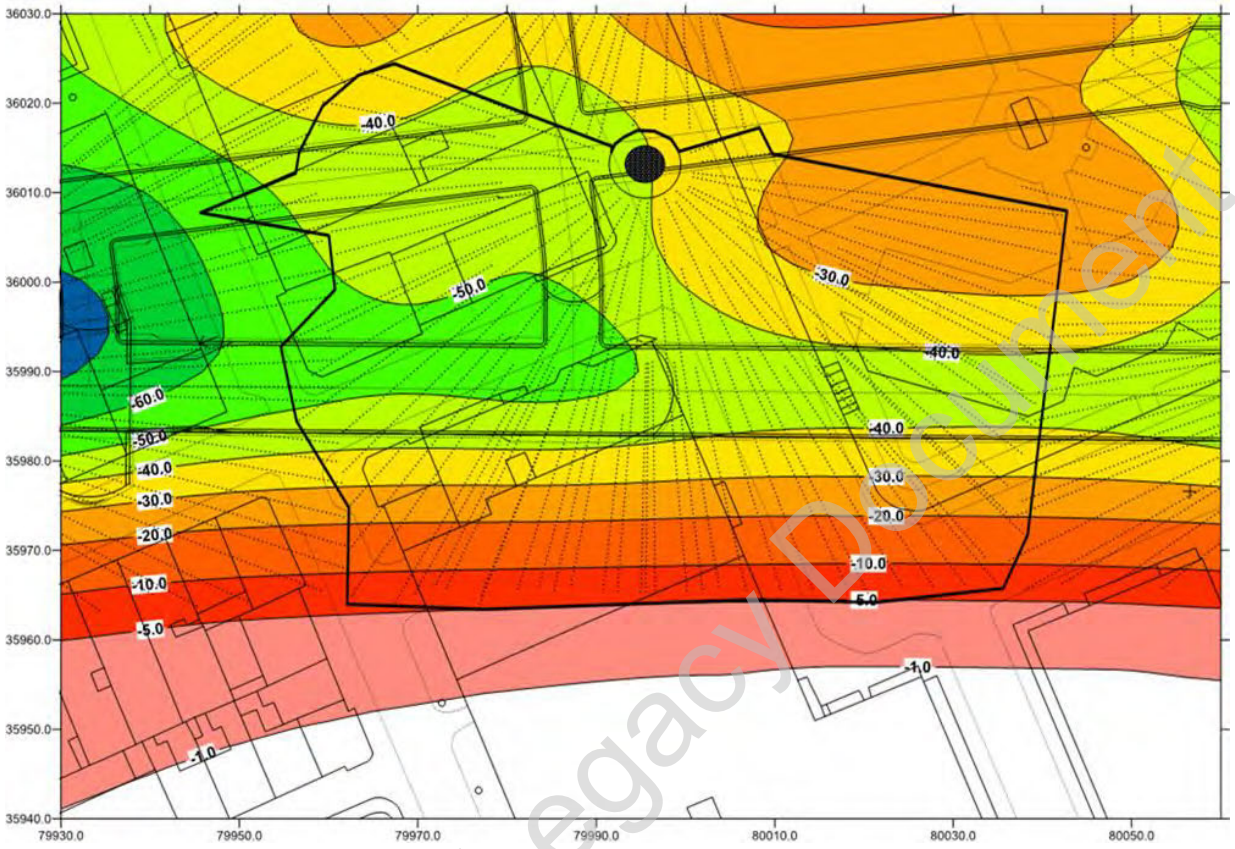
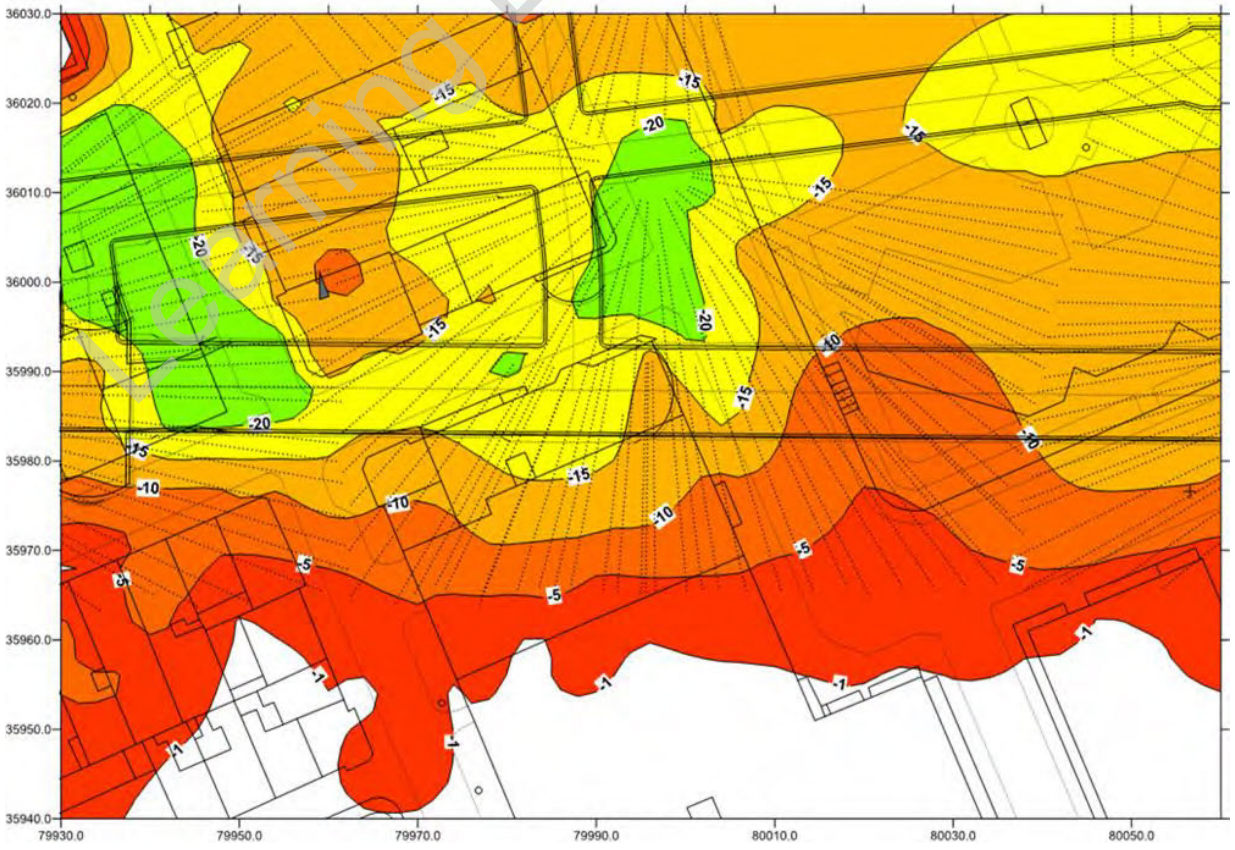


Figure 3.1.2 Observed settlement contour in February2014 (end of construction – Period F)



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 monitoring (under PMI C300-PMI-01858) in September 2015 has been divided into a number of periods, based largely on tunnel excavation progress. The construction activities completed in each period are summarised in Table 2.3.

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: Prior to tunnelling

Period A includes all of the preparatory work prior to the commencement of tunnelling, including demolition of the buildings prior to diaphragm walling and piling for the Western Ticket Hall. BFK works comprised excavation of the WTH, shaft sinking and the drilling of TaMs from TCR GS3. 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: the effects within the GS3 area are negligible.

The calculated short term movements associated with excavation of the WTH are shown in Figure 3.2.2 (as supplied by C122). A maximum settlement of 15mm is indicated at the north-west extremity of the GS3 arrays.

The observed settlements (adjusted to allow for movements prior to the start of BFK monitoring) are shown on Figure 3.2.3. In general, negligible settlement is indicated with a maximum of 2.5mm in local areas due to the WTH excavation and TaM drilling.

Figure 3.2.1 Contours of settlement at completion of C421 works

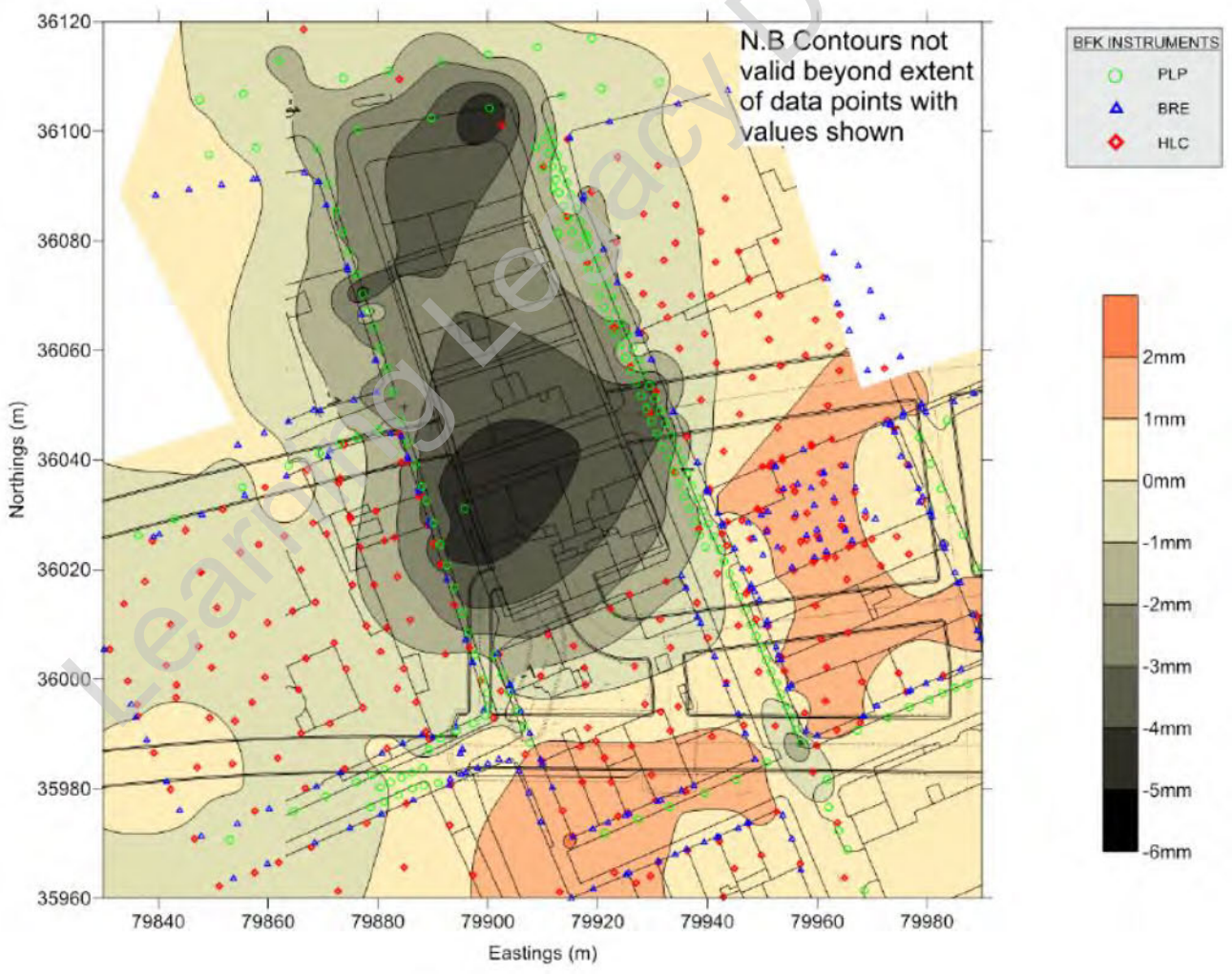


Figure 3.2.2 Period A: Total predicted greenfield settlement contours (supplied by C122)

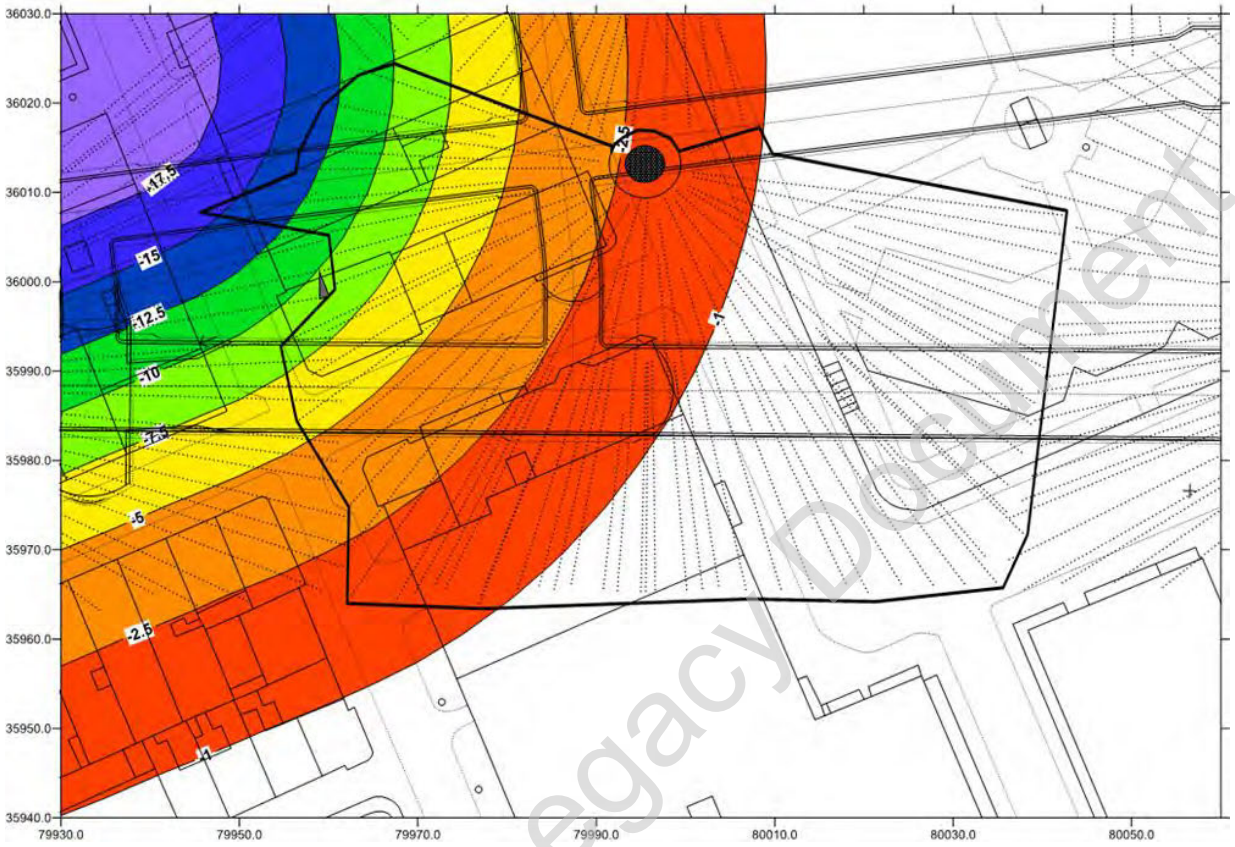
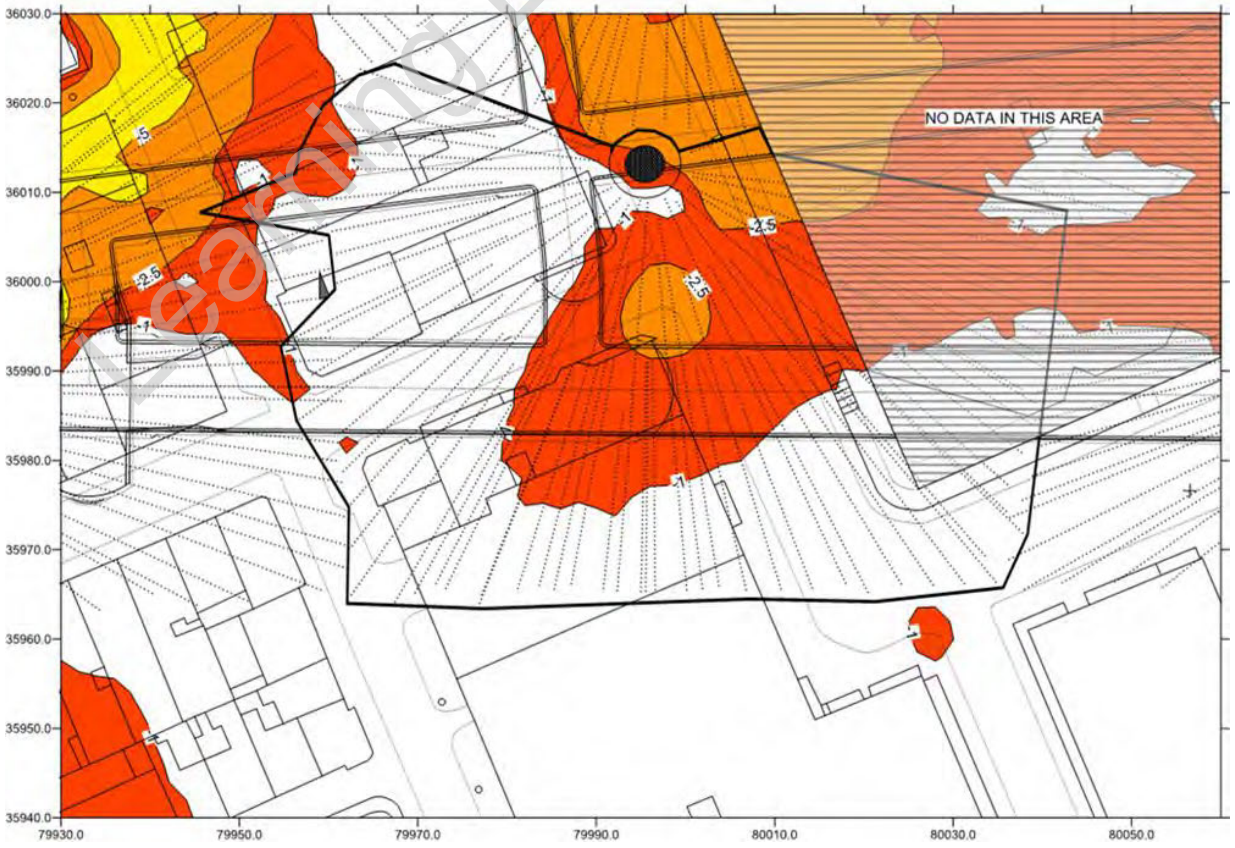
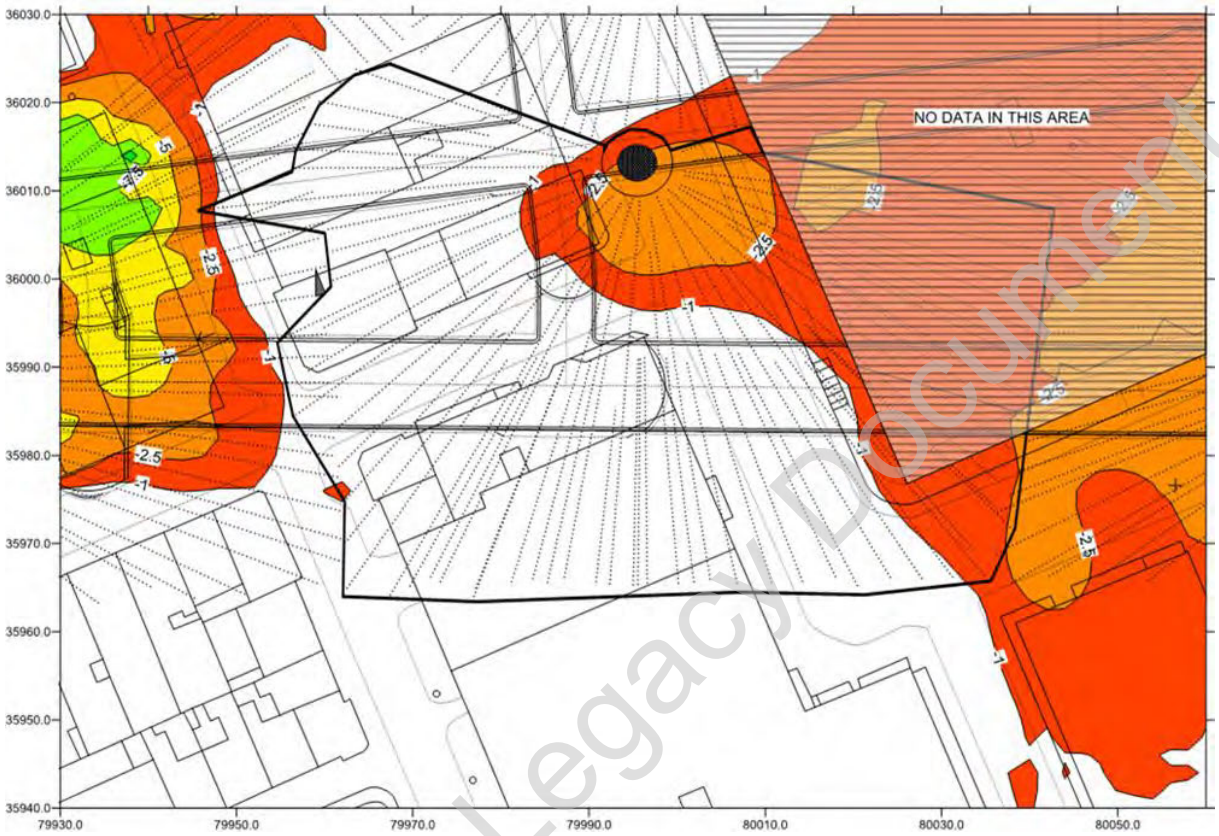


Figure 3.2.3 Period A: Total measured settlement



3.3. Period B: 25/10/12 - 09/05/13 Pre-treatment & Grout Jacking

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



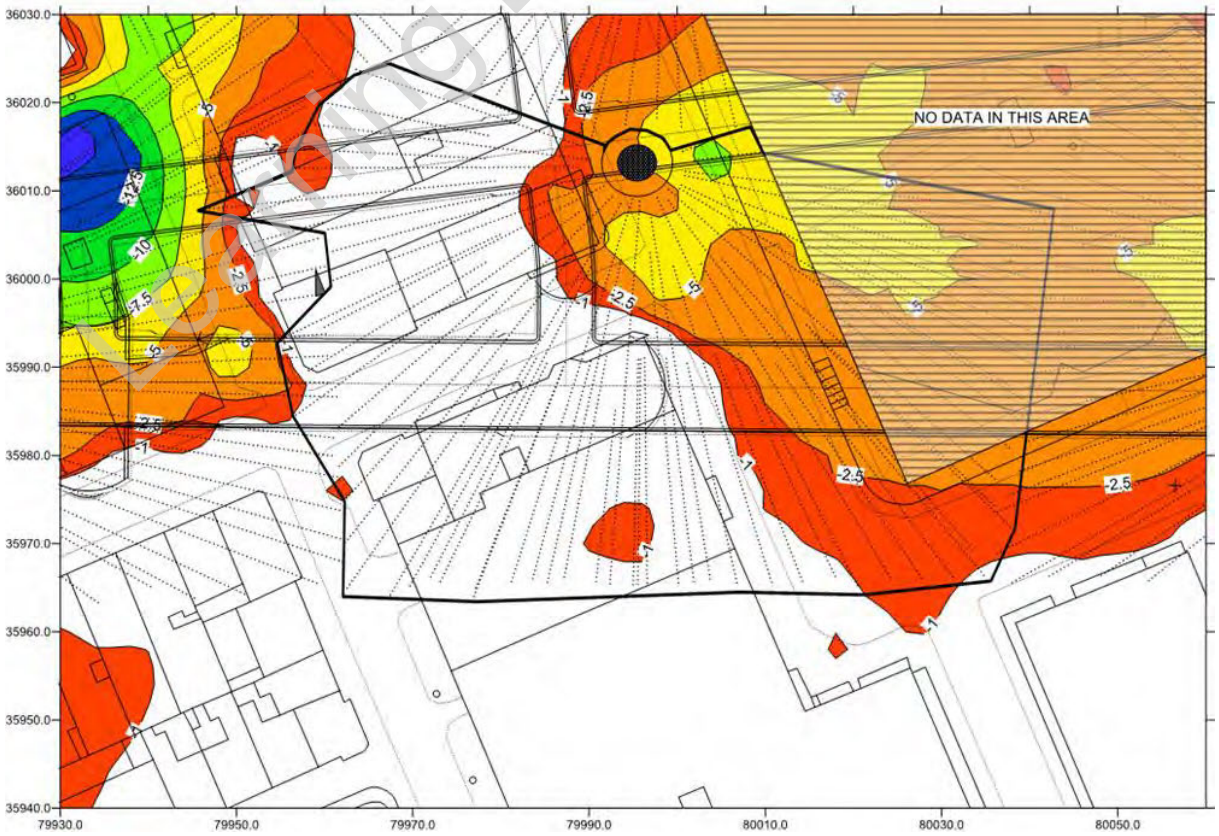


Figure 3.3.2 Period B: Distribution of grout injected from TCR GS3: Pre-treatment grouting. Grout Intensity (mm).

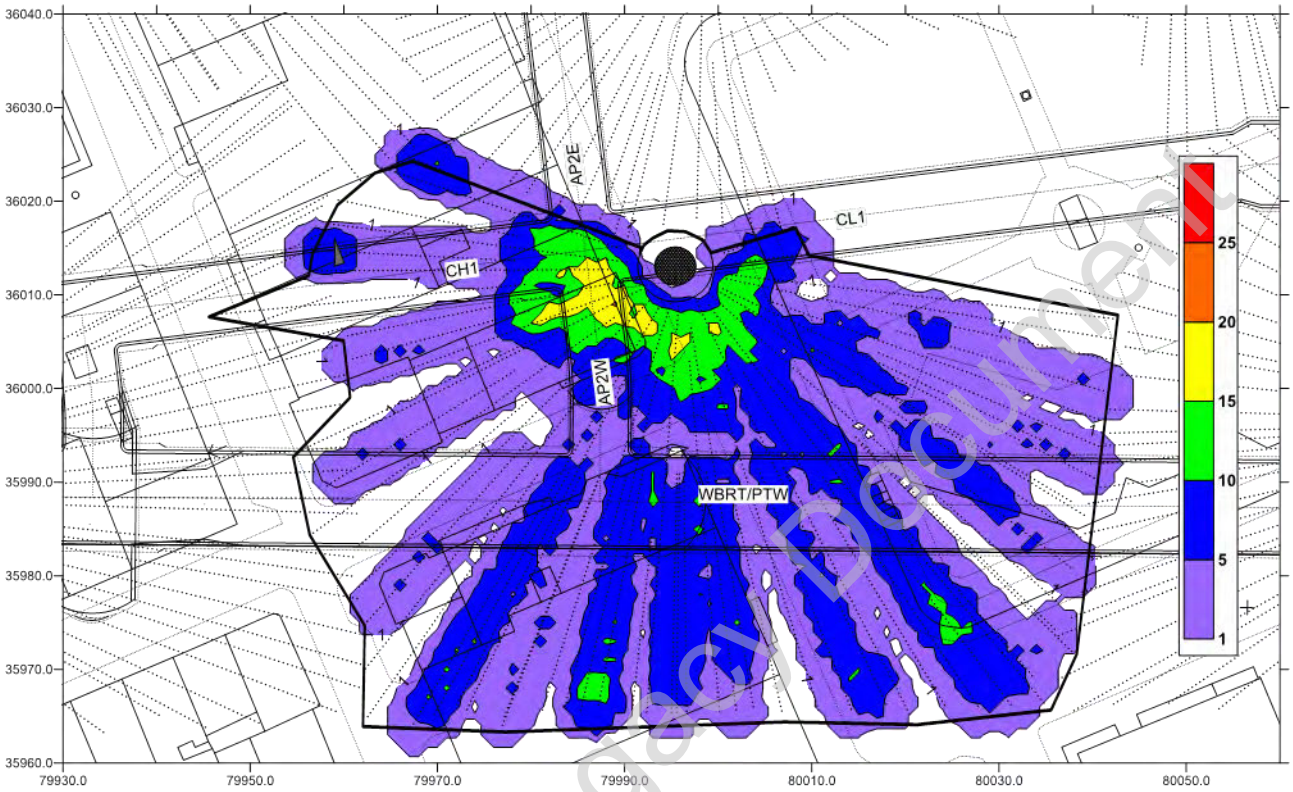


Figure 3.3.3 Period B: Distribution of grout injected from TCR GS3: Grout jacking. Grout Intensity (mm).

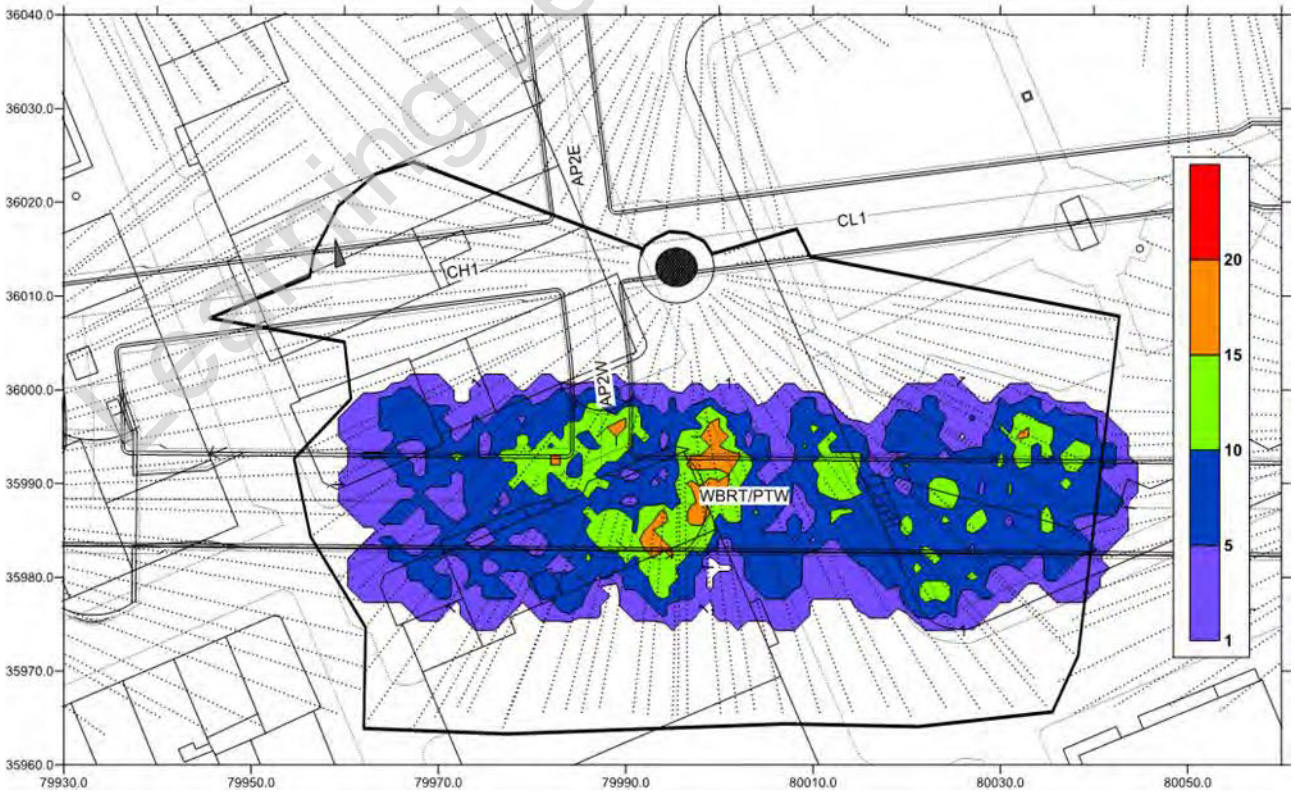
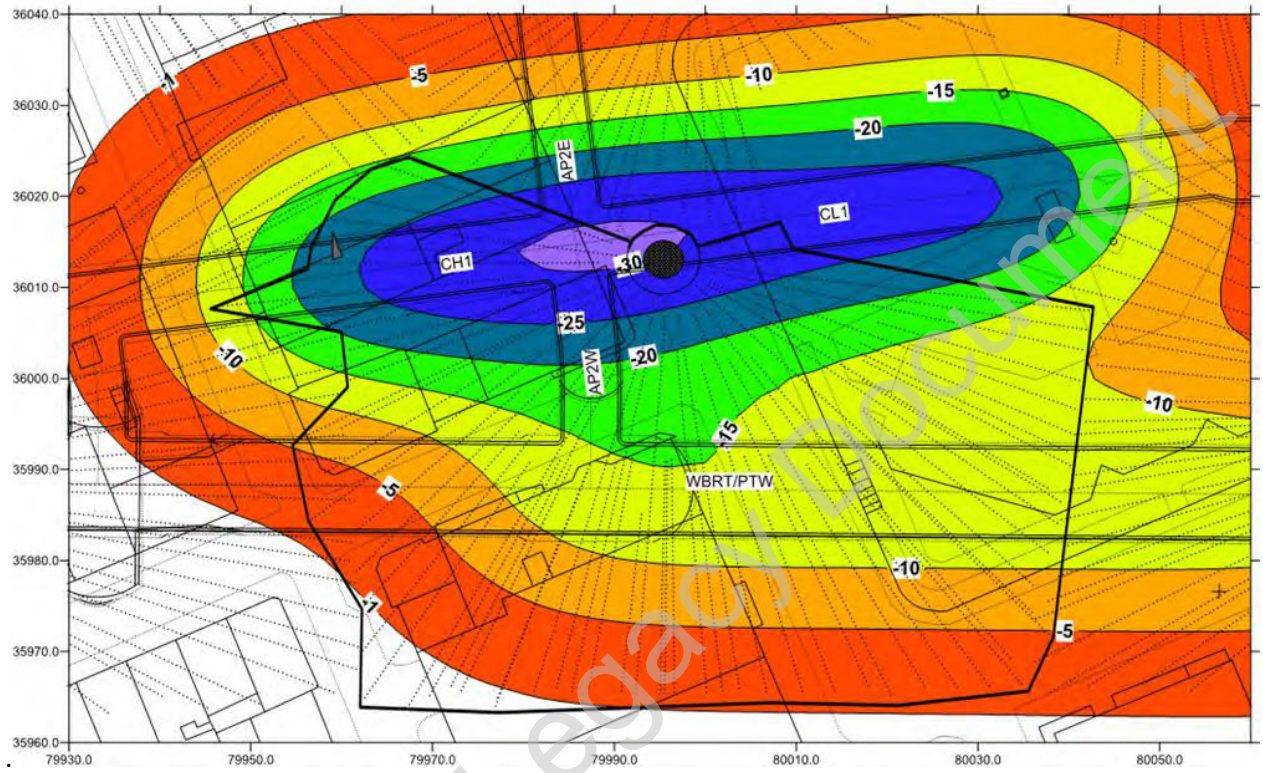


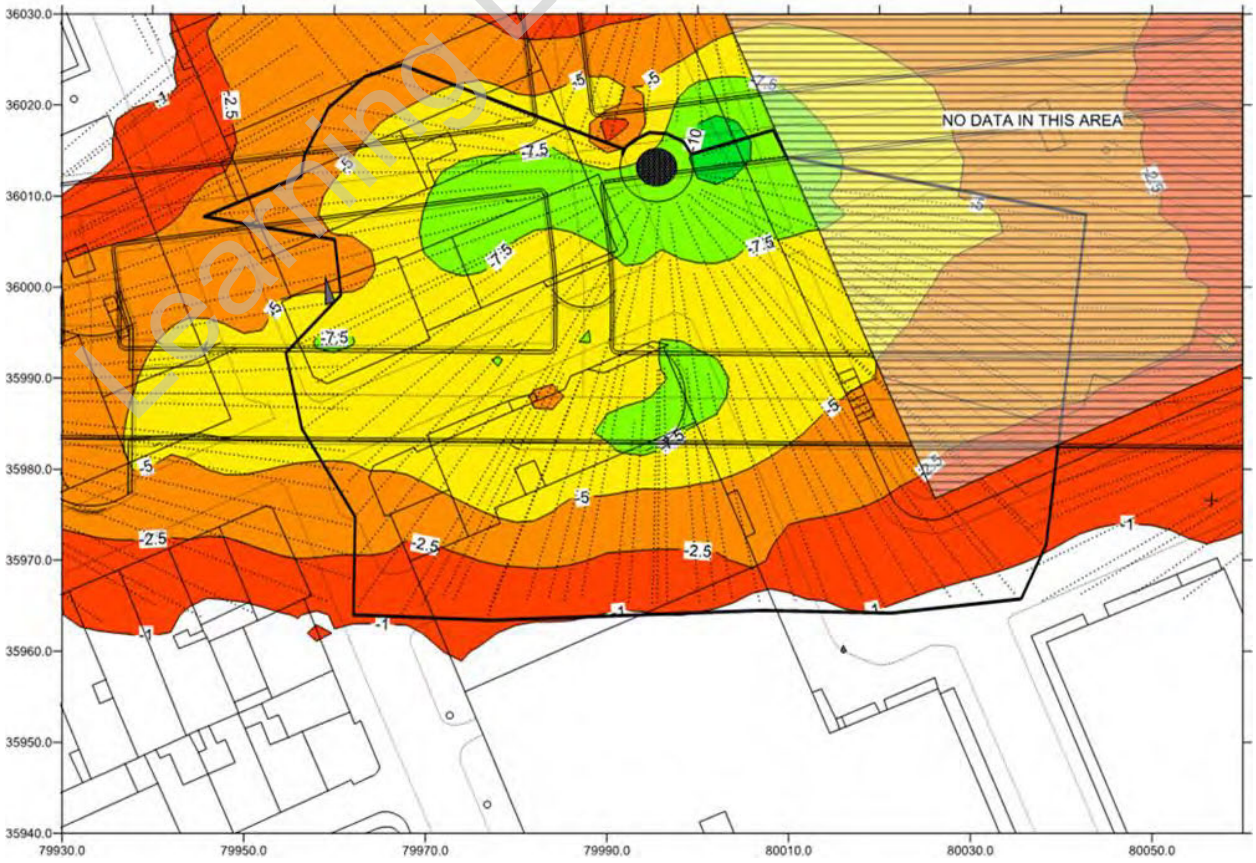
Figure 3.3.1(a) shows that there was negligible change in settlement over most of the GS3 area during Period B. The greatest change is an increase in settlement local to the shaft, with a maximum total settlement of about 8mm immediately to the east of the shaft (Figure 3.3.1(b)). Thus, there are only minor differences between the total settlement contour in Figure 3.3.1(b) and the comparable figure for Period A, within the GS3 area. There are more significant movements to the west of the GS3 area associated with tunnelling in the GS1 area (C300-BFK-C4-RGN-CRT00_ST005_51225).

The grouting undertaken for pre-treatment (Figure 3.3.2) and for pre-jacking ahead of the WBRT (Figure 3.3.3) effectively mitigated ongoing time related settlement giving small residual movements.

3.4. Period C: 09/05/13 – 18/06/13 CH1Ext, CL1, WBRT, concurrent grouting

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





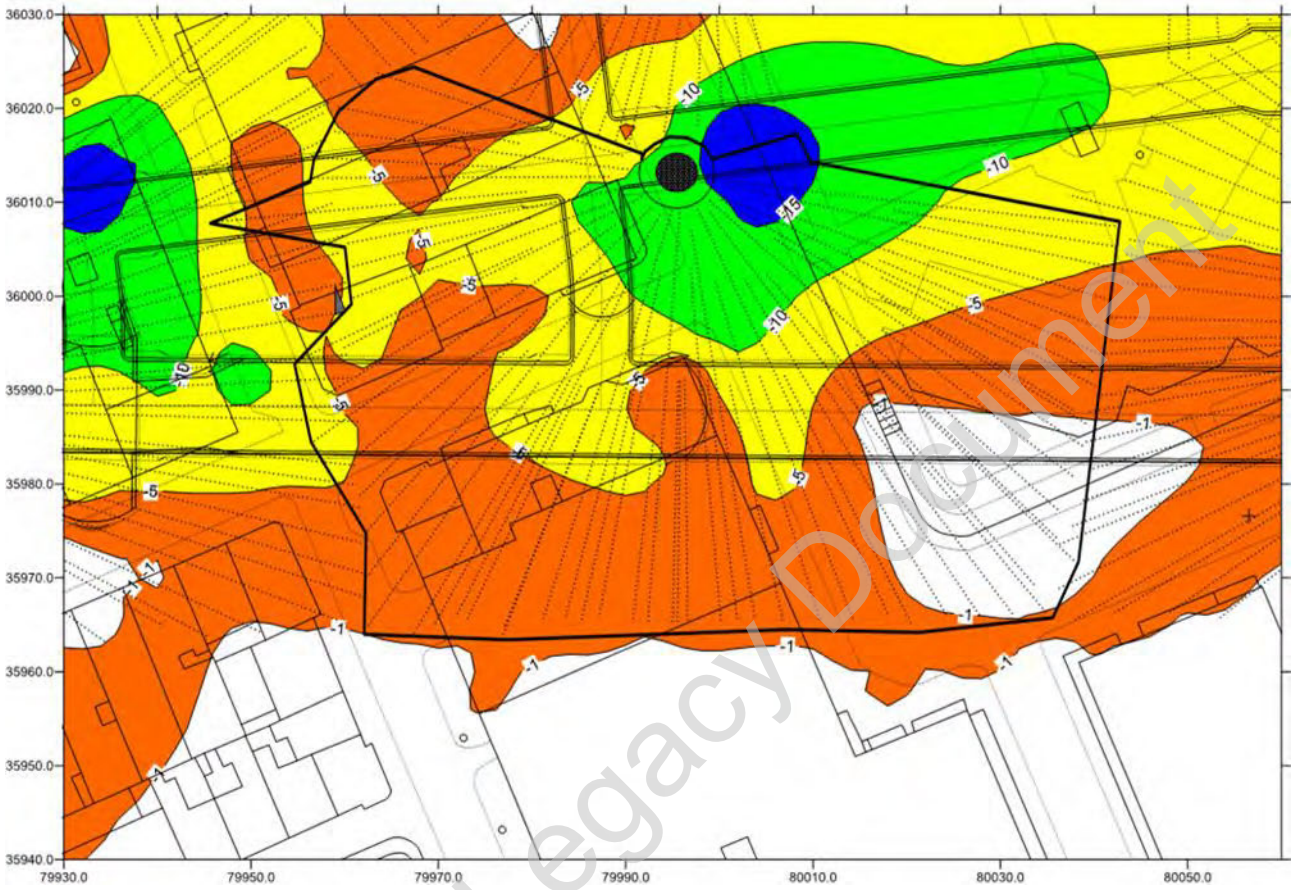


Figure 3.4.2 Period C: Distribution of grout injected from TCR GS3: Concurrent grouting. Grout Intensity (mm).

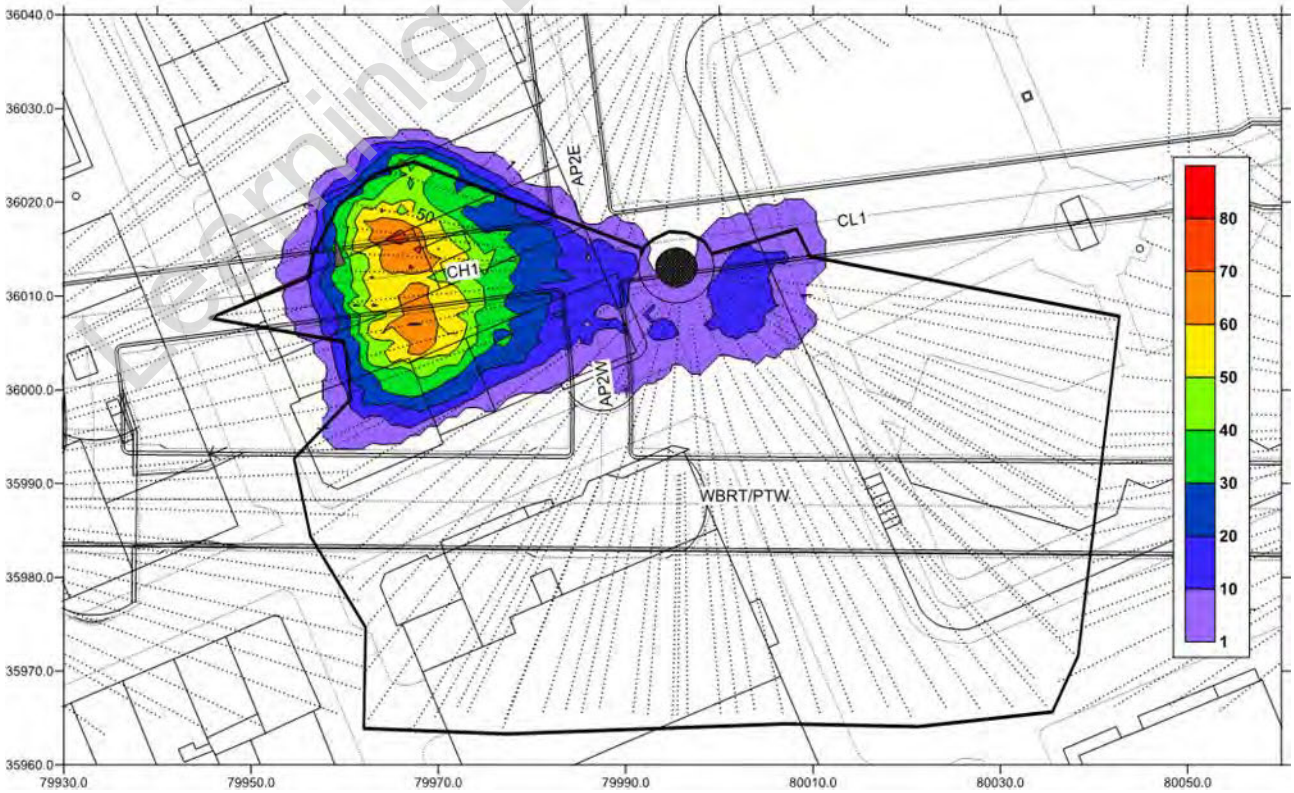


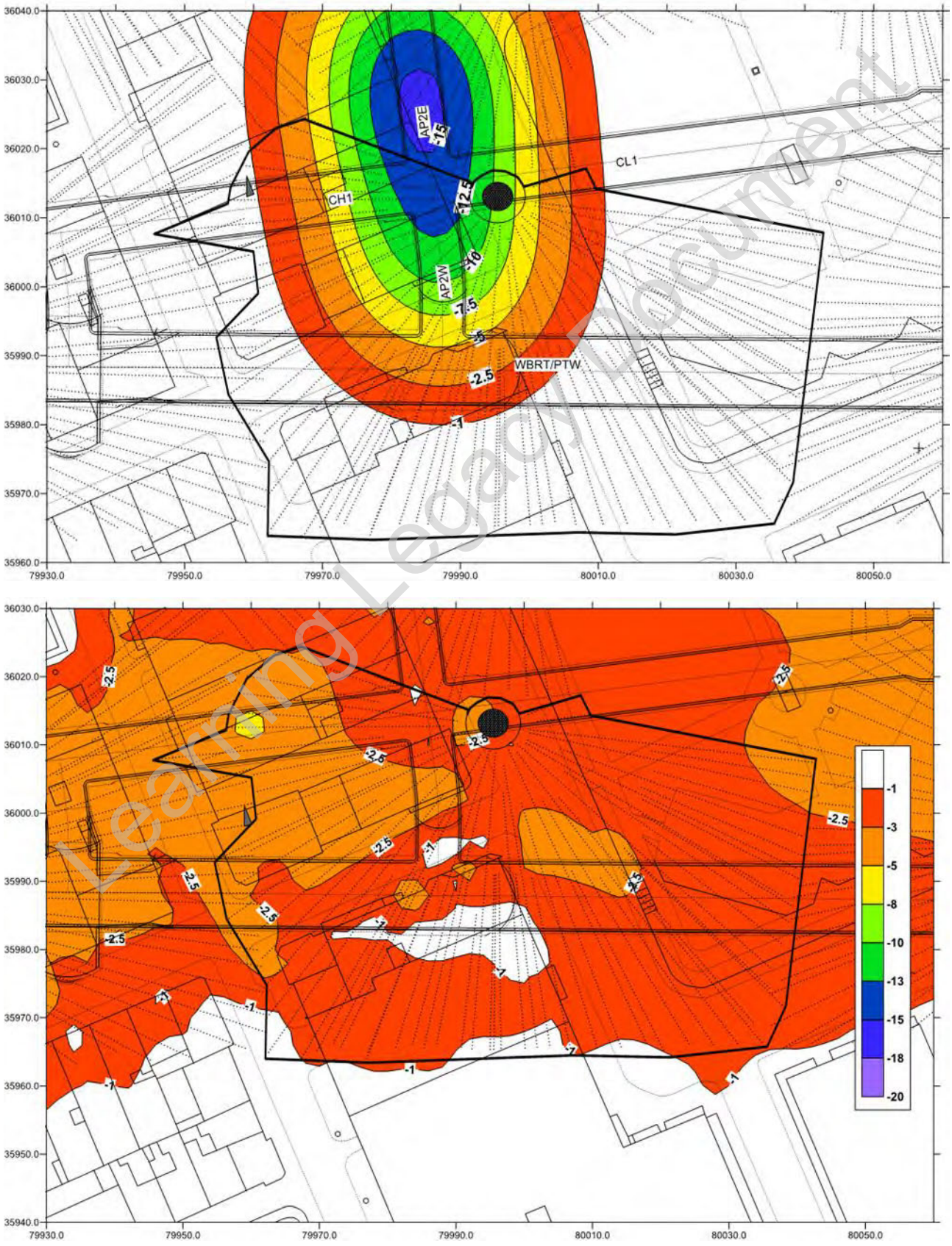
Figure 3.4.1(a) shows that over 30mm volume loss settlement was anticipated for CH1Ext / CL1 and about 12mm maximum for the WBRT on its own. Where the zone of settlement from CH1/CL1 extends over the WBRT the maximum combined settlement above the centerline is 15mm. Figure 3.4.1(b) shows the recorded settlement which has a maximum of 10mm over CH1Ext / CL1 and 8mm locally over the WBRT.

The maximum movement within the TCR GS3 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.

It is noted that no concurrent grouting was undertaken with either CL1 or the WBRT (see Section 2.3), implying that volume loss settlement were less than the specified values. The distribution of the concurrent grouting undertaken with CH1Ext is shown in Figure 3.4.2 with much greater volumes injected to the west as a result of the exclusion zones over the tunnel face and around the shaft itself.

3.5. Period D: 18/06/13 - 13/09/13 AP2W; AP2E, concurrent grouting, jack grouting.

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



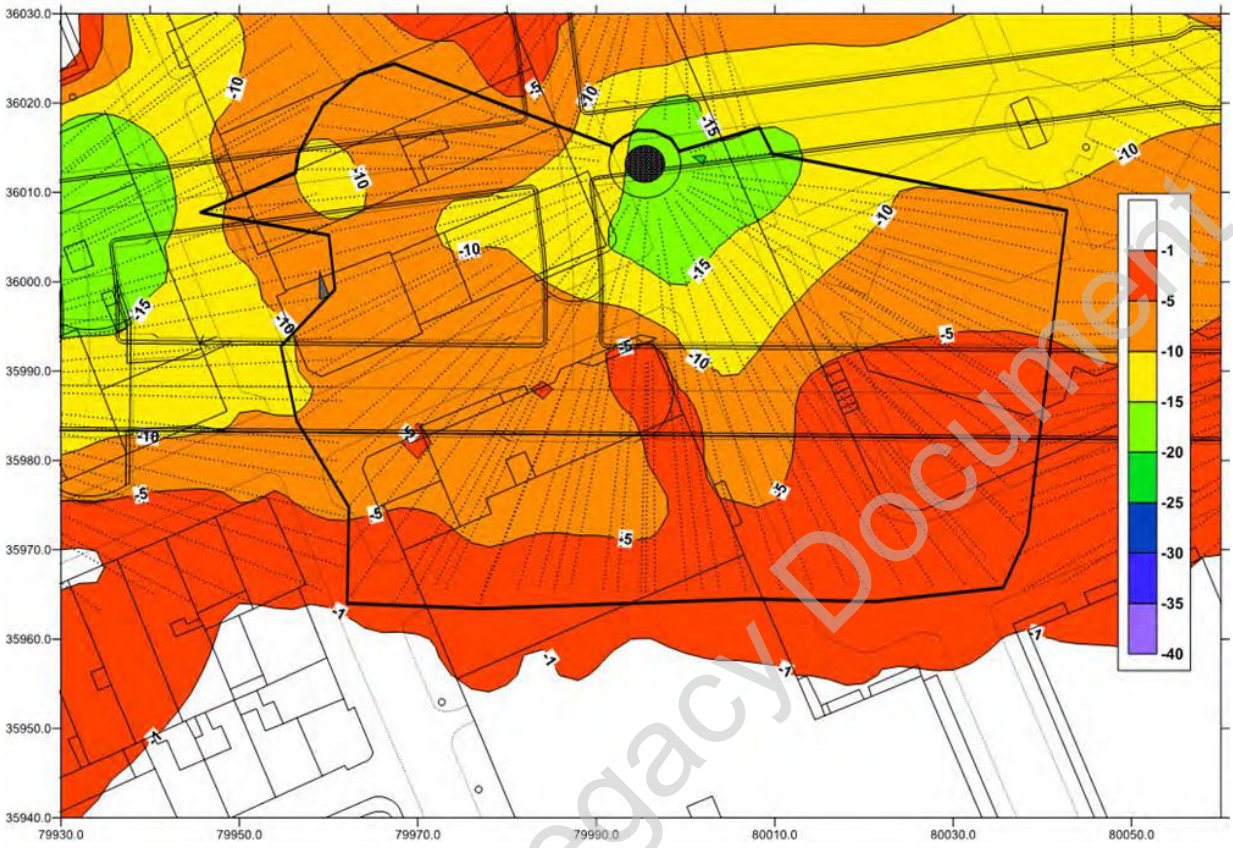


Figure 3.5.2 Period D: Distribution of grout injected from TCR GS3: Concurrent grouting. Grout Intensity (mm).

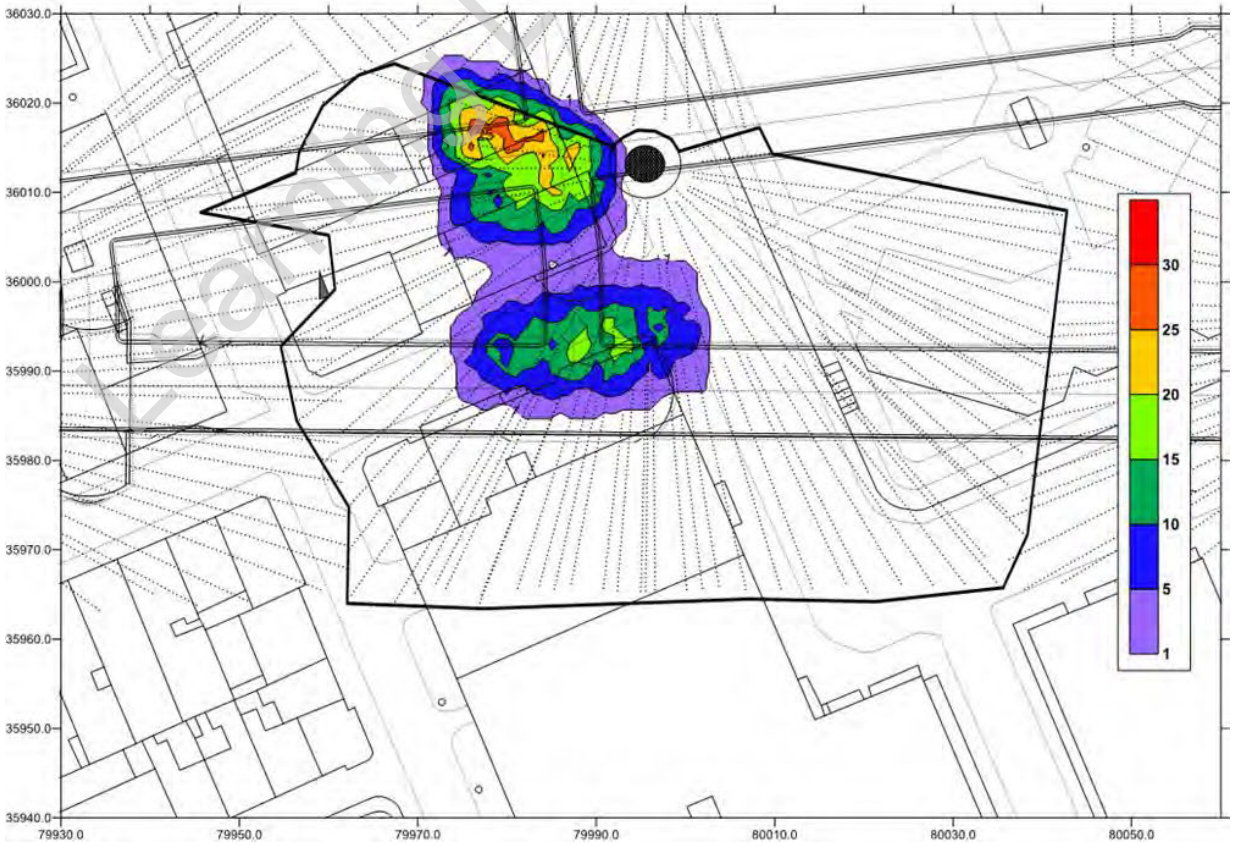
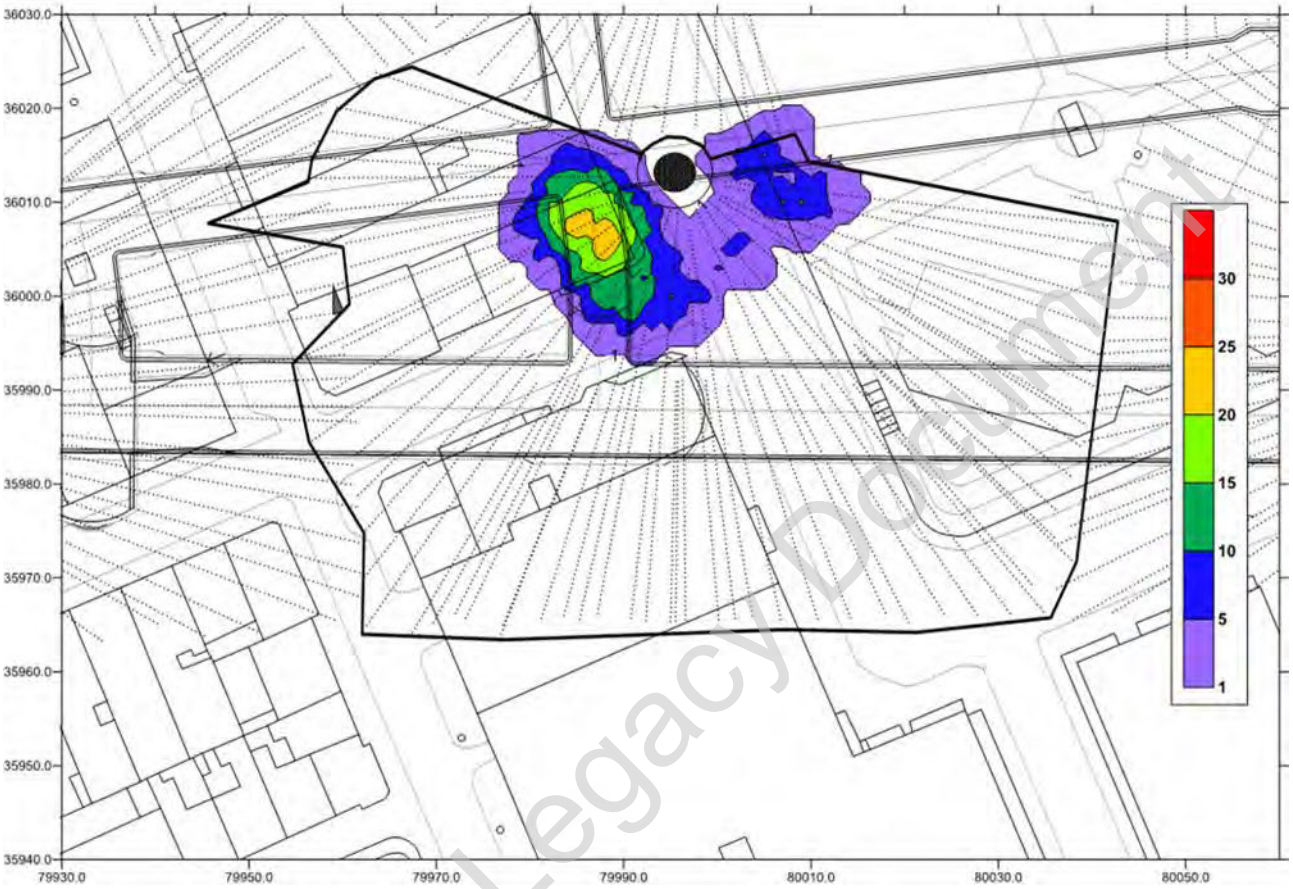


Figure 3.5.3 Period D: Distribution of grout injected from TCR GS3: Grout jacking. Grout Intensity (mm).

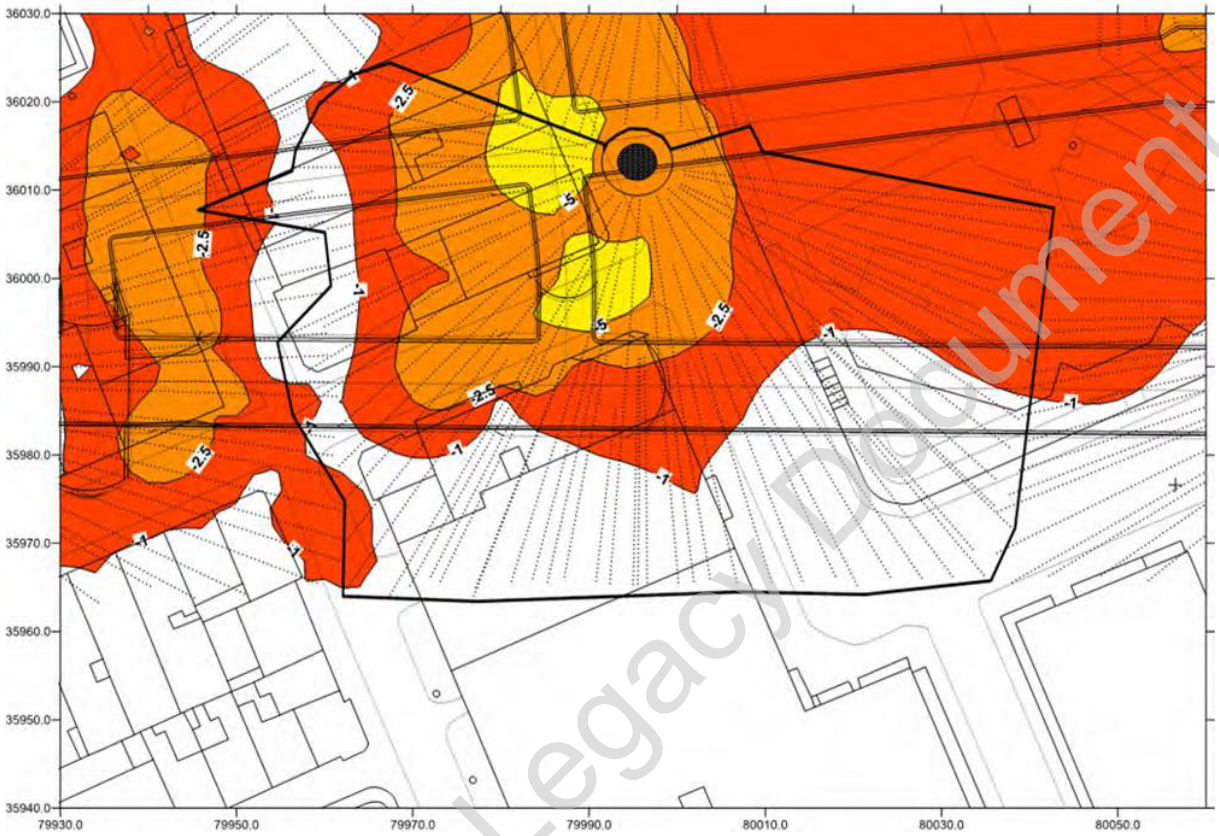


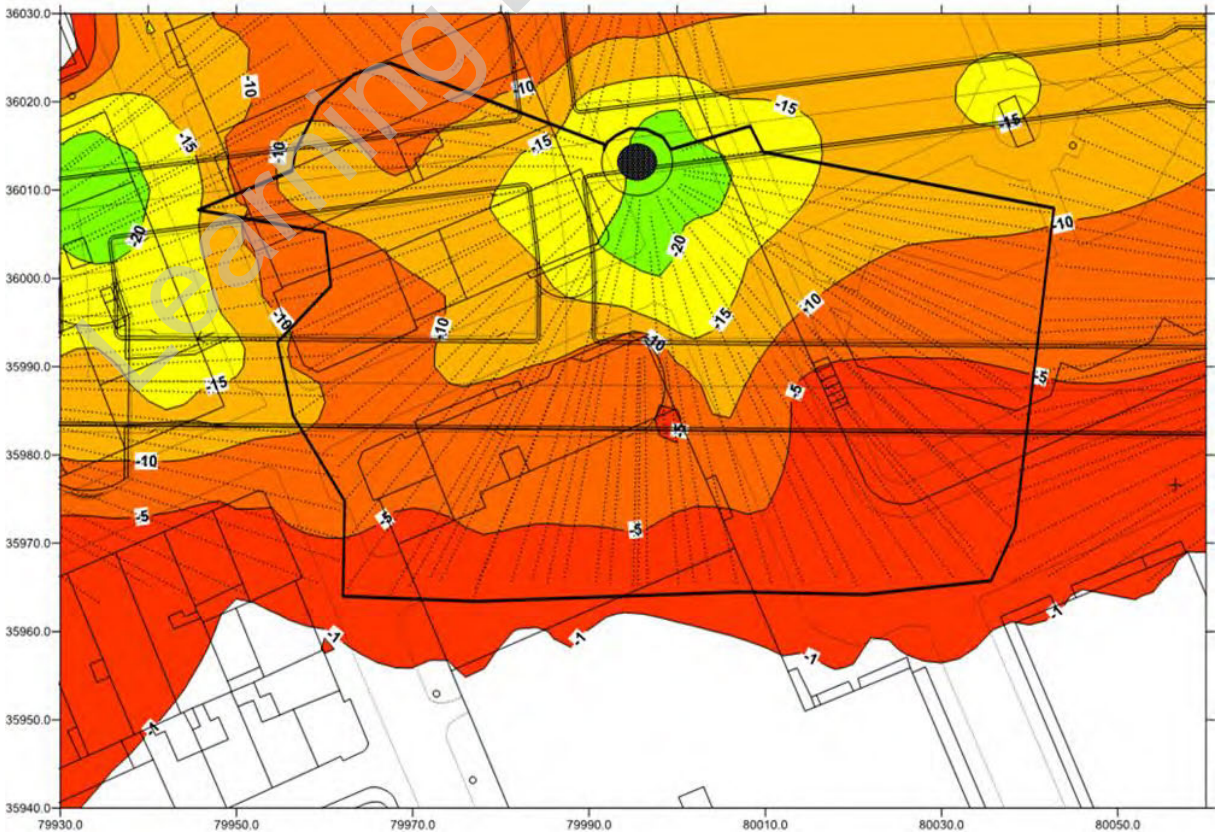
The volume loss settlement from construction of AP2W and AP2E is shown in Figure 3.5.1(a) and indicates a maximum combined effect of just under 15mm within the area of TCR GS3. The maximum observed increase in settlement in Period D was 5mm locally outside the volume loss zone (Figure 3.5.1(b)) due to consolidation settlement over the CH1: volume loss settlement were controlled within the remainder of the area to less than 5mm by a combination of concurrent grouting (Figure 3.5.2) and grout jacking (Figure 3.5.3).

The maximum total settlement remained at less than 20mm with a similar pattern to the end of Period C.

3.6. Period E: 13/09/13 – 08/12/13 No Tunnelling

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

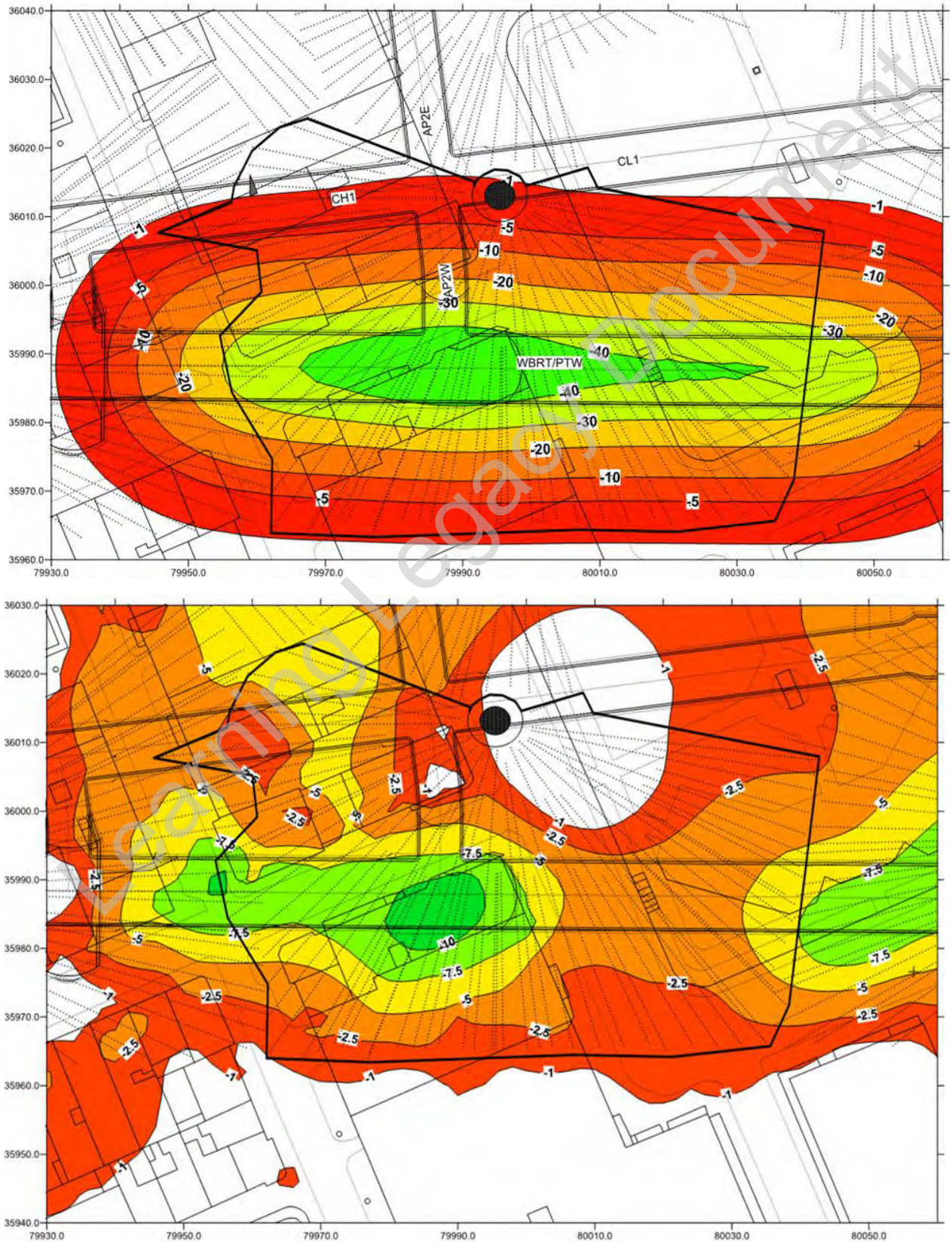




Post construction settlement over the 3 month duration of Period E above AP2W and AP2E amounted to about 5mm (Figure 3.6.1(a)). No grout jacking was deemed necessary and as a result the maximum observed settlement increased to over 20mm (Figure 3.6.1(b)).

3.7. Period F: 08/12/13 – 04/03/14 PTW, AP2W junction, concurrent & jack grouting.

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



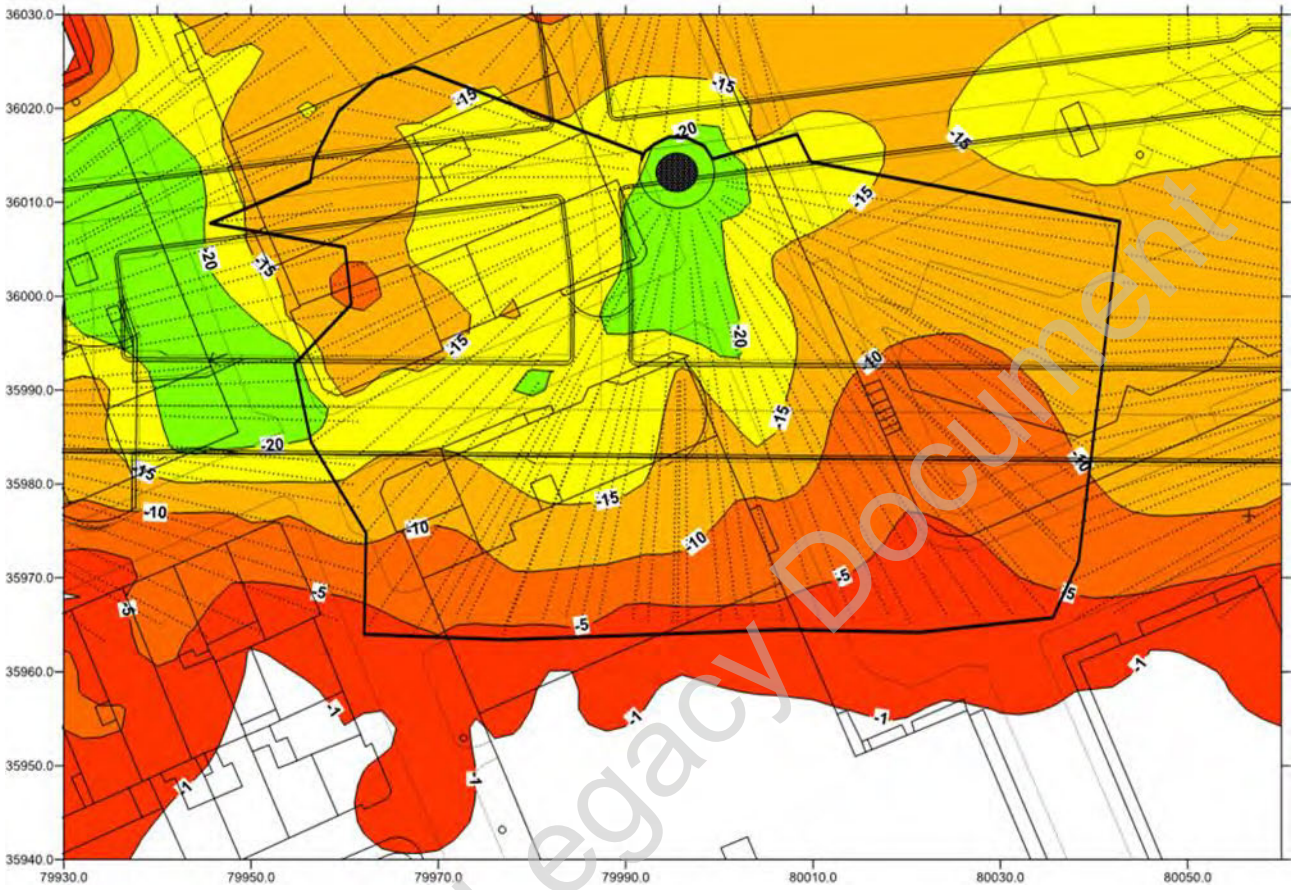


Figure 3.7.2 Period F: Distribution of grout injected from TCR GS3: Concurrent grouting. Grout Intensity (mm).

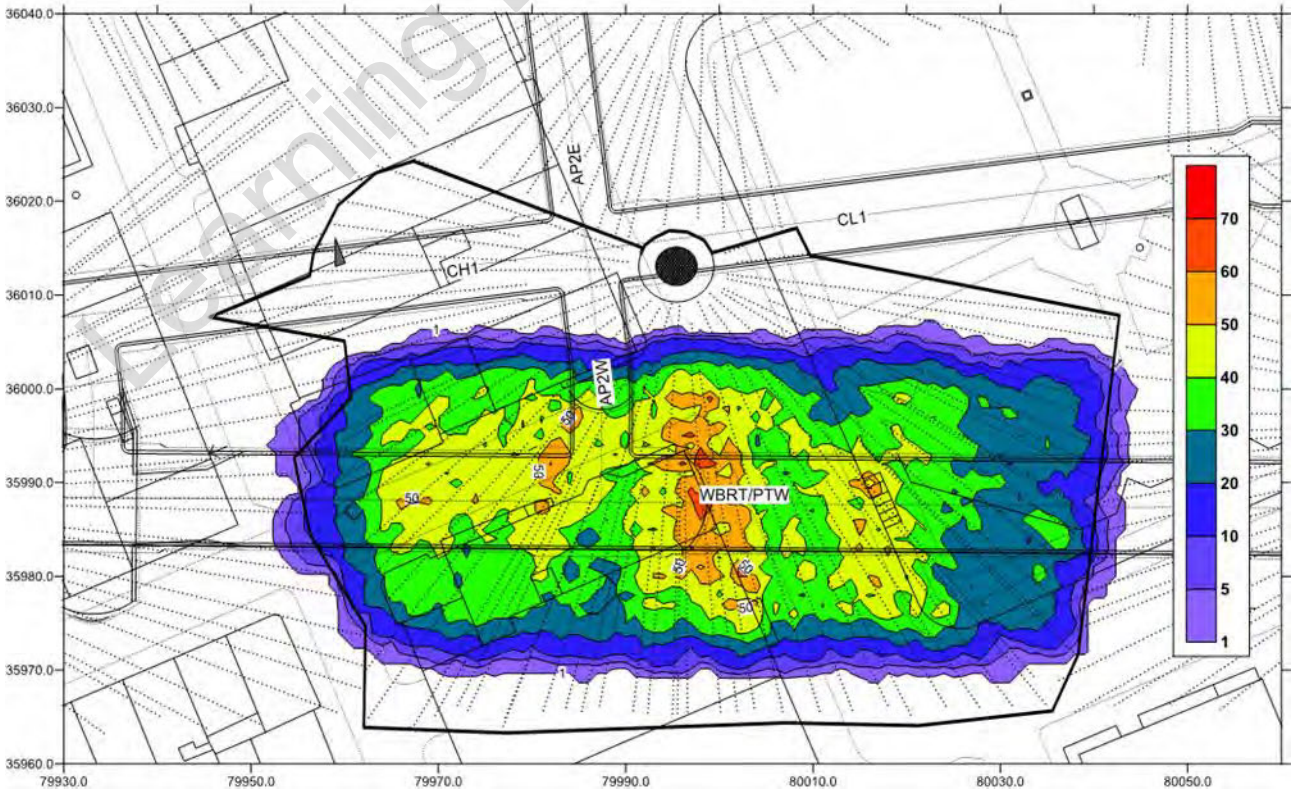
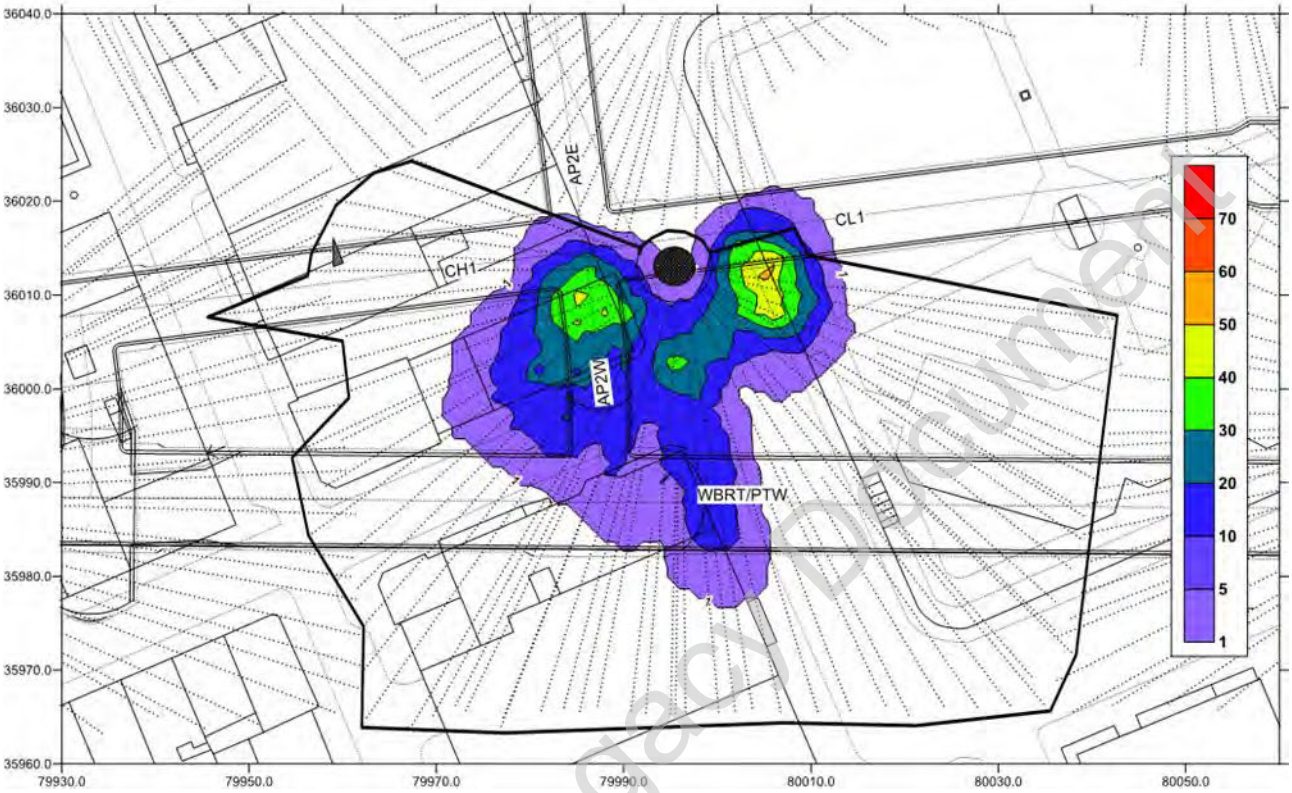


Figure 3.7.3 Period F: Distribution of grout injected from TCR GS3: Grout jacking. Grout Intensity (mm).



Construction of the PTW would generate a maximum settlement of about 40mm at a volume loss of 1.25% as shown on Figure 3.7.1(a). The maximum observed settlement in Period F is 10mm over the junction between AP2W and PTW. The concurrent grouting distribution for the PTW is shown in Figure 3.7.2 and indicates a maximum intensity of 60mm, with generally about 40mm over the plan extent of the tunnel. It is noted that no concurrent grouting was undertaken with the junction works due to the exclusion zone over the tunnel face specified in the SCoGM.

Grout jacking was undertaken in Period F, with up to 40mm thickness to either side of the shaft (Figure 3.7.3): that the effect of this in controlling settlement is clearly evident in Figure 3.7.1(b) where negligible change is recorded in the areas of high intensity grouting over the 4 month duration of Period F.

3.8. Period G: Post Construction

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

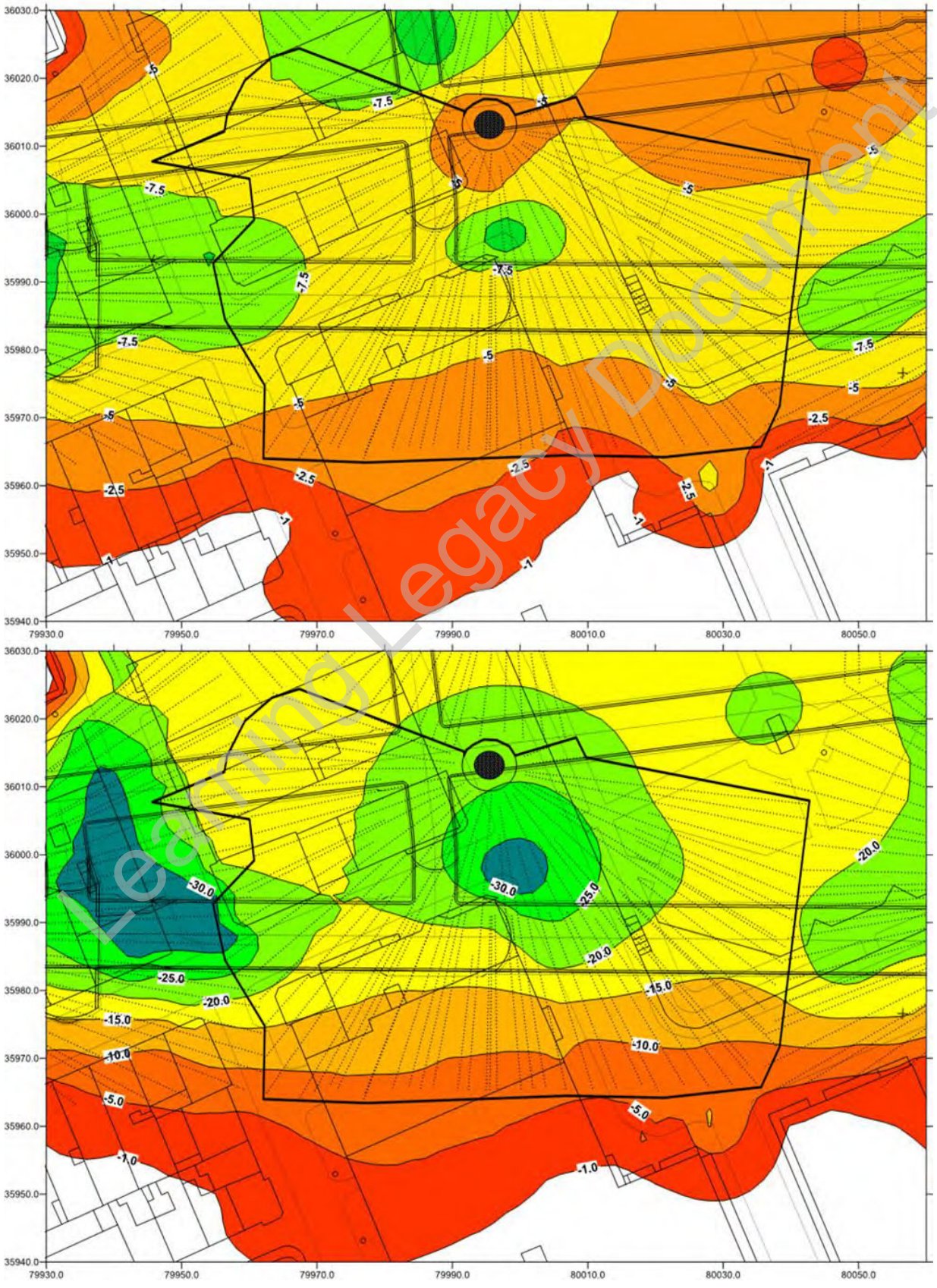


Figure 3.8.1(a) shows an increase of settlement of up to 10mm during the 18 months since the completion of tunnelling from consolidation settlement. The maximum movement is located above the PTW and the contours are approximately aligned with the tunnel.

The total settlement at the end of Period G is shown on Figure 3.8.1(b) with around 20mm settlement over the PTW but locally up to 30mm on the corner of Carlisle Street and Soho Square

There was no concurrent grouting in Period G 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 and HLC monitoring of party walls on Figure 4.1.1. A larger version of Figure 4.1.1 is included in Appendix C. Details are given in Table 4.1.

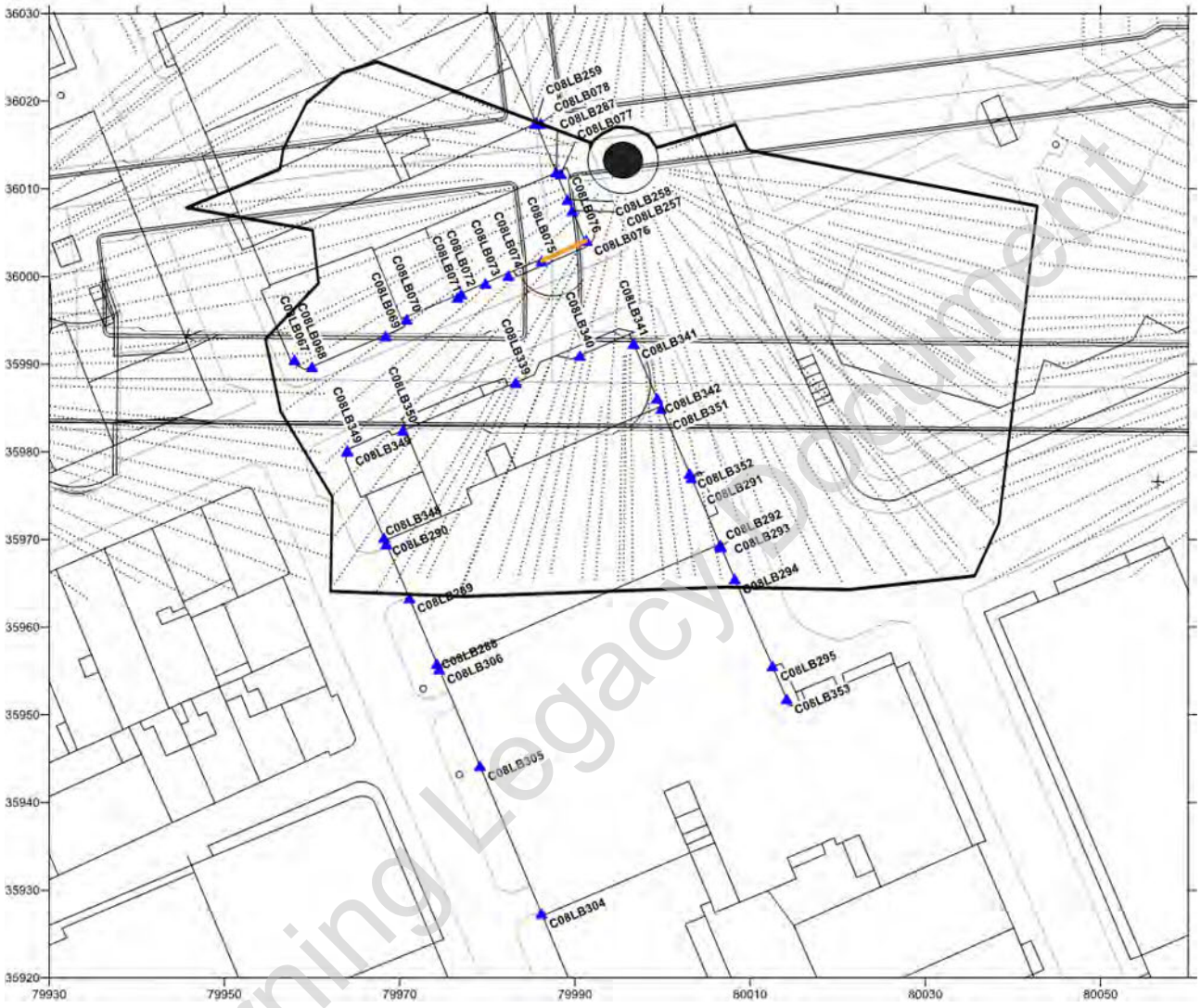
Slope triggers are as follows:

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

Table 4.1 Details of Amber breaches on BRE & HLC

BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Carlisle Street East – North:					
C08LB075-C08LB076	Amber	Transitory slope during enlargement of PTW – reduced by subsequent grout jacking (28/01/14)	16/12/13	1.18	0.46
Carlisle Street East – South: NONE					
Soho Square – West: NONE					
Dean Street – East: NONE					

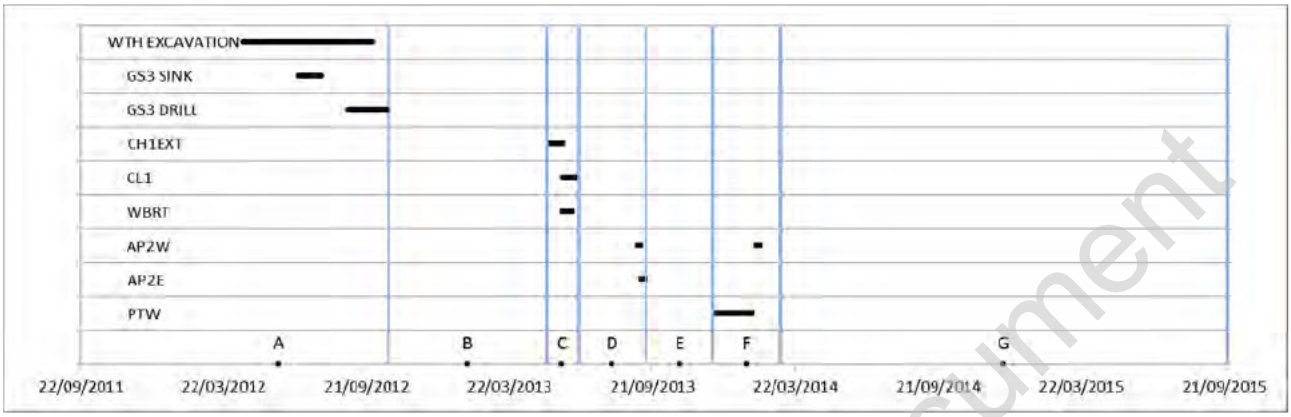
Figure 4.1.1 Locations of BREs and building slope Amber trigger.

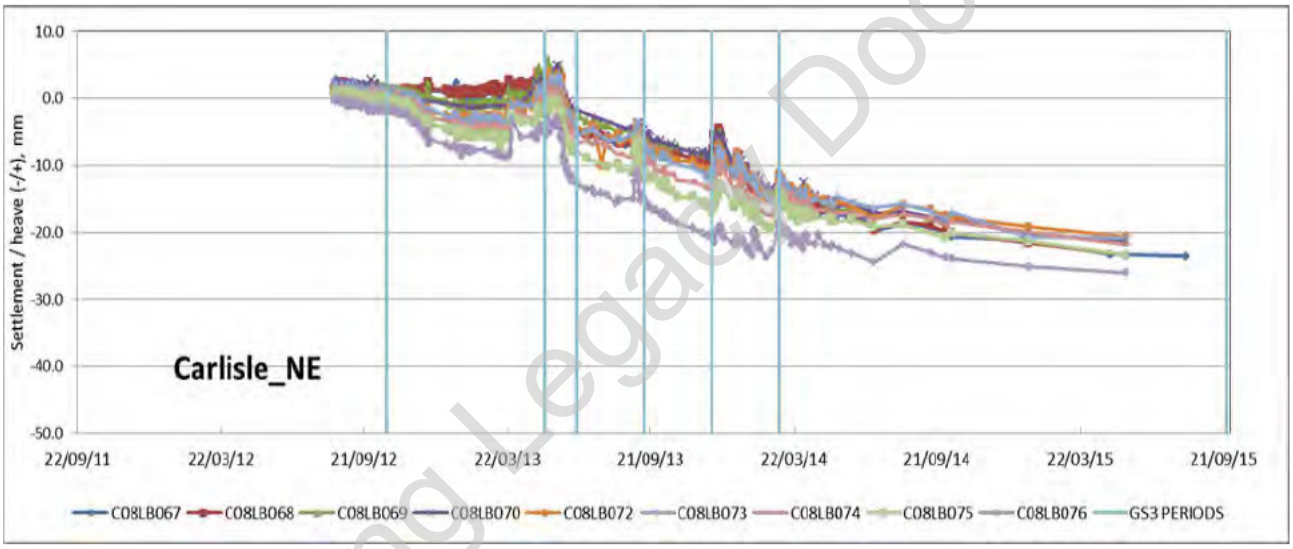


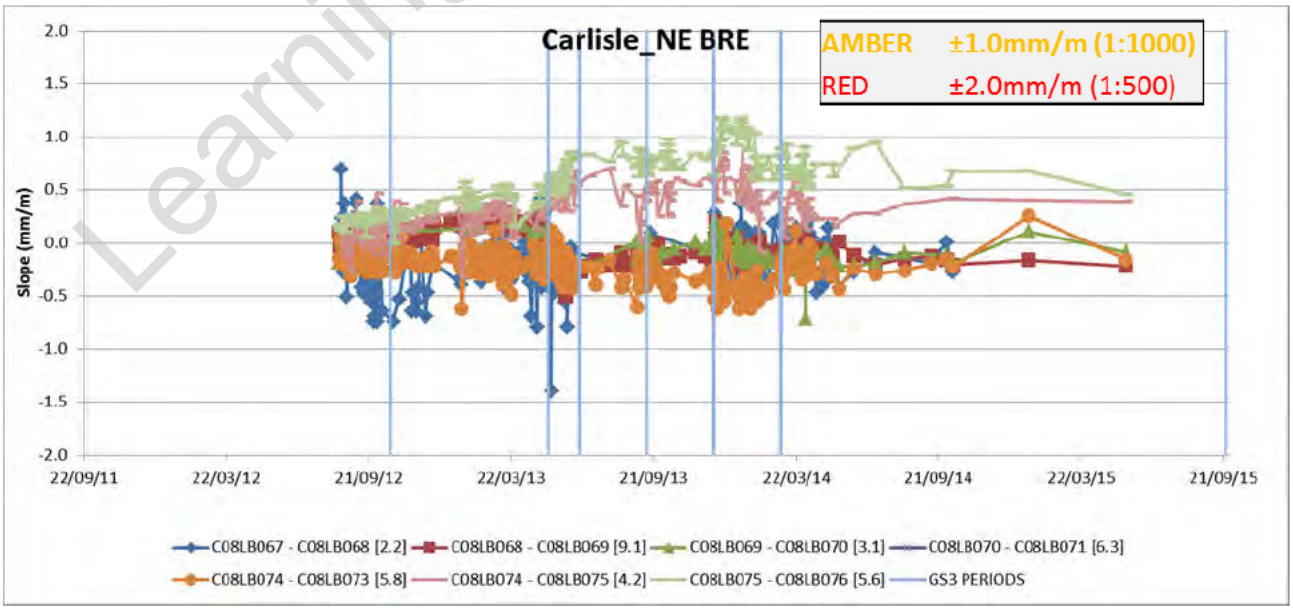
BRE monitoring data from the facades within the footprint of GS3 are presented in the following sections, namely Carlisle Street north and south, Soho Square west and Dean Street east. The plots presented for each comprise, as appropriate:

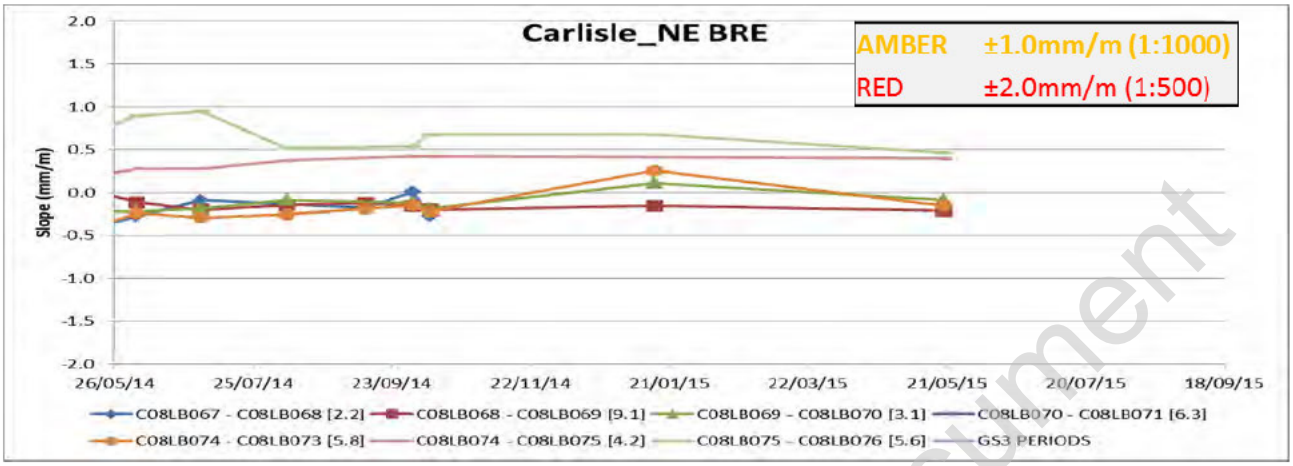
1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres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

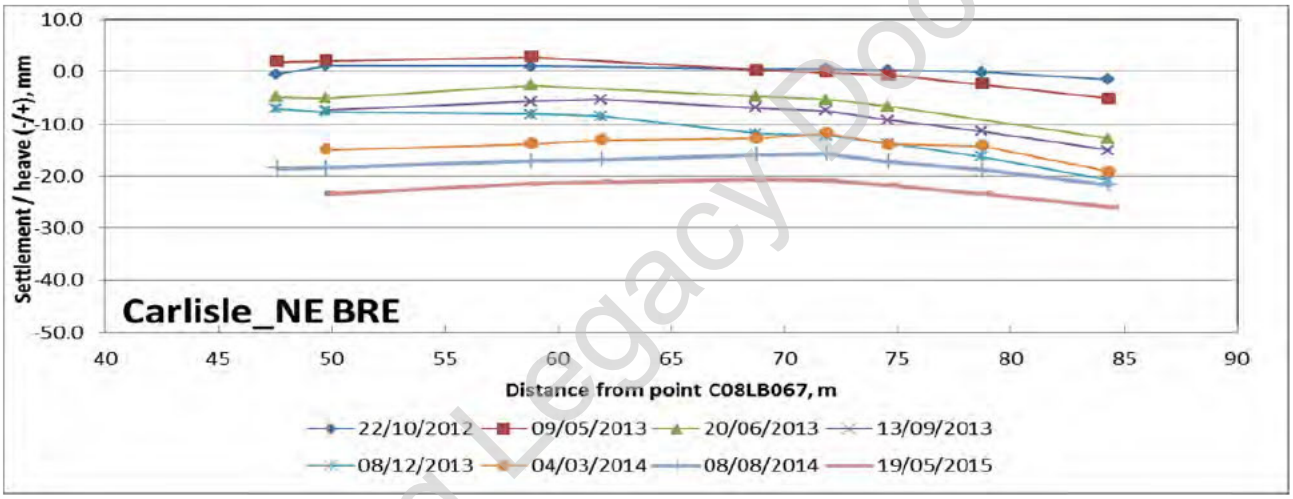
4.2. Carlisle Street North – East







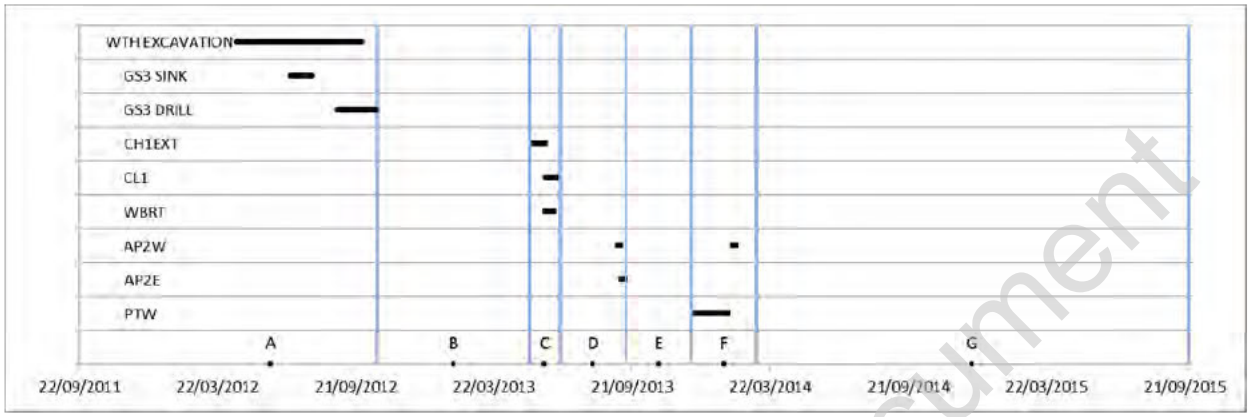


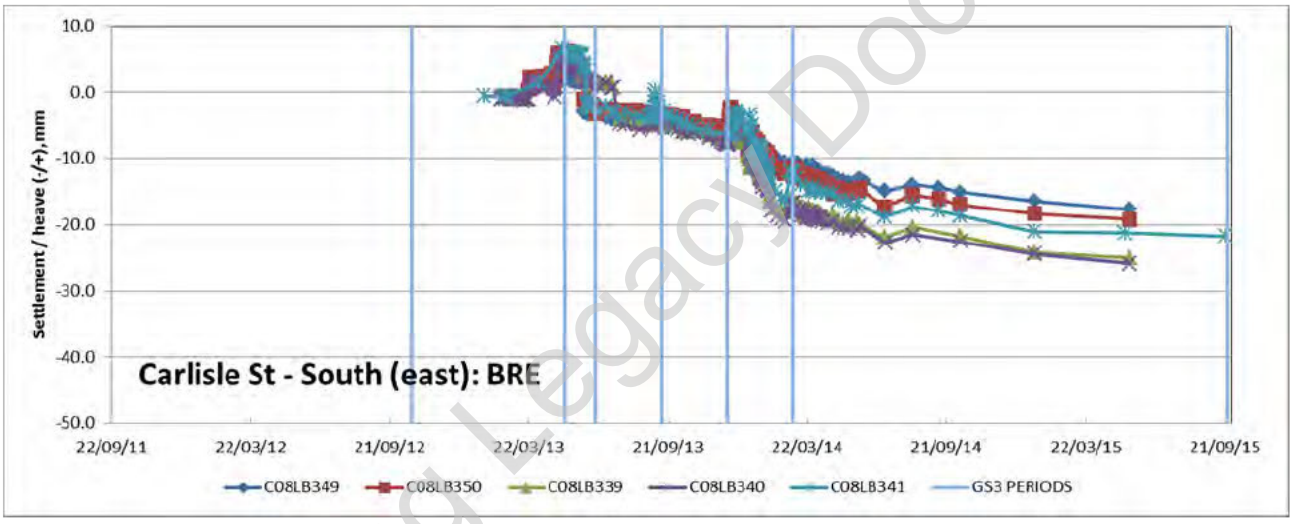


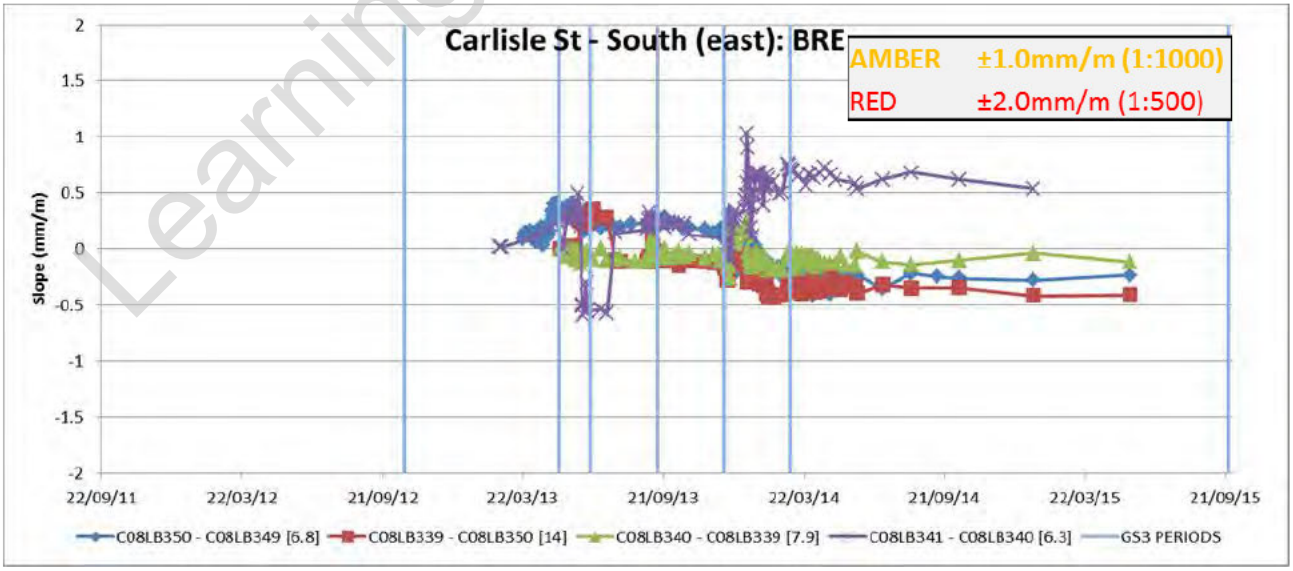
The following points are noted:

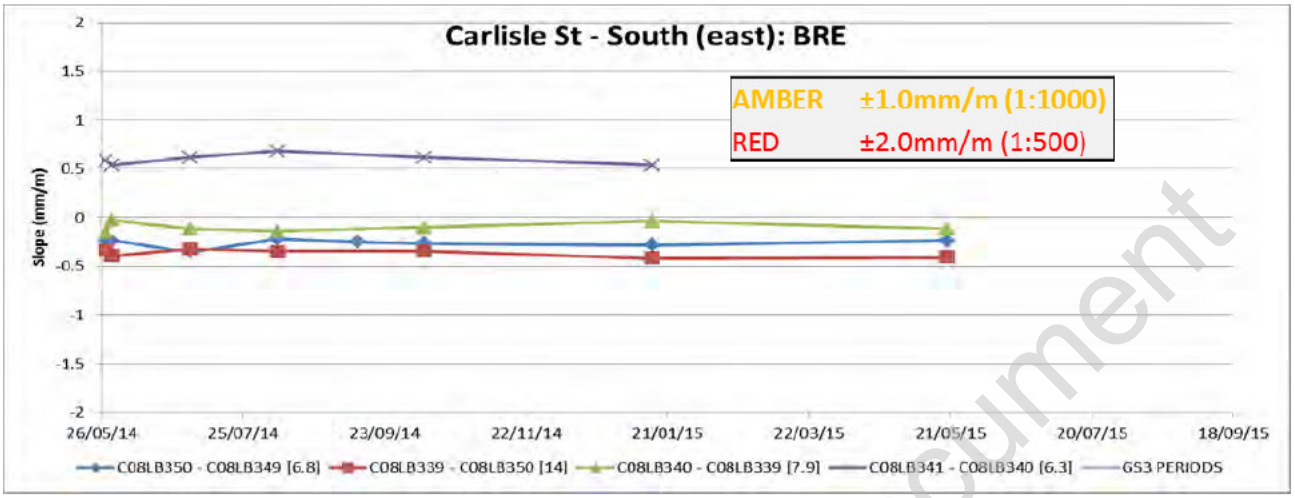
- Data are presented for the BRE located on the north facade of Carlisle Street to the east of Dean Street (see GS1 report for points west of Dean Street). All points are within the plan extent of the GS3 arrays.
- Overall settlement was ~5mm or less at the end of Period B as a result of pretreatment and pre-TBM grout jacking reversing settlement which followed completion of TaM installation. Settlement increased to a maximum of 12mm in Period C, associated with CH1Ext, CL1 and WBRT excavation, the latter two tunnels without concurrent grouting.
- No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D as a result of a combination of concurrent grouting and grout jacking. Settlement increased gradually between tunnel drives and reached about 21mm at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F. Settlement associated with the junction with AP2W was reversed by grout jacking resulting in negligible net change in movement.
- The rate of post construction settlement in Period G has reduced continually with the final readings showing near stable conditions.
- Slopes were less than the Amber trigger value at the end of construction and subsequently during Period G. A transitory slope trigger occurred during the PTW enlargement between C08LB075 and C08LB076 at the corner of Soho Square, as detailed in Table 4.1.

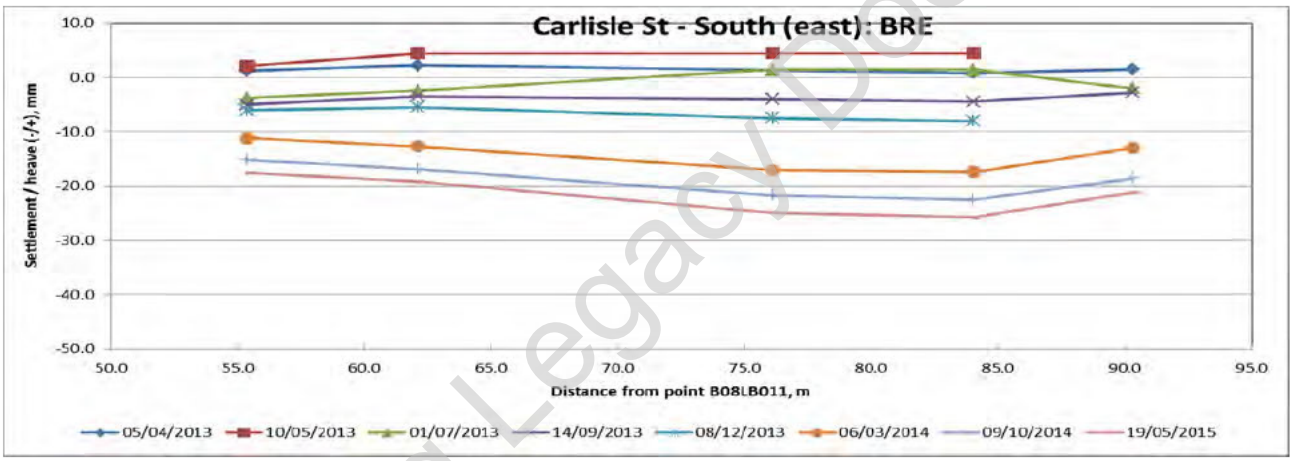
4.3. Carlisle Street South – east







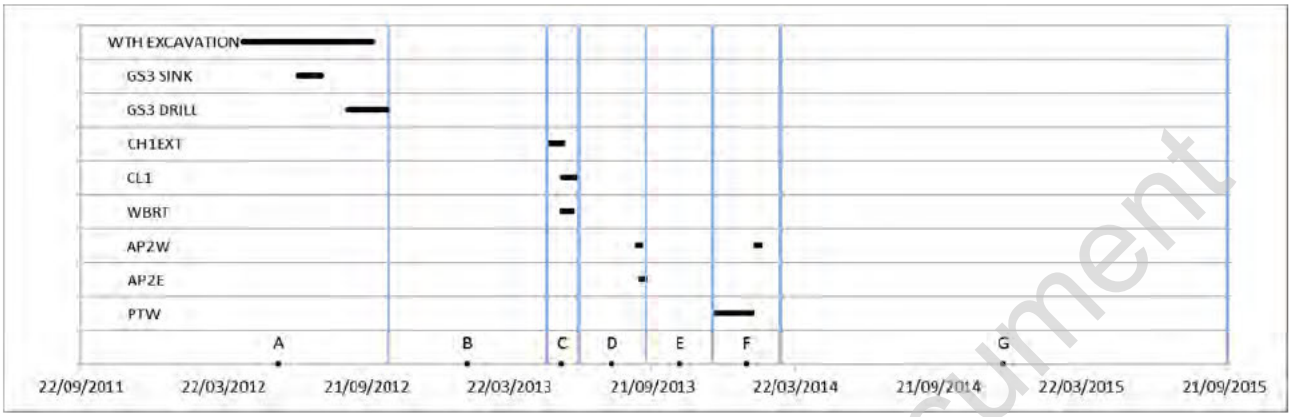


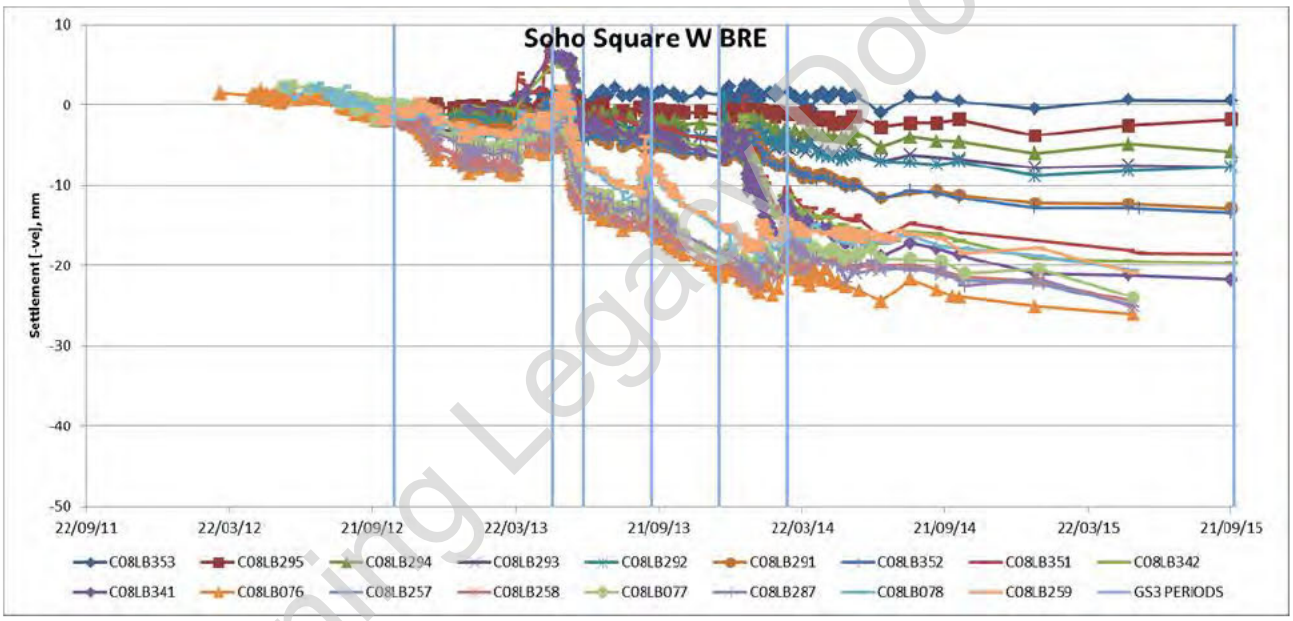


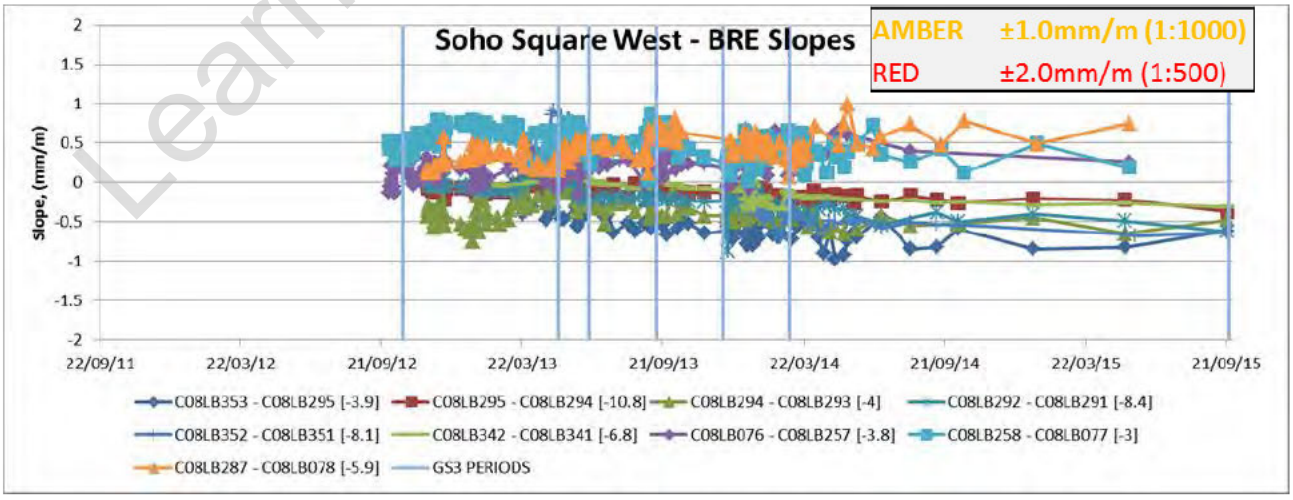
The following points are noted:

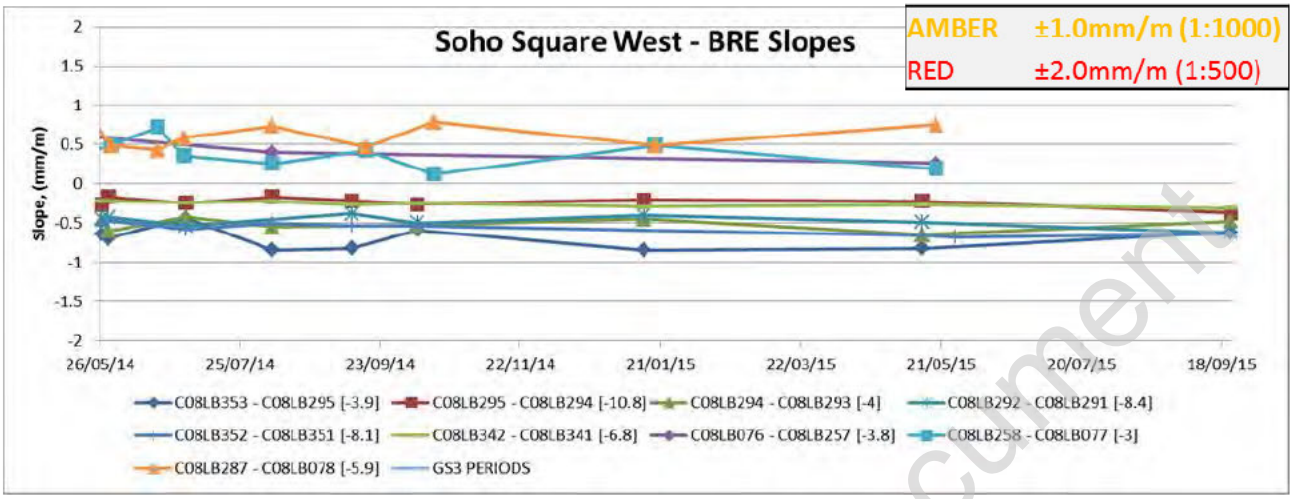
- Data are presented for the BRE located on the south façade of Carlisle Street to the east of Dean Street (see GS1 report for points west of Dean Street). All points are within the plan extent of the GS3 arrays.
- Overall a small heave was generated at the end of Period B as a result of pretreatment and pre-TBM grout jacking reversing settlement which followed completion of TaM installation. Settlement increased to a maximum of 5mm in Period C, associated with CH1Ext, CL1 and WBRT excavation, the latter two tunnels without concurrent grouting.
- No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D as a result of a combination of concurrent grouting and grout jacking. Settlement increased gradually between tunnel drives and reached about 8mm at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F. Settlement subsequently increased by up to 10mm associated with the AP2W junction.
- The rate of post construction settlement in Period G has reduced continually with the final readings showing near stable conditions.
- Slopes were less than the Amber trigger value at the end of construction and subsequently during Period G. A single data point indicated a slope trigger during the PTW enlargement between points C08LB341 and C08LB340. Since this was not confirmed by any subsequent readings it is not included in Table 4.1.

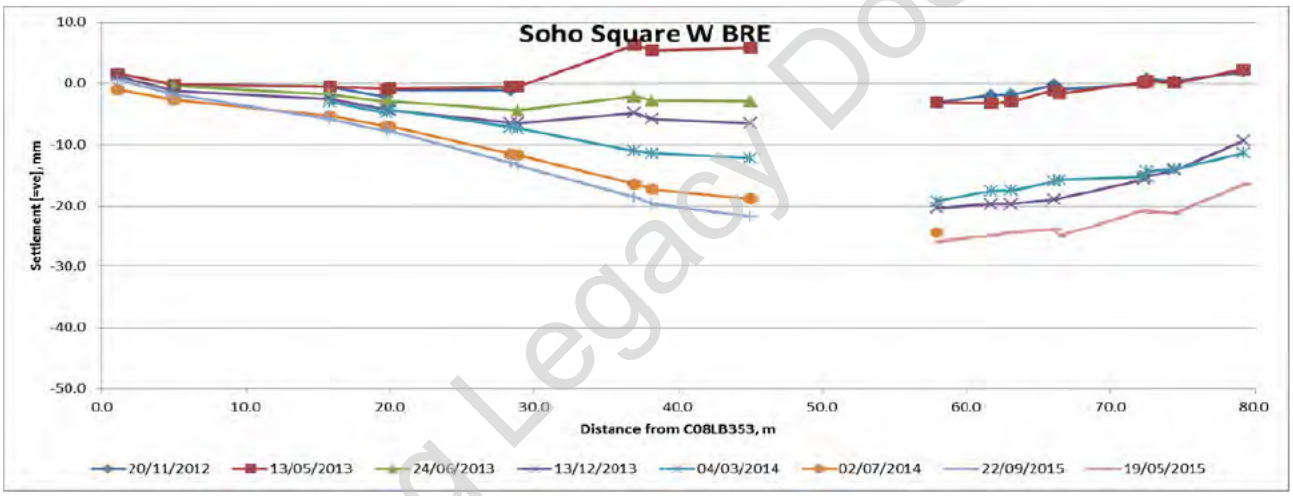
4.4. Soho Square West







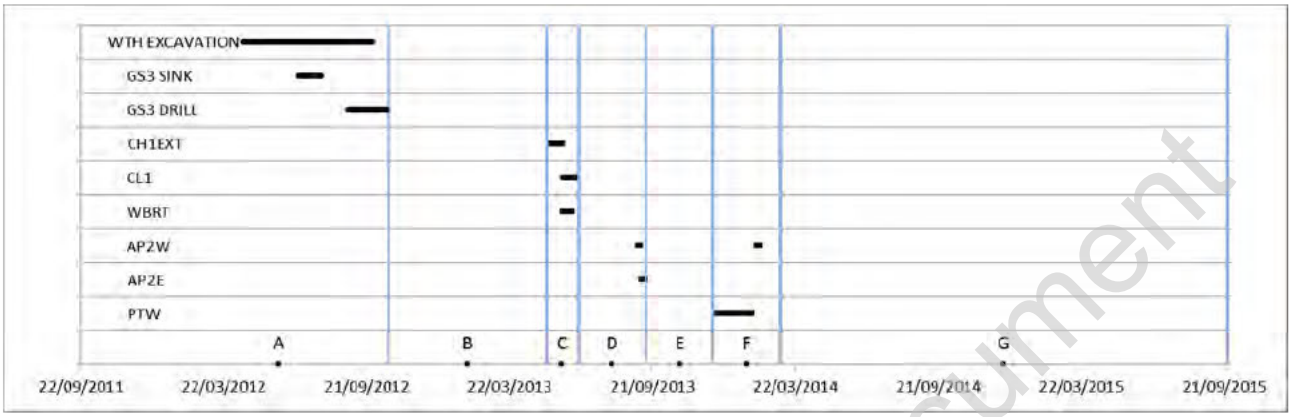


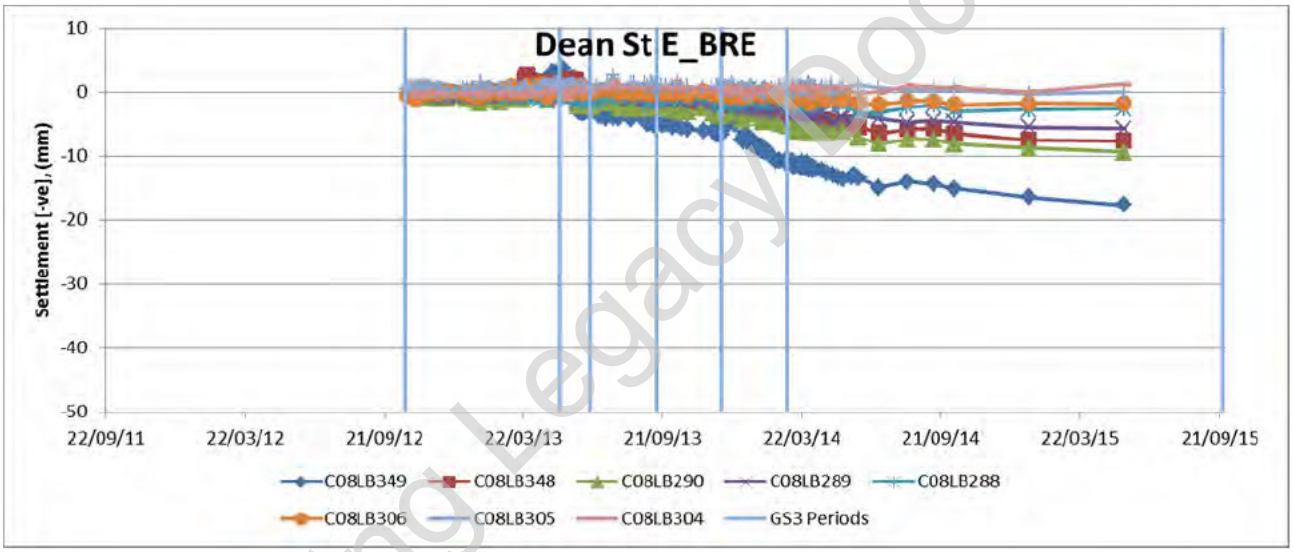


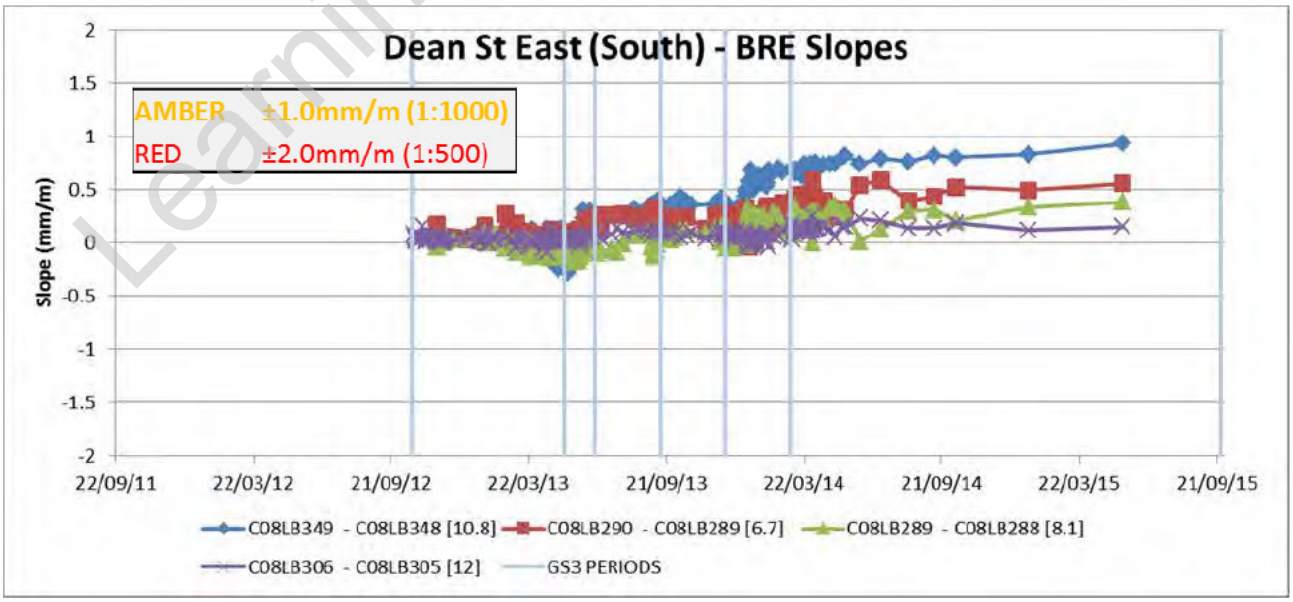
The following points are noted:

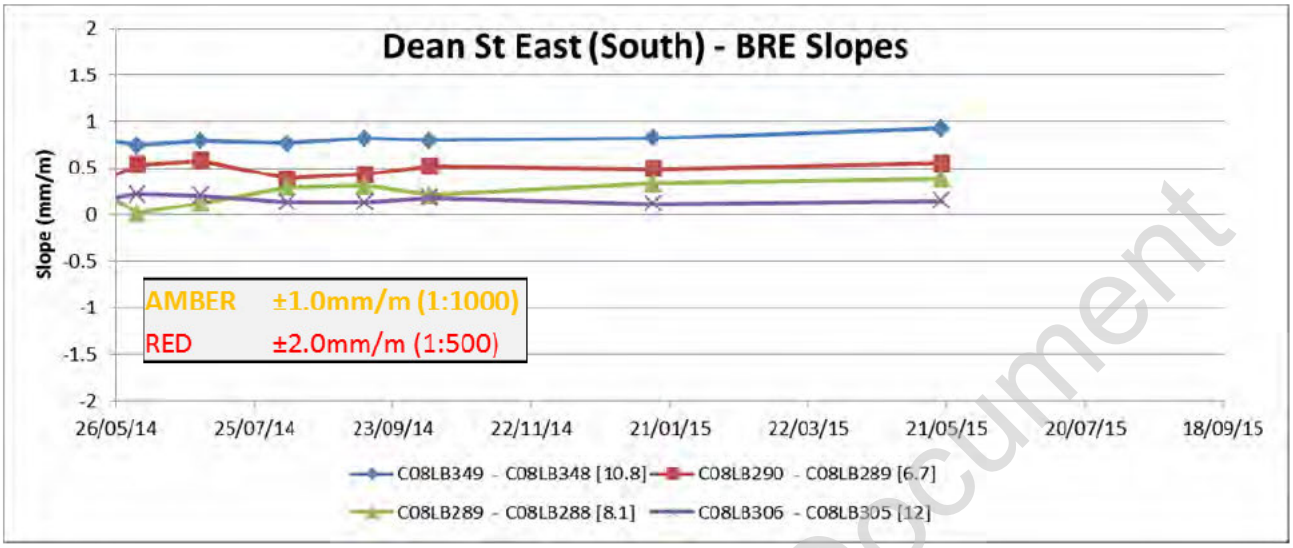
- Data are presented for the BRE located on the west facade of Soho Square within the GS3 area. Points at a distance of over 5m from C08LB353 are within the plan extent of the GS3 arrays.
- Overall settlement was ~5mm at the end of Period B as a result of pretreatment and pre-TBM grout jacking reversing settlement which followed completion of TaM installation. Settlement increased to a maximum of 13mm in Period C, associated with CH1Ext, CL1 and WBRT excavation: the latter two tunnels without concurrent grouting.
- No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D: settlement increased gradually to 15mm at the end of Period D and 20mm at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F but some settlement occurred with the excavation of the AP2W junction which was partially reversed by grout jacking. Final measured settlement at the end of the works was 27mm.
- The rate of settlement in Period G has reduced continually with the final readings up to September 2015 show stable conditions.
- Slopes were less than the Amber trigger value throughout construction and subsequently during Period G.

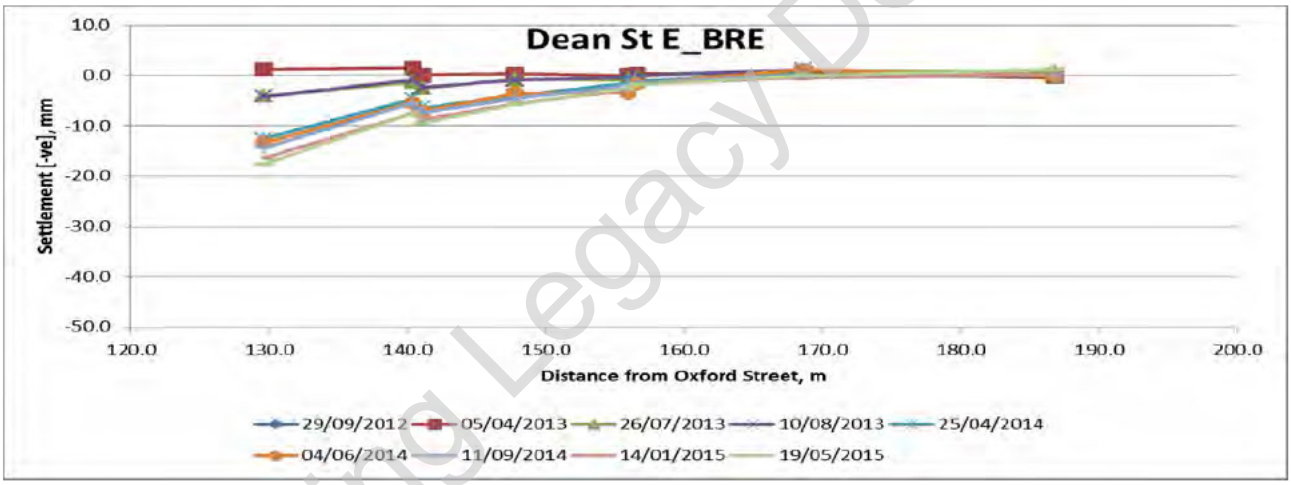
4.5. Dean Street East – south











The following points are noted:

- The Dean Street east facade to the south of Carlisle Street is within the plan extent of the GS3 arrays up to distance 145m (from Oxford Street).
- Settlement was minor in Periods A and B and increased to a maximum of 3mm in Period C, associated with CH1Ext, CL1 and WBRT excavation. No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D. Settlement increased gradually to about 7mm on at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F but with negligible net change in movement. Post construction settlement is shown in the remainder of Period F extending into Period G. The final measured settlement at the end of the works was 18mm.
- The rate of settlement in Period G has decreased gradually with a higher rate evident on C08LB349 on the corner of Carlisle Street.
- Slopes were less than the Amber trigger value throughout construction and up to the cessation of monitoring in Period G. The trends essentially stable within the accuracy of the data.

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. 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 kerblines within the footprint of GS3 are presented in the following sections, namely Carlisle Street north and south, Soho Square inner and outer and Dean Street east. The plots presented for each comprise, as appropriate:

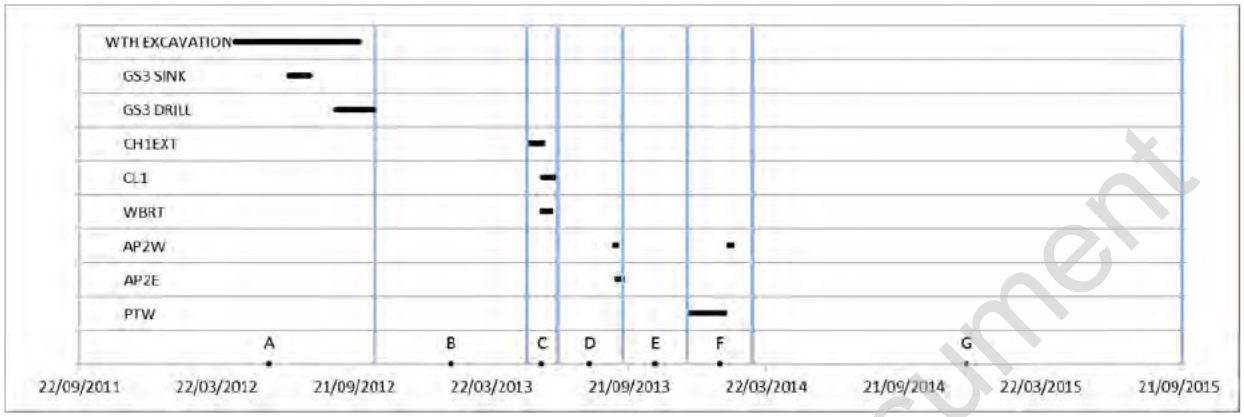
1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres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

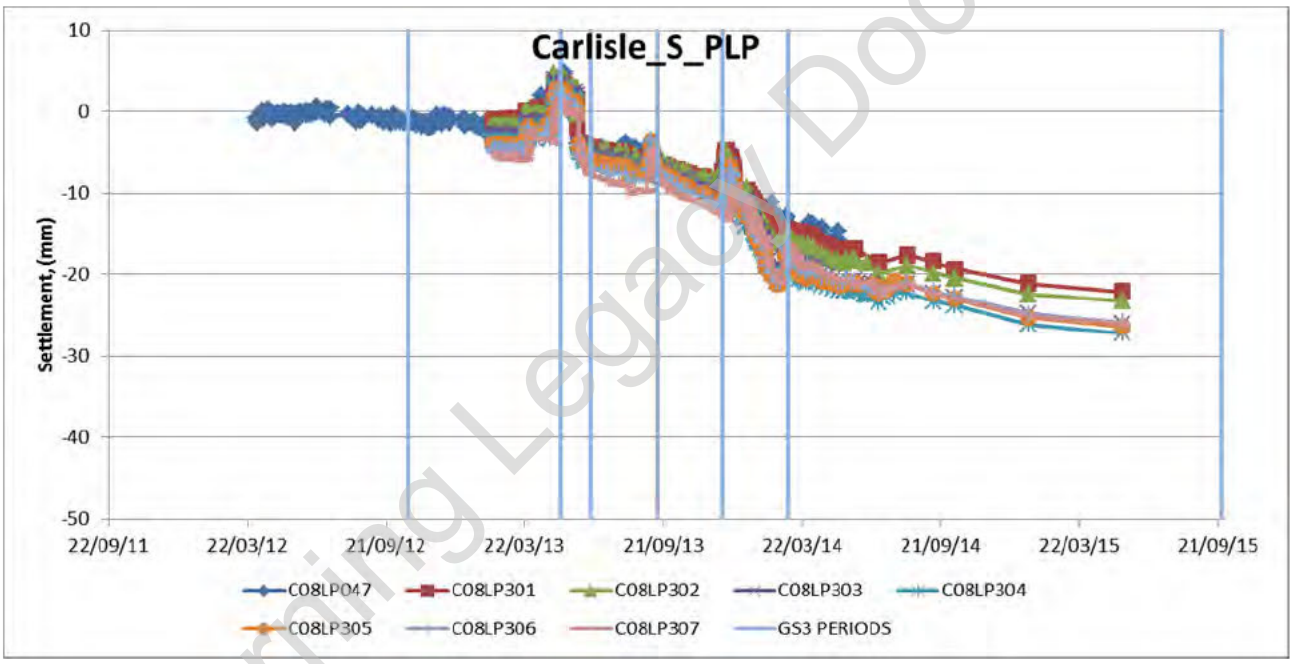
Table 5.1 Details of Amber breaches on PLP

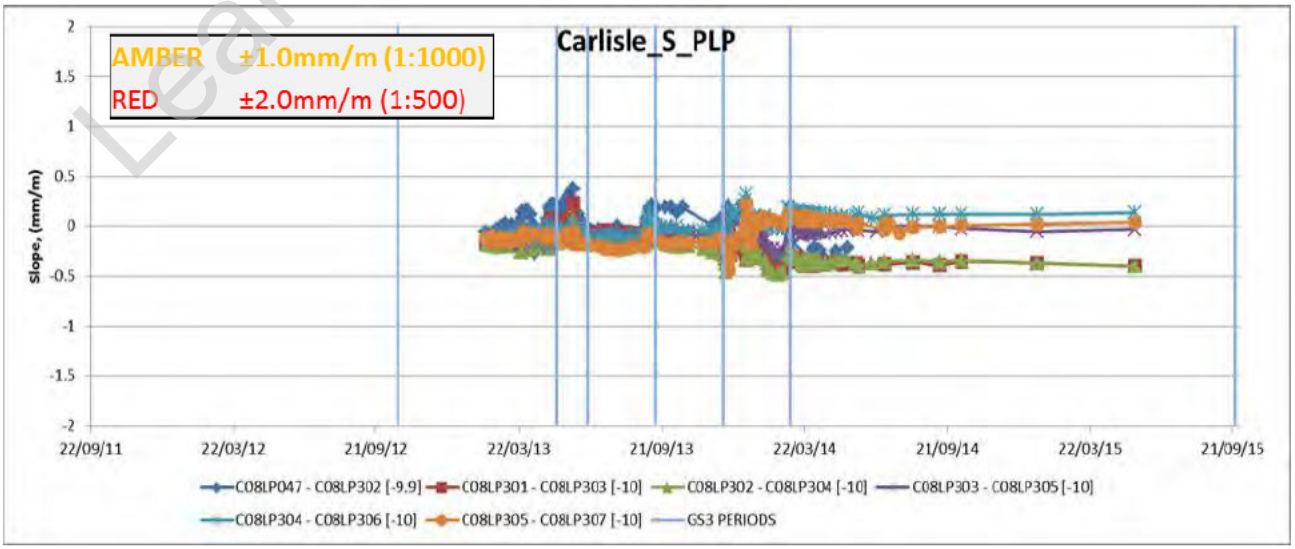
Kerb Line		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Carlisle Street East – North: NONE					
Carlisle Street East – South: NONE					
Soho Square – West inner:					
C08LP192 – C08LP196	-	Single reading of 1.07mm/m (>Amber) on 23/01/14 – not validated by subsequent reading			0.55
C08LP191 – C08LP195	Amber	Transitory slope during enlargement of PTW – reduced by subsequent grout jacking (19/02/14)	12/01/14	1.34	0.87
C08LP196 – C08LP200	Amber	Generated by CL1 (no concurrent grouting). Reduced to below Amber by jack grouting episodes in Period F	07/03/13	1.24	0.88
C08LP197 – C08LP201	Amber	Generated by CL1 (no concurrent grouting). Reduced to below Amber by jack grouting episodes in Period F	05/03/13	1.32	0.85
Soho Square – West outer:					
C08LP061 – C08LP063	Amber	Marginal – occurred 9 months after the end of construction	14/01/15	1.01	1.03
Dean Street - East					
C08LP044 – C08LP046	Amber	Trigger occurred 5 months after end of construction. Increased rate of settlement on point on corner kerb – probable damage to point	08/08/14	1.41	1.41

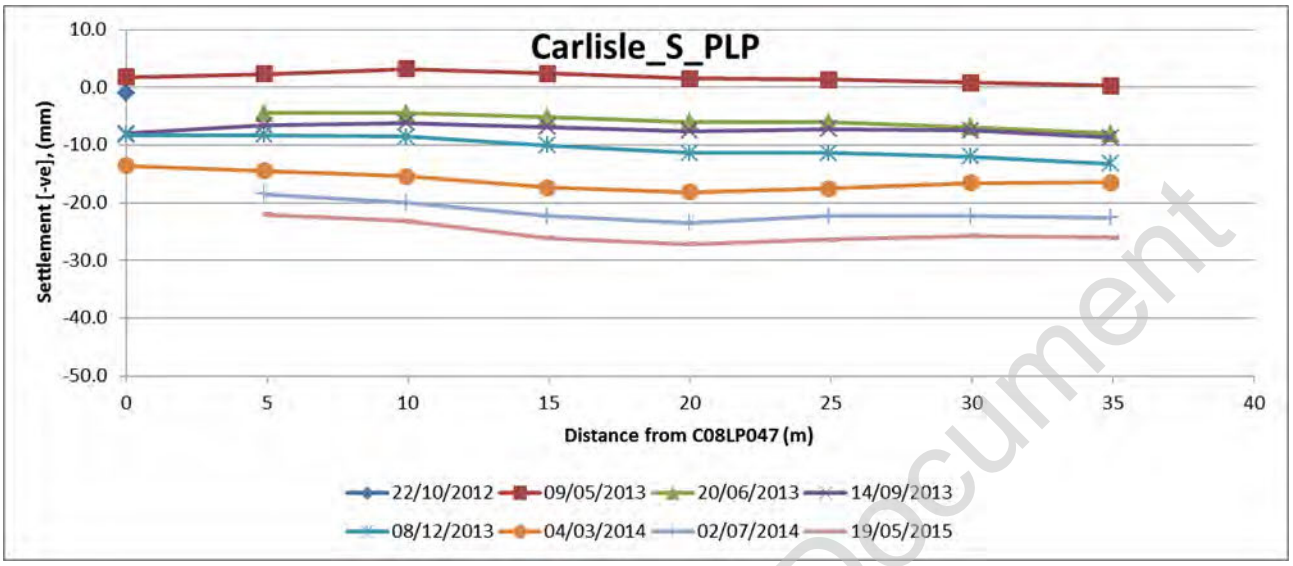
Figure 5.1.1 Location of PLP and Amber slope triggers

5.2. Carlisle Street South – east





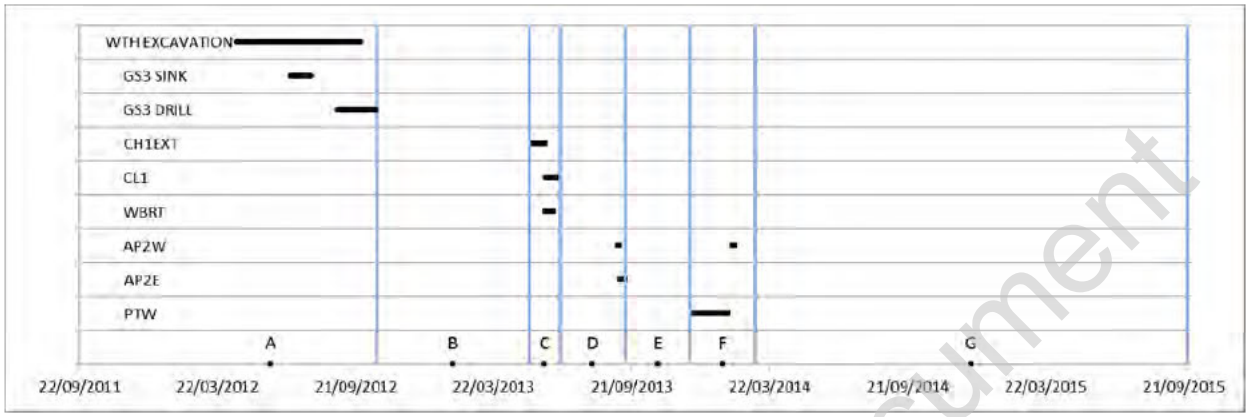


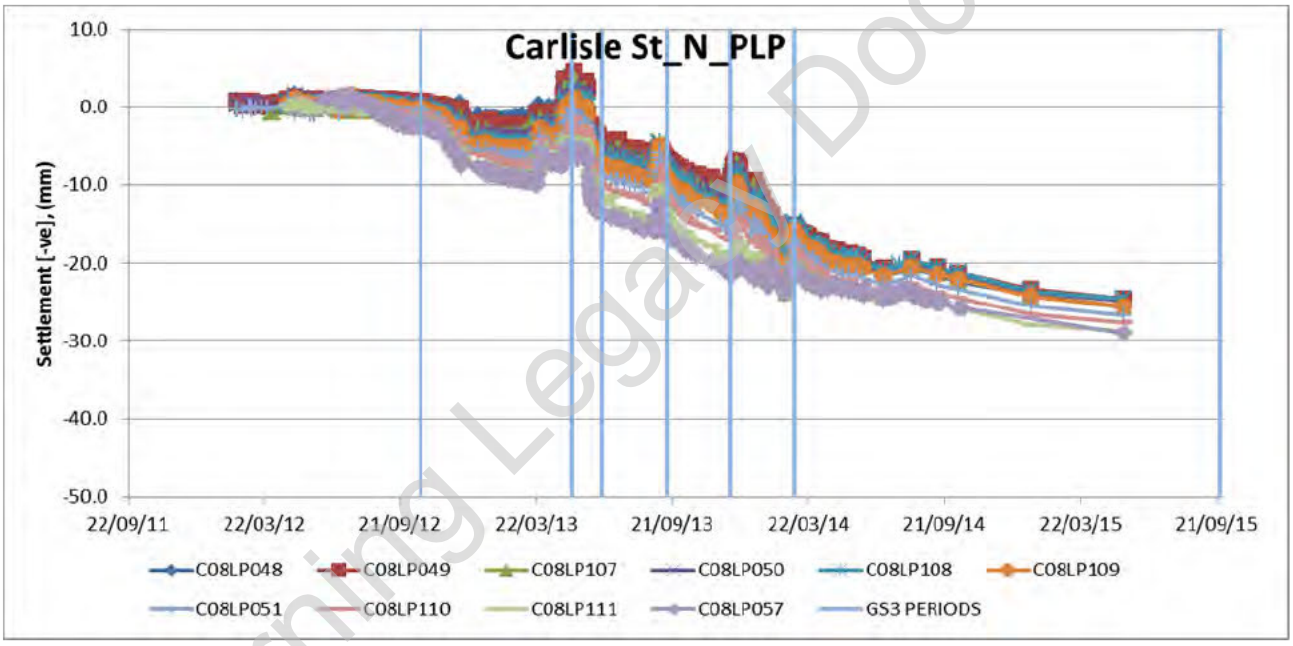


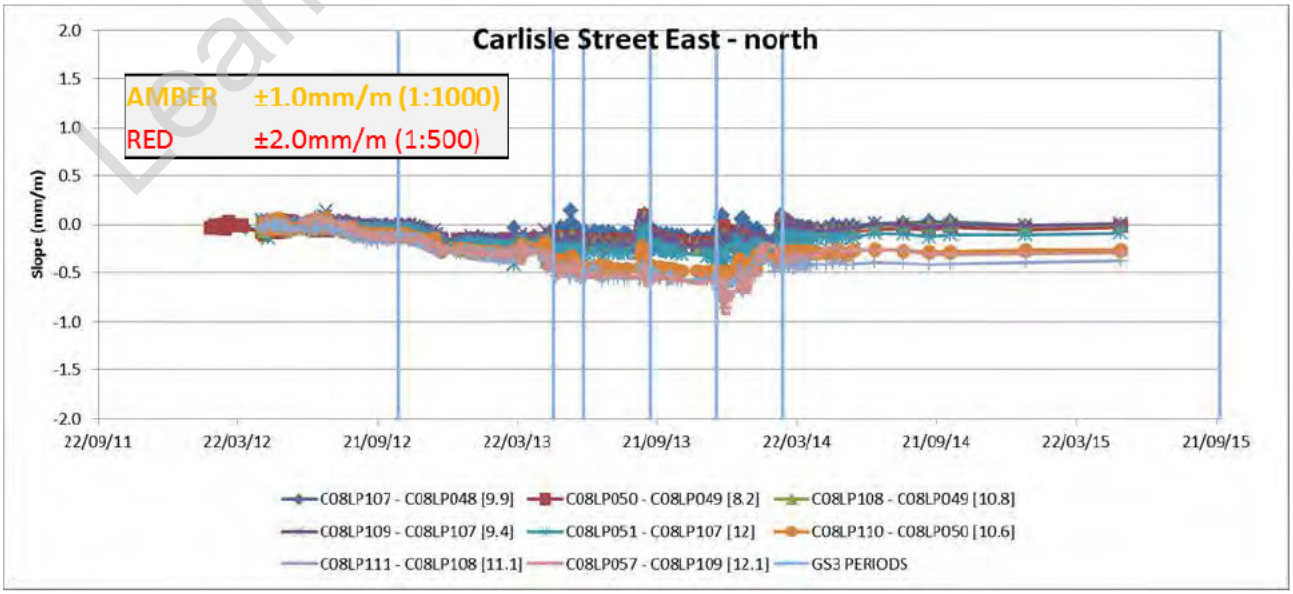
The following points are noted:

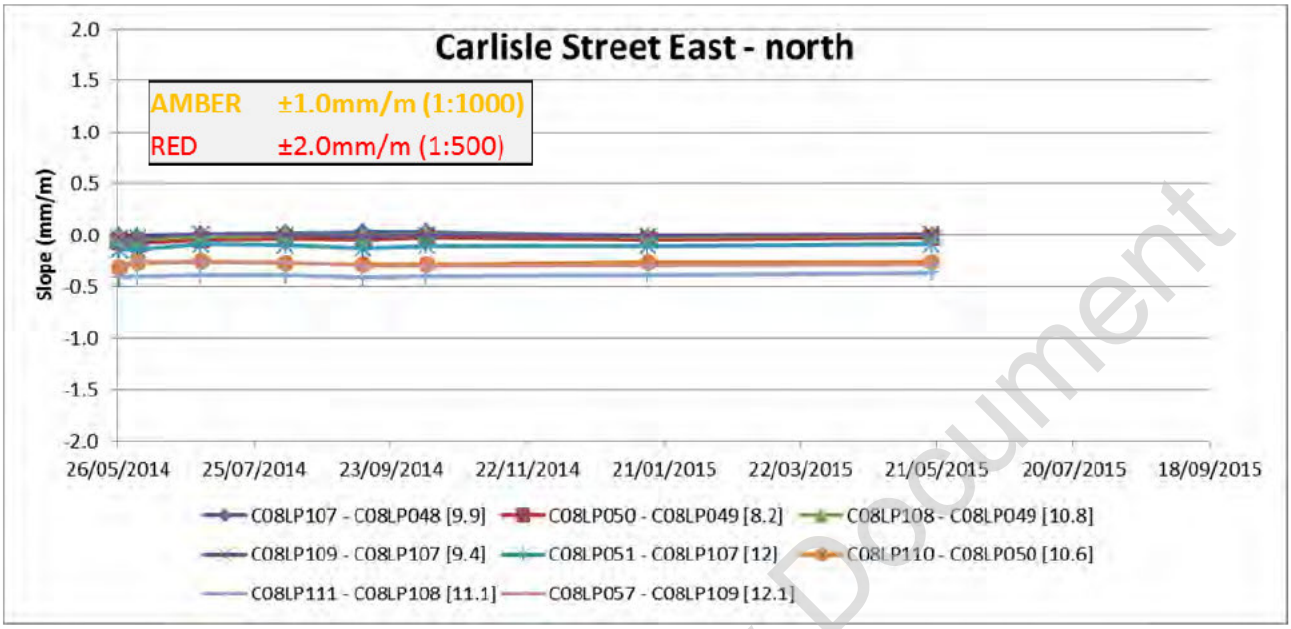
- Data are presented for the PLP located on the south kerb line of Carlisle Street to the east of Dean Street (see GS1 report for points west of Dean Street). All points are within the plan extent of the GS3 arrays.
- Overall settlement was minor at the end of Period B as a result of pretreatment reversing settlement which followed completion of TaM installation and pre-jacking prior to the WBRT. Settlement increased to a maximum of 8mm in Period C, associated with CH1Ext, CL1 and WBRT excavation, the latter two tunnels without concurrent grouting. No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D as a result of concurrent grouting and a small grout jacking episode. Settlement increased gradually between tunnel drives and reached about 12mm at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F followed by settlement, in part associated with the construction of the junction with AP2W, giving a maximum of 21mm which was reduced to 19mm at the end of construction, by a grout jacking episode.
- The rate of post construction settlement in Period G has reduced continually with the final readings showing near stable conditions at a maximum settlement of about 27mm.
- Slopes were less than the Amber trigger value throughout construction and subsequently. There is no increase in slopes during Period G.

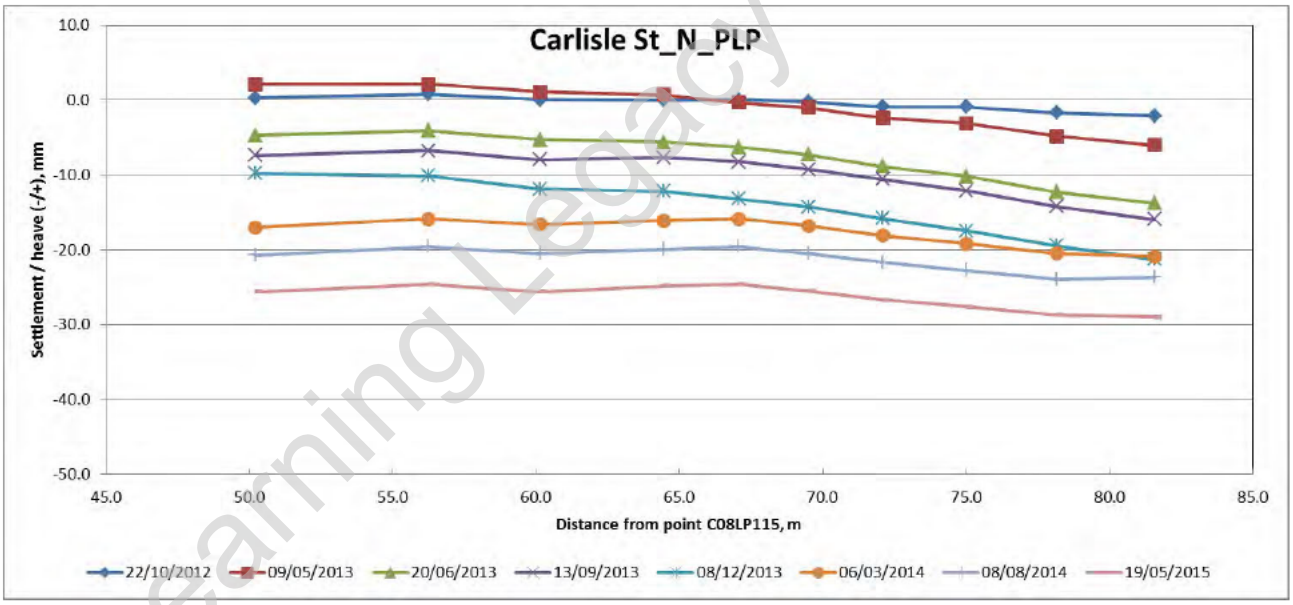
5.3. Carlisle Street North – east











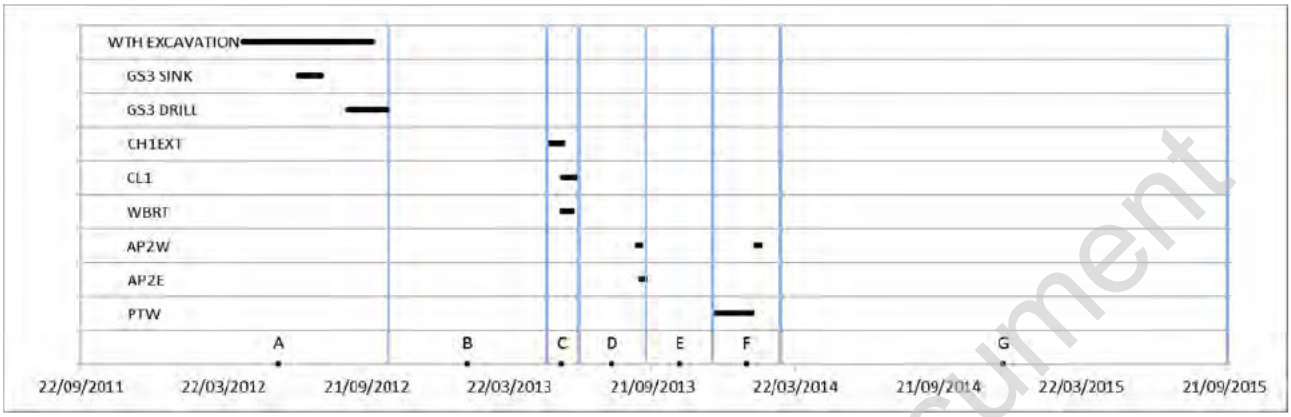
The following points are noted:

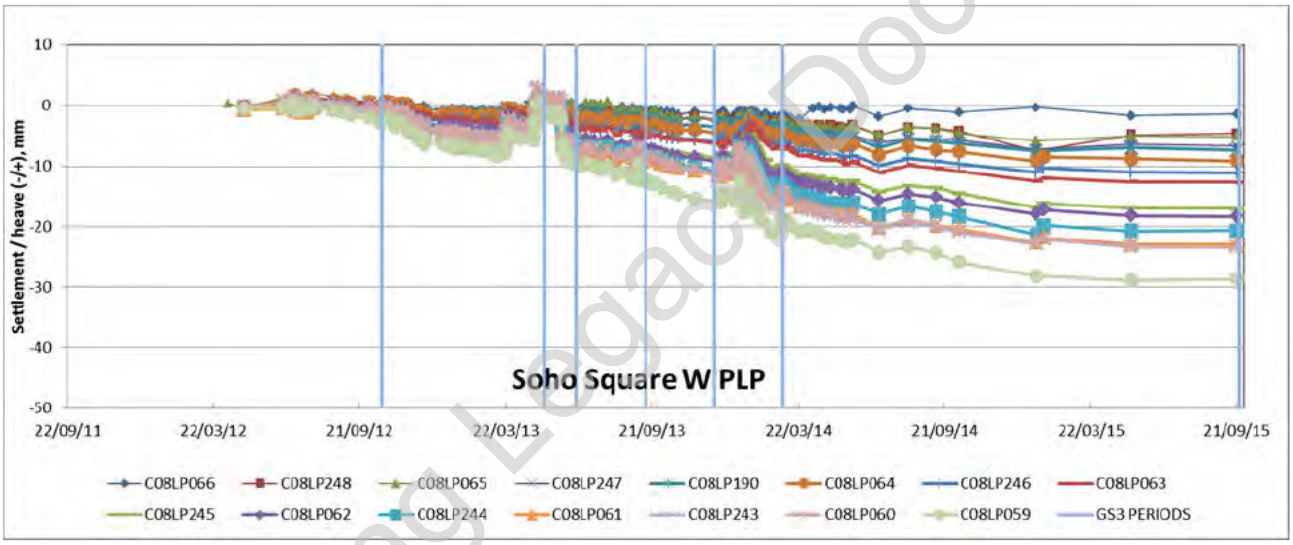
- Data are presented for the PLP located on the north kerb line of Carlisle Street to the east of Dean Street (see GS1 report for points west of Dean Street). All points are within the plan extent of the GS3 arrays.
- Overall settlement was ~5mm at the end of Period B as a result of pretreatment reversing settlement which followed completion of TaM installation and pre-jacking prior to the WBRT. Settlement increased to a maximum of 13mm in Period C, associated with CH1Ext, CL1 and WBRT excavation: the latter two tunnels without concurrent grouting and a small grout jacking episode. No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D as a result of concurrent grouting. Settlement increased gradually between tunnel drives and reached about 21mm on C08LP057 at the corner of Soho Square at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F followed by settlement, in part associated with the construction of the junction with AP2W. A subsequent grout

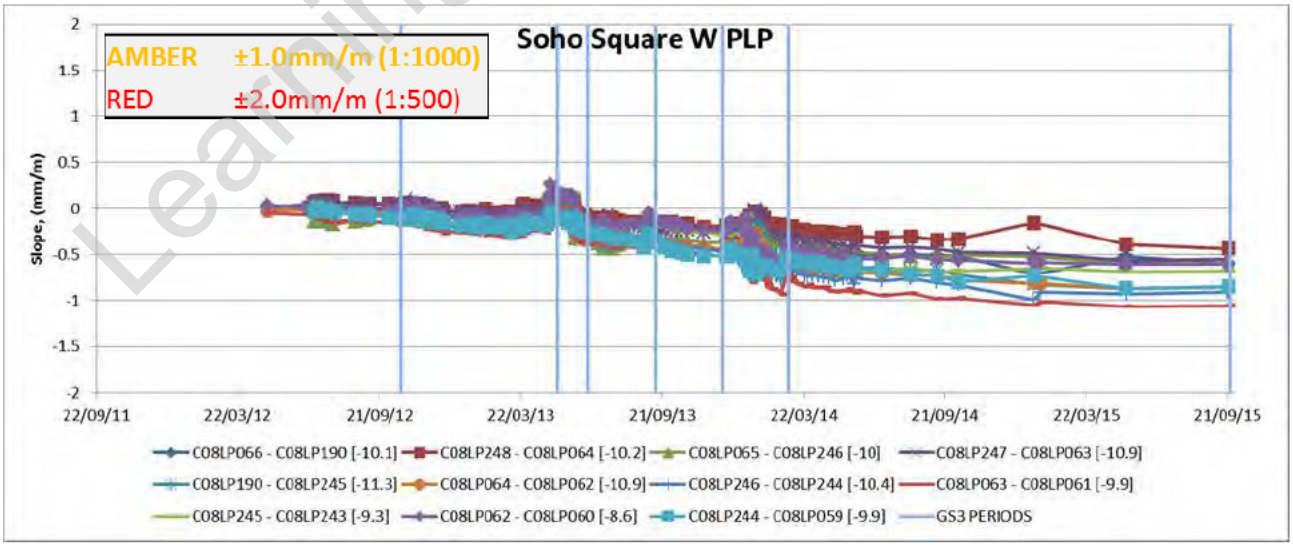
jacing episode , restricted the increase in maximum settlement to 22mm at the end of construction. The final measured settlement at the termination of monitoring was 29mm.

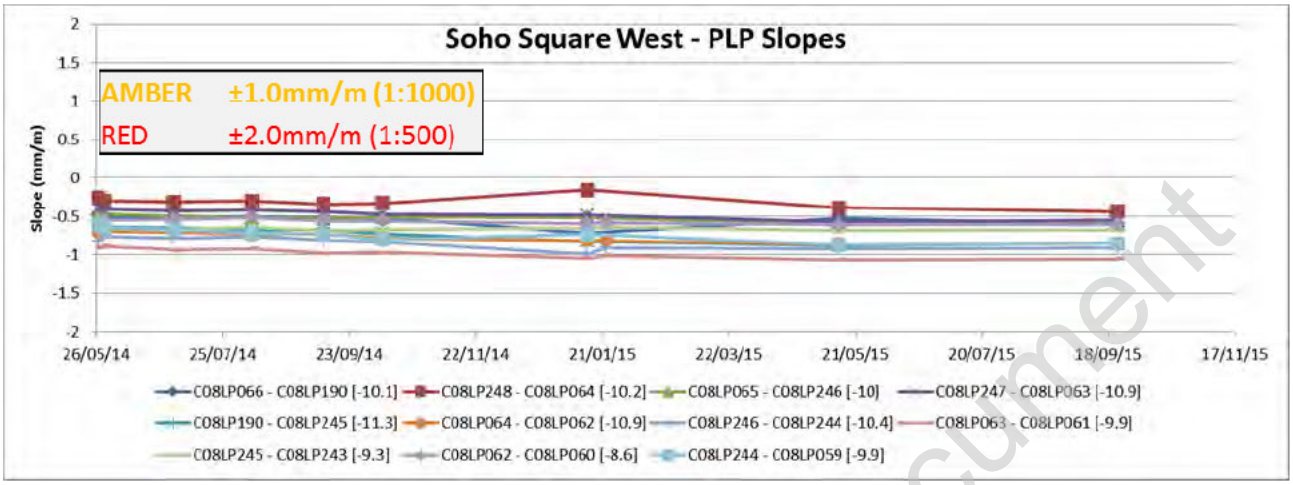
- The rate of post construction settlement in Period G has reduced continually with the final readings showing near stable conditions.
- Slopes were less than the Amber trigger value throughout construction and subsequently. There is no increase in slopes during Period G.

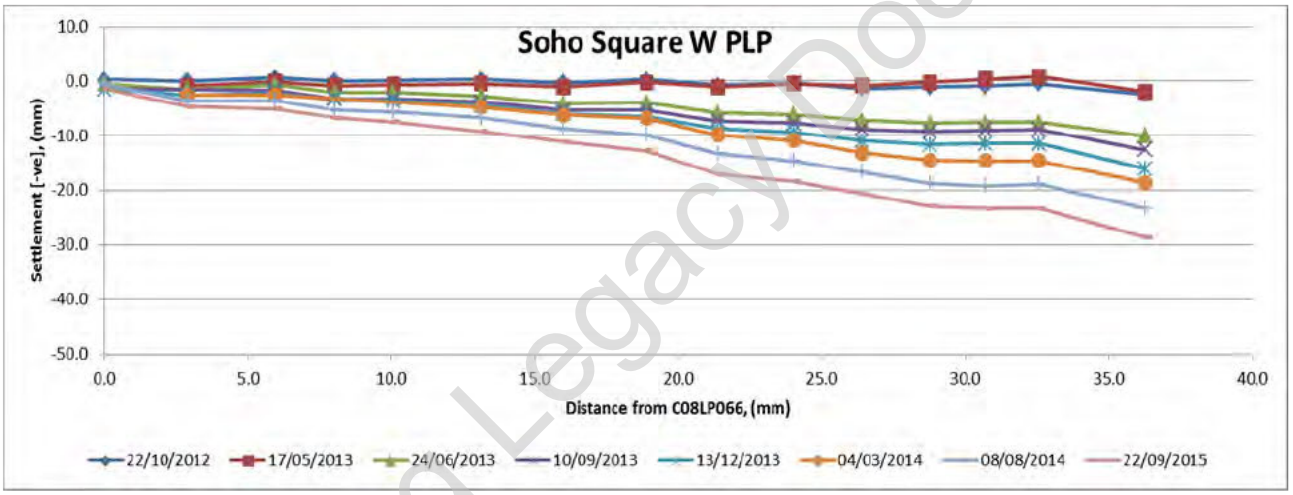
5.4. Soho Square West – outer









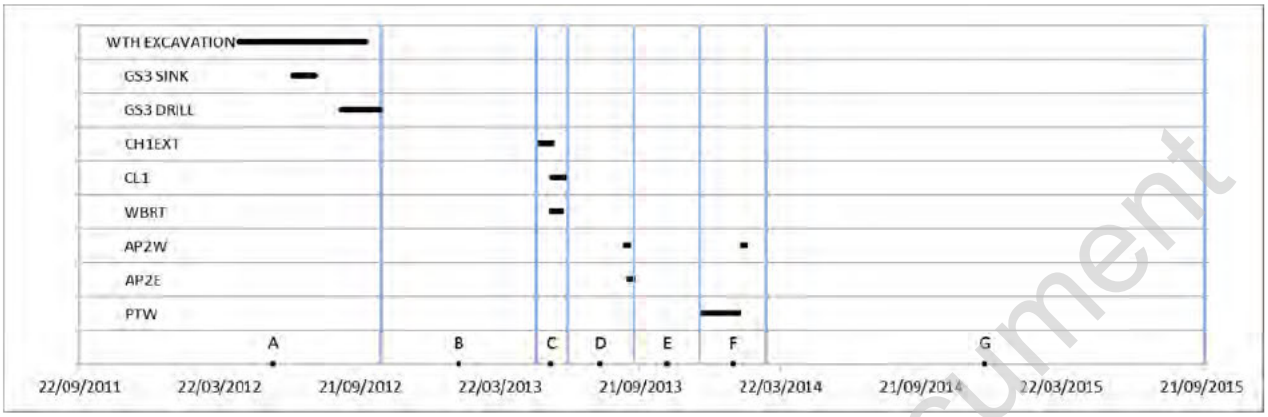


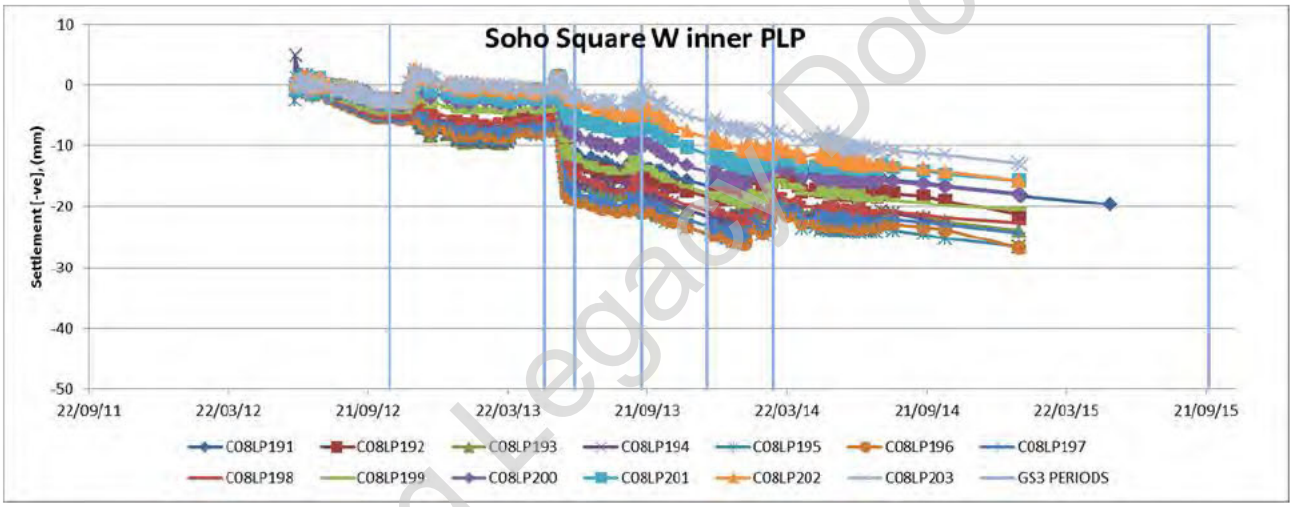
The following points are noted:

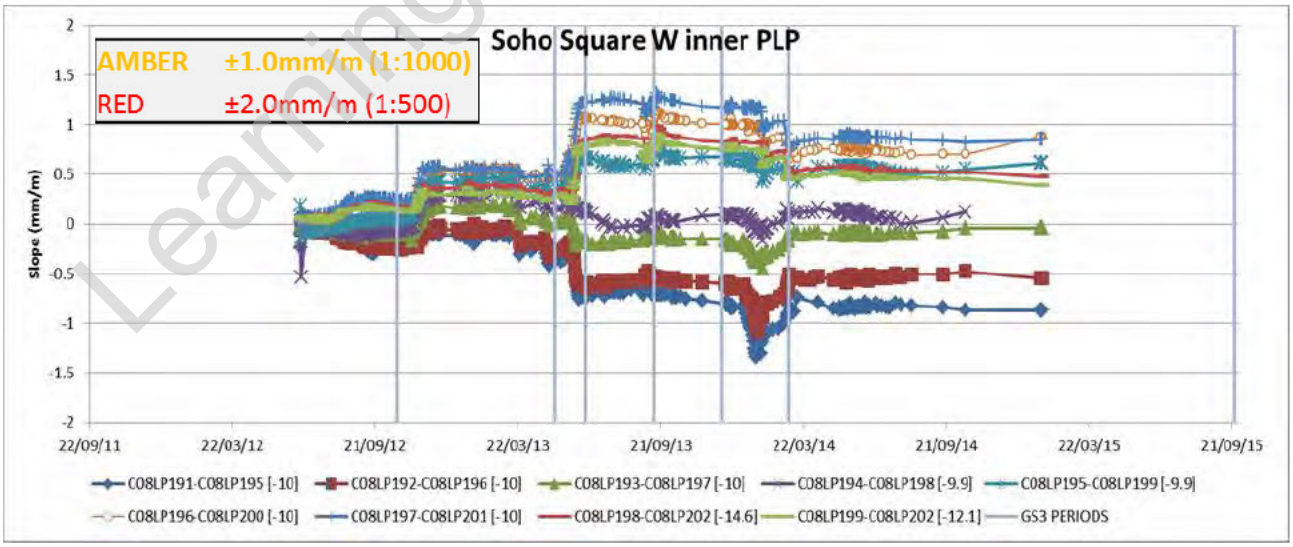
- Data are presented for the PLP located on the outer kerb line of Soho Square to the south of Carlisle Street (see GS2 report for points north of Carlisle Street). Points at a distance of over 5m from C08LP066 are within the plan extent of the GS3 arrays.
- Overall settlement was minor at the end of Period B as a result of pretreatment reversing settlement which followed completion of TaM installation and pre-jacking prior to the WBRT. Settlement increased to a maximum of 10mm in Period C, associated with CH1Ext, CL1 and WBRT excavation: The latter two tunnels without concurrent grouting. No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D as a result of concurrent grouting and a small episode of grout jacking. Settlement increased gradually to about 16mm on C08LP059 at the corner of Carlisle Street at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F but with negligible net change in movement. Post construction settlement is shown in the remainder of Period F extending into Period G. The maximum settlement at the end of construction was ~19mm. The final measured settlement at the termination of monitoring was 29mm
- The rate of settlement in Period G has reduced continually with the final readings up to September 2015 show stable conditions.

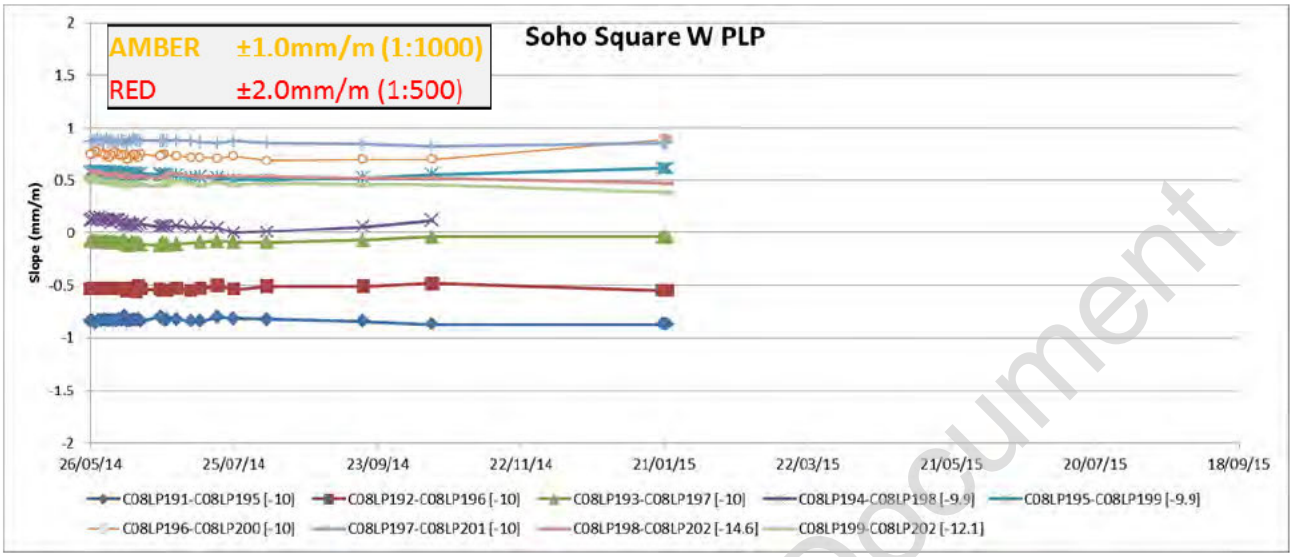
- Slopes were less than the Amber trigger value throughout construction and up to January 2015 in Period G when the slope between C08LP063 and C08LP061 was recorded with a value of 1.01mm/m increasing marginally with a value of 1.03mm/m recorded in the final survey in September 2015.

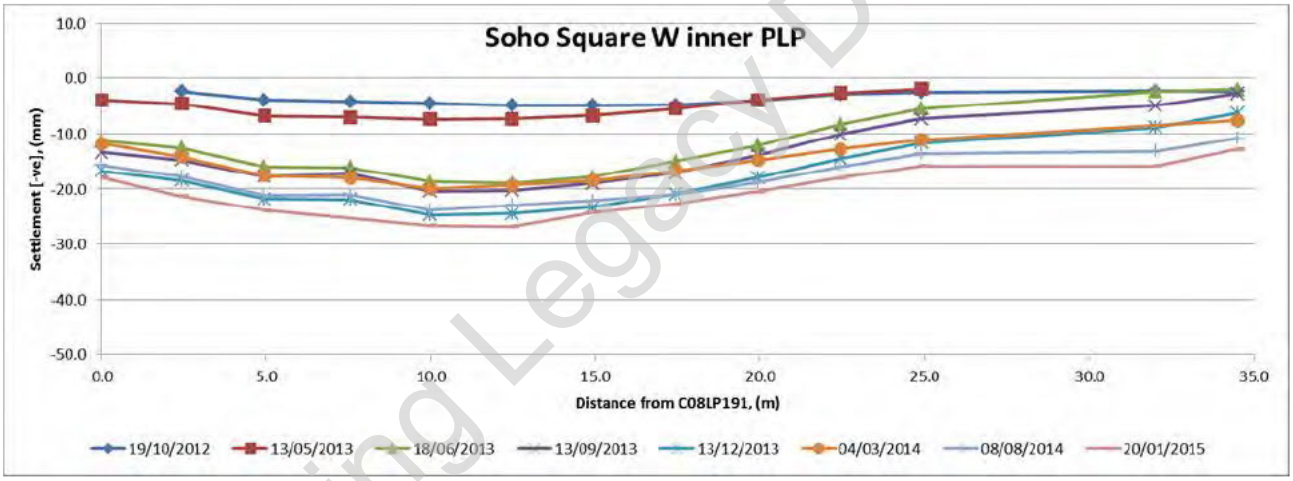
5.5. Soho Square West – inner









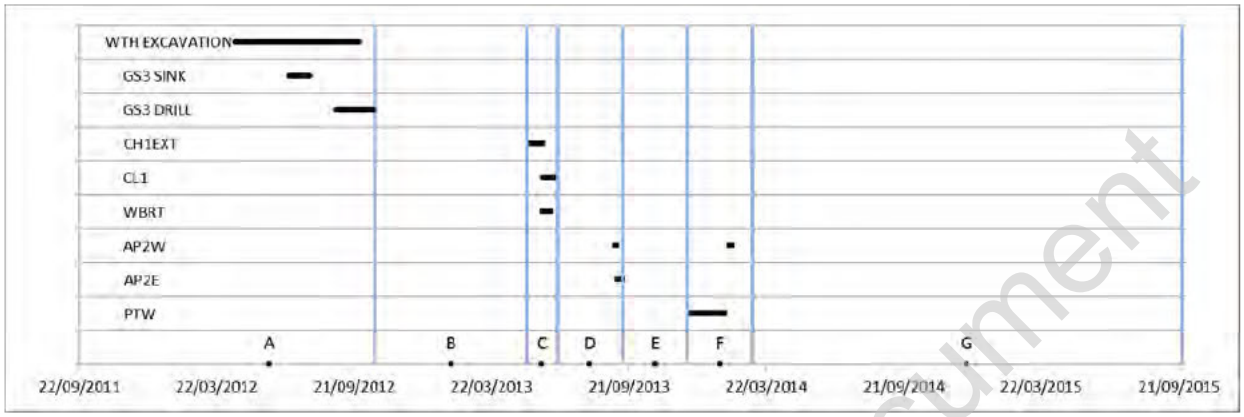


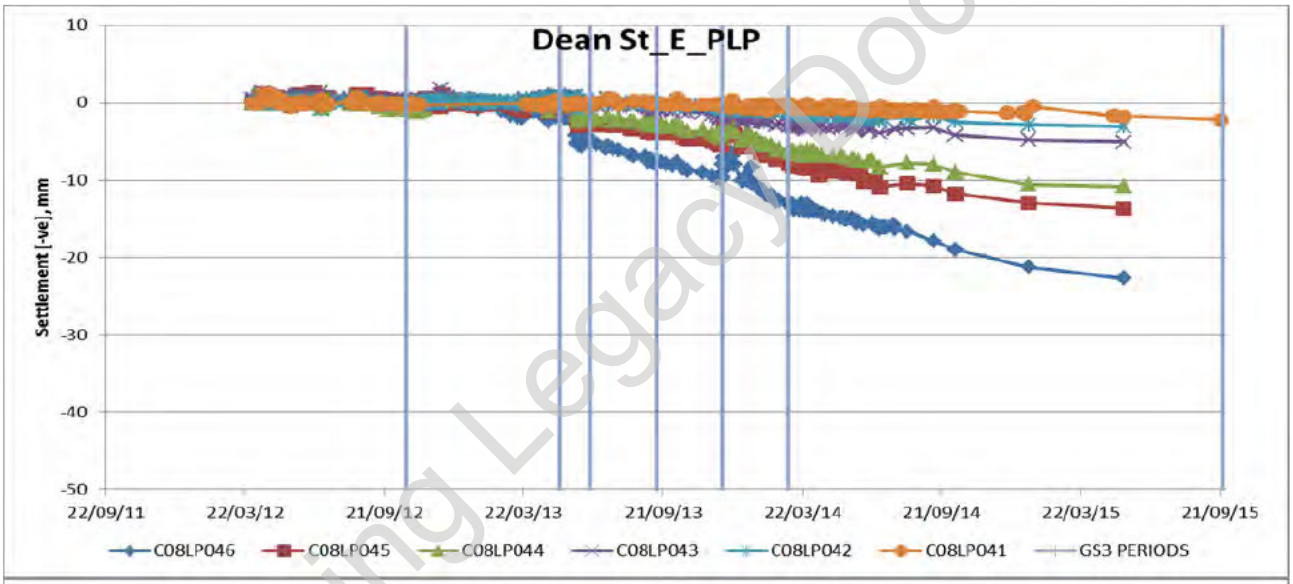
The following points are noted:

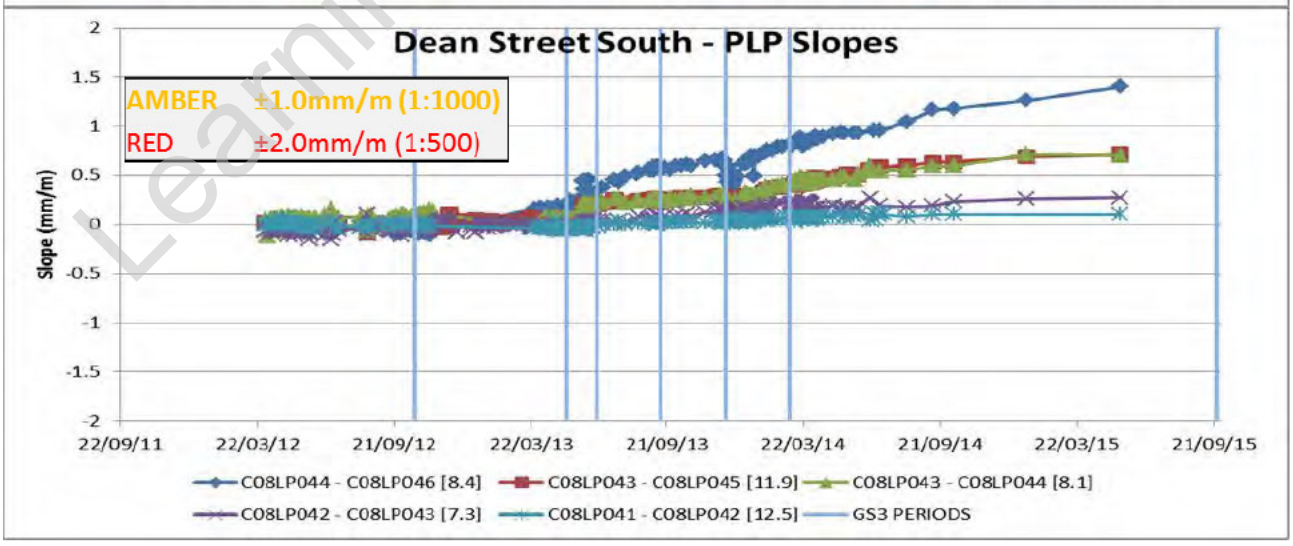
- Only part of the profile is within the TCR GS3 array (up to distance 15m): however, data from all points are presented as shown in Figure 5.1.
- The effect of pre-treatment in the adjacent GS2 area is evident early in Period B. A small uplift is evident from pre-treatment of GS3 arrays later in Period B.
- 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. The effect of a number of grout jacking episodes in Periods D and F is evident by the sharp reductions in settlement.
- The maximum settlement at the end of construction was 22m and this had increased to 27mm at the termination of monitoring. 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.

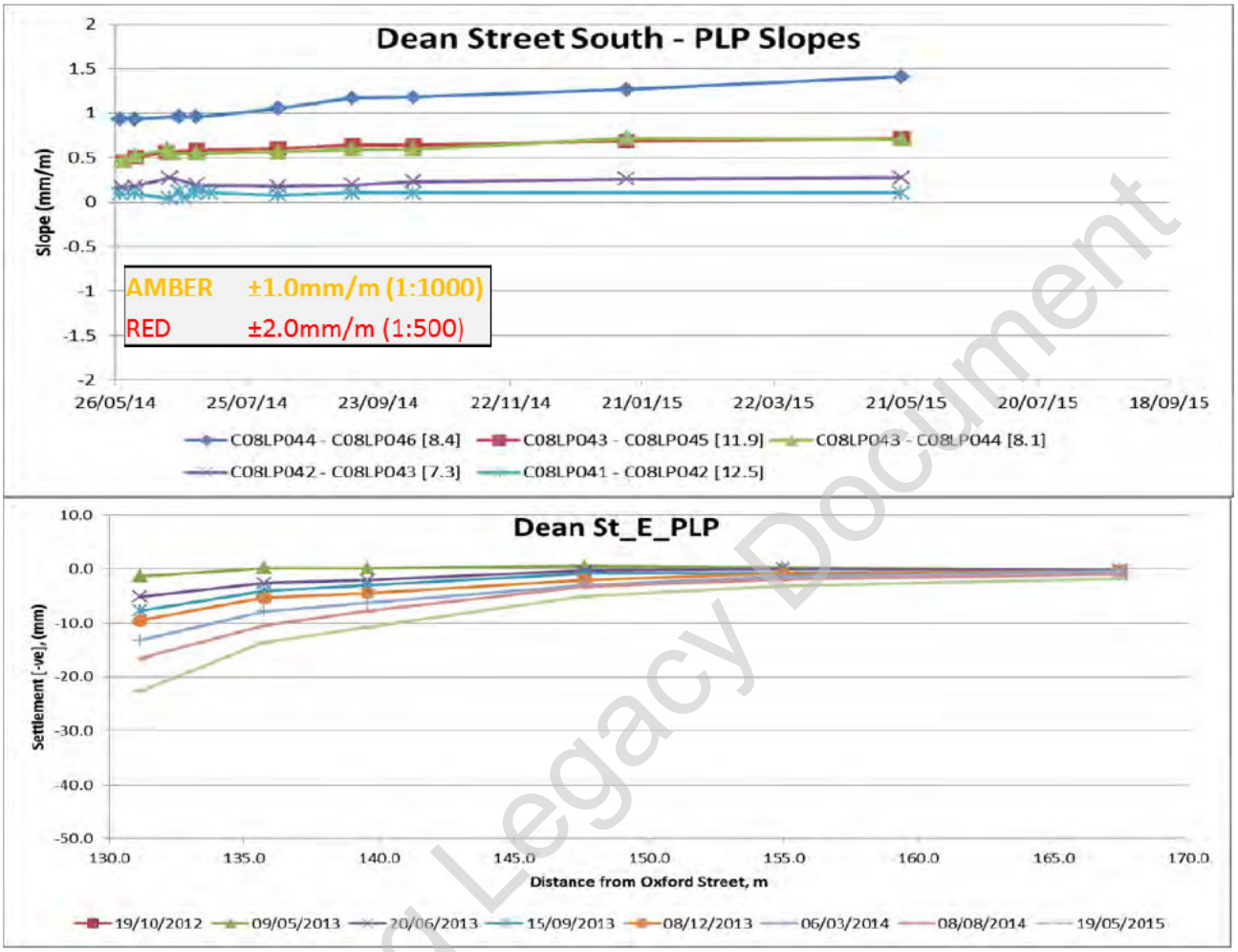
- The slope data plots show that Amber slope trigger levels were exceeded between points C08LP197 - C08LP201 and C08LP196 - C08LP200 in Period C due to construction of CL1 with no concurrent grouting. The slopes were reduced to below the Amber trigger value by grout jacking episodes in Period F.
- Further Amber triggers occurred temporarily in Period F as a result of the construction of PTW and the junction with AP2W (the latter without concurrent compensation grouting). Within the GS3 area, 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. The slopes were reduced to below the Amber trigger value by grout jacking episodes.

5.6. Dean Street – East









The following points are noted:

- The Dean Street PLP profile to the south of Carlisle Street is within the plan extent of the GS3 arrays up to distance 145m (from Oxford Street).
- Settlement was minor in Periods A and B and increased to a maximum of 5mm in Period C, associated with CH1Ext, CL1 and WBRT excavation. No concurrent grouting was undertaken with CL1 and WBRT. No significant increase in settlement is evident as a result of the AP2 tunnels constructed in Period D. Settlement increased gradually to about 10mm on C08LP046 at the corner of Carlisle Street at the end of Period E.
- The effect of concurrent compensation grouting with PTW is evident at the start of Period F but with negligible net change in movement. Post construction settlement is shown in the remainder of Period F extending into Period G. The final measured settlement at the termination of monitoring was 23mm.
- The rate of settlement in Period G was approximately constant up until July 2014 when an increased rate is apparent before a further gradual reduction in rate. The effect is most apparent on C08LP046 which is located on the corner of Carlisle Street, a position which is more susceptible to damage.
- Slopes were less than the Amber trigger value throughout construction and up to July 2014 in Period G when a stabilising trend was evident. The increased rate of settlement after this time resulted in an

Amber slope trigger breach between C08LP046 and C08LP044. The slope continued to increase up until the cessation of monitoring in May 2015.

6. DISCUSSION

The preceding presentation of settlement monitoring data shows that the Compensation Grouting Performance Criteria (CGPC) on slope has been exceeded in a number of locations within the footprint of the arrays installed from Grout Shaft 3. There was only one Amber trigger breach on building facades which was corrected by grout jacking. Of the six Amber slope triggers on PLP, four also occurred during construction and were corrected by grout jacking. The other two PLP slope triggers occurred months after the end of construction and consequently there were no slope triggers extant at the end of construction. It can be directly concluded that there were no deflection ratio triggers exceeded.

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 GS3 would be required based on an abridged version of this report submitted in August 2014 (C300-CCM-08749): Grout Shaft 3 was subsequently decommissioned.

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 GS3 area was terminated under C300-PMI-01858, and consequently this report comprises a Final and Close Out report.

A separate report is provided for the ATS network (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 after 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.

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 that 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:

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

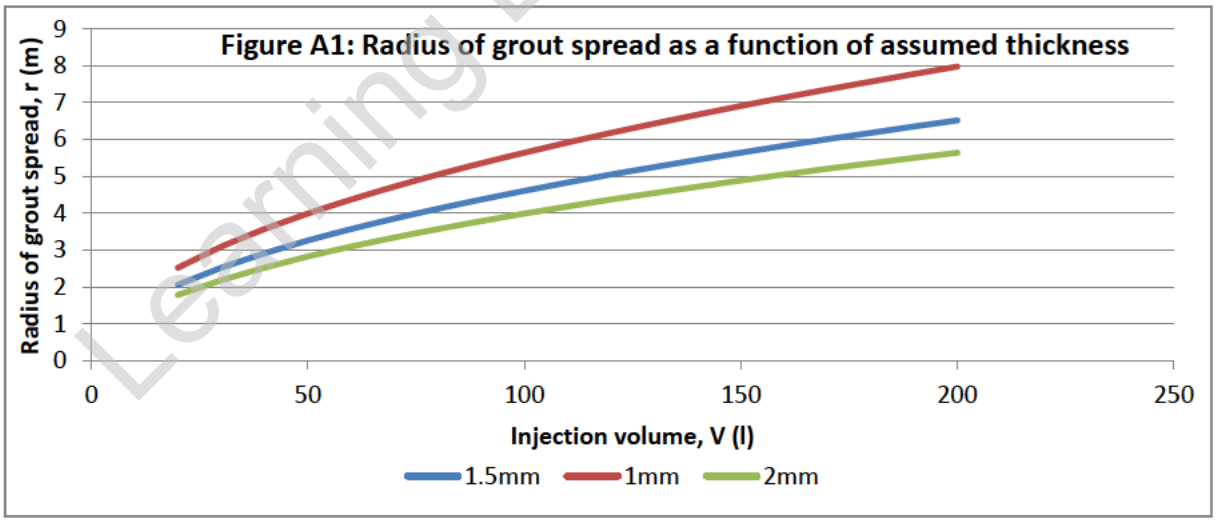


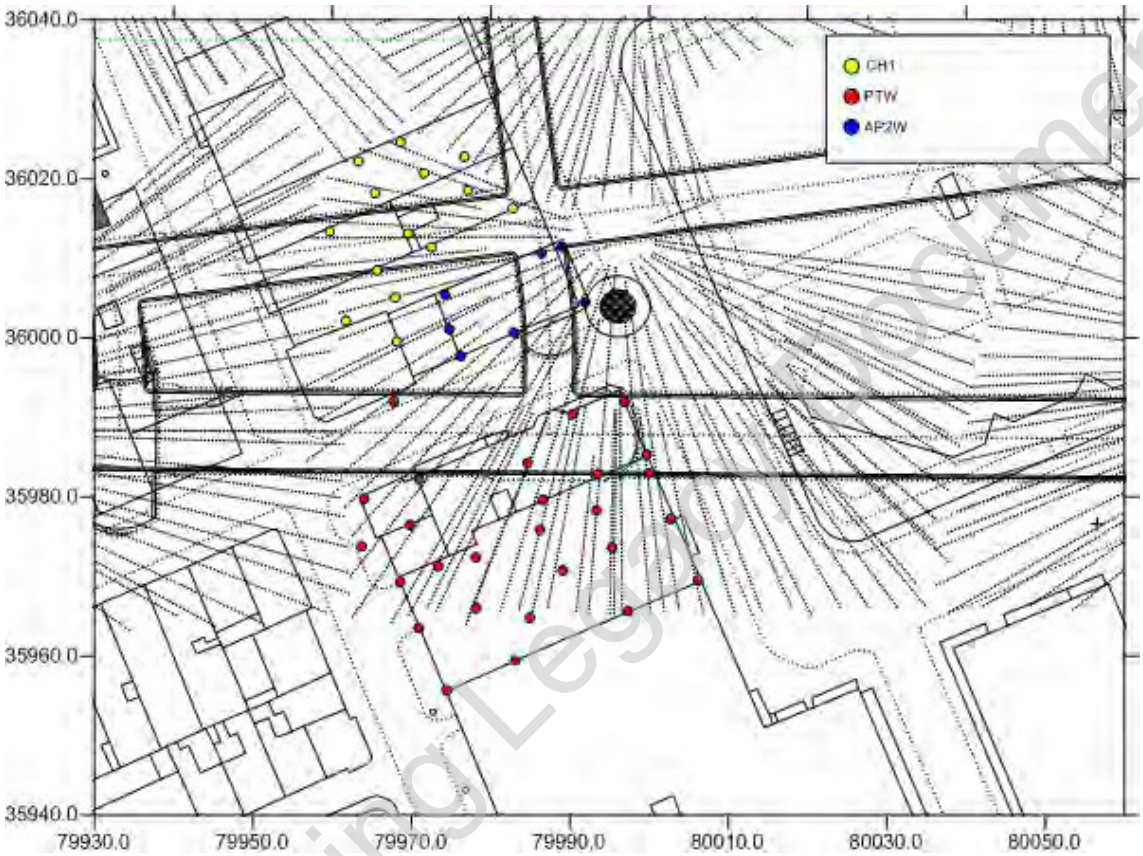
Figure A1: Radius of grout spread as a function of assumed thickness

Observation 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.

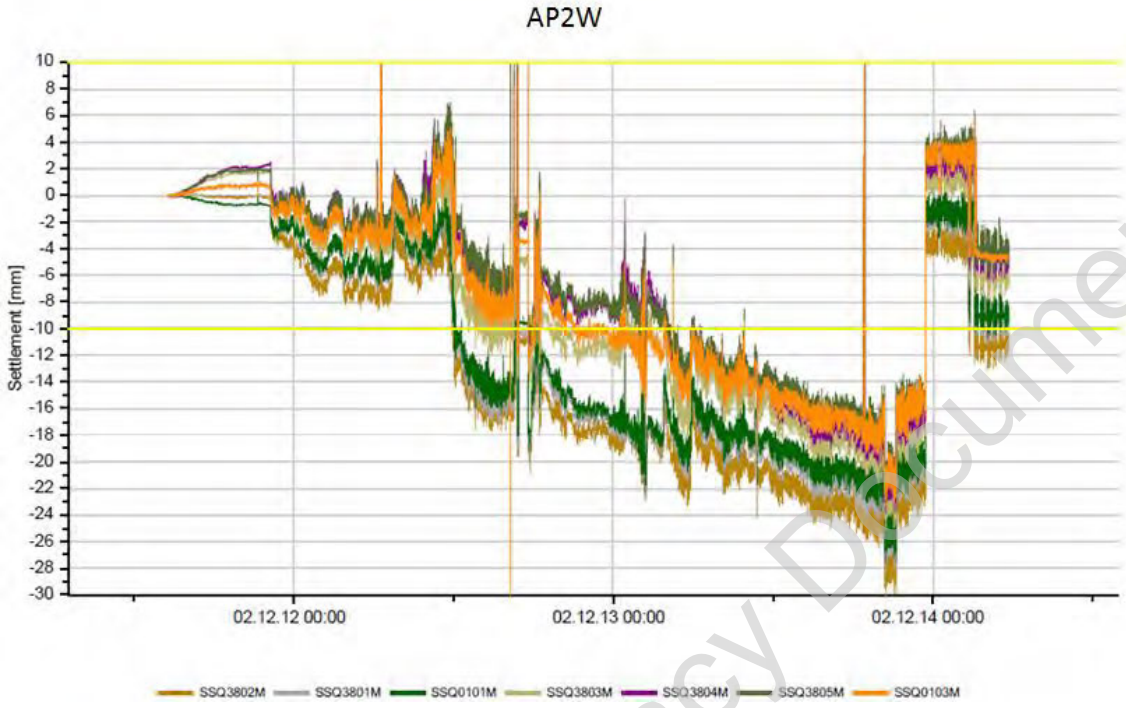
The contribution of each injection within a specified data set are summed at each node within a grid. This grid file is then contoured within Surfer.

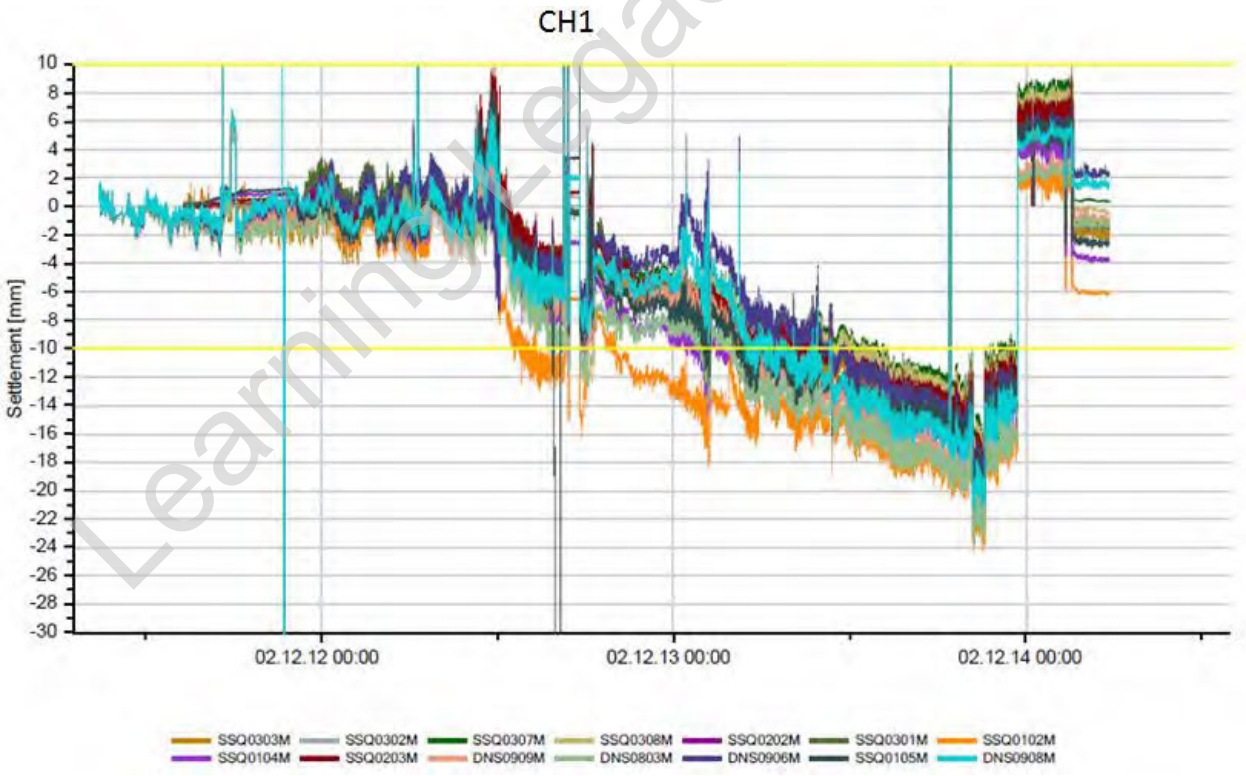
Appendix B

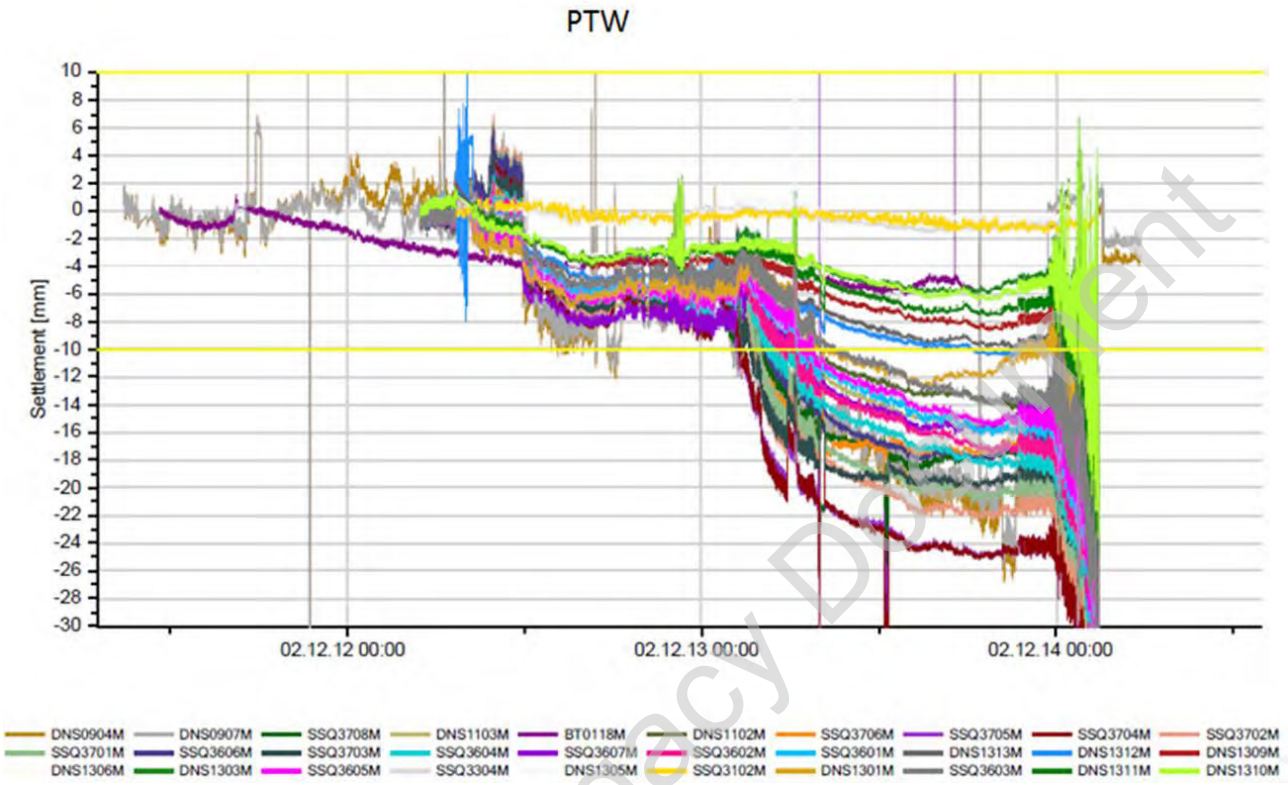
Example plots of HLC and Horizontal SAA data

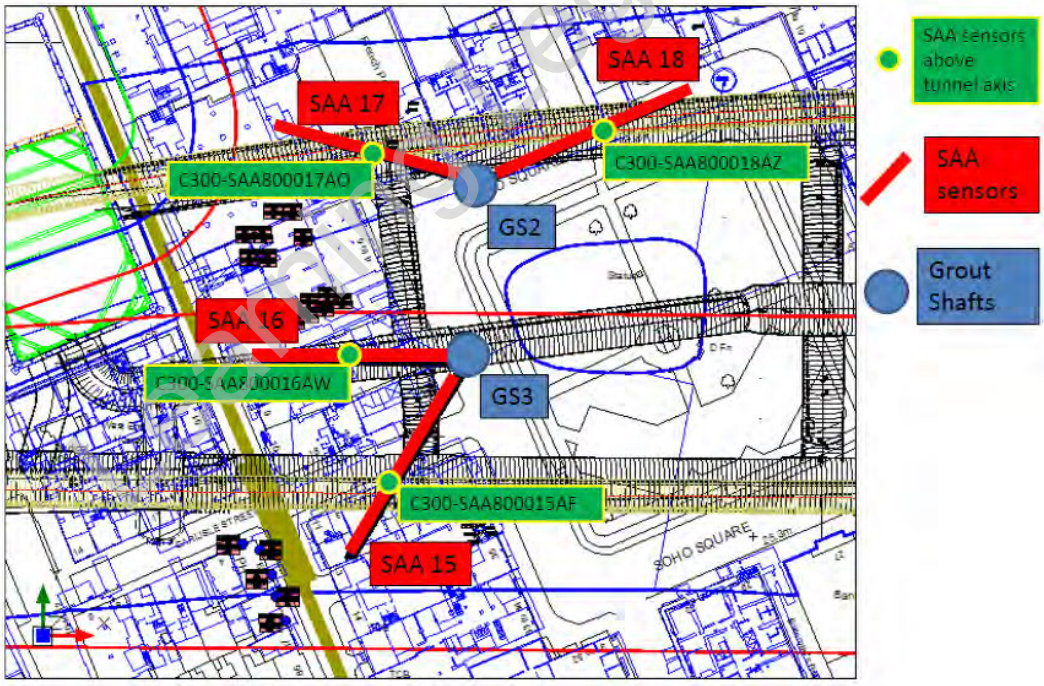


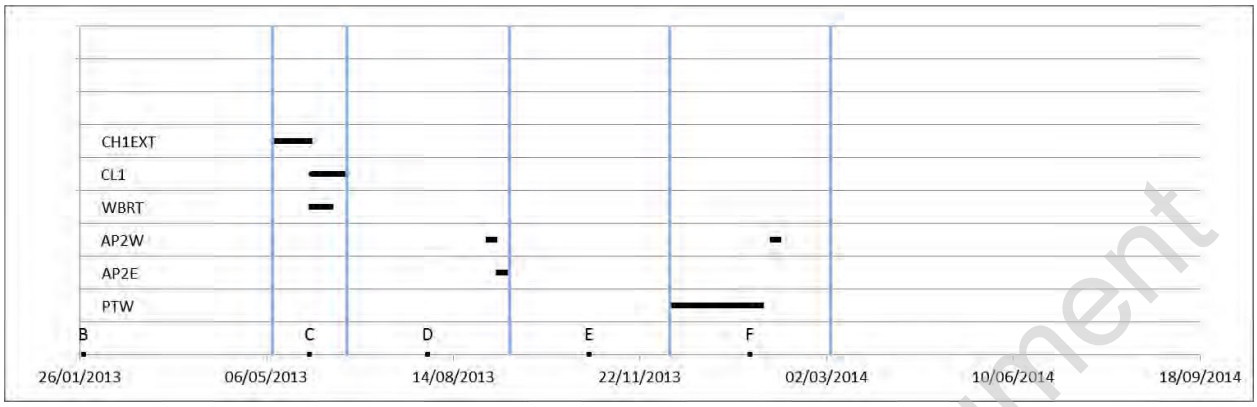
HLC were primarily used for control of compensation grouting giving data at 15 minute intervals. The system was left operational after the completion of the tunnelling to provide information on post –construction movements. Scatter observed in HLC data during December 2014 and February 2015 was due to 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.

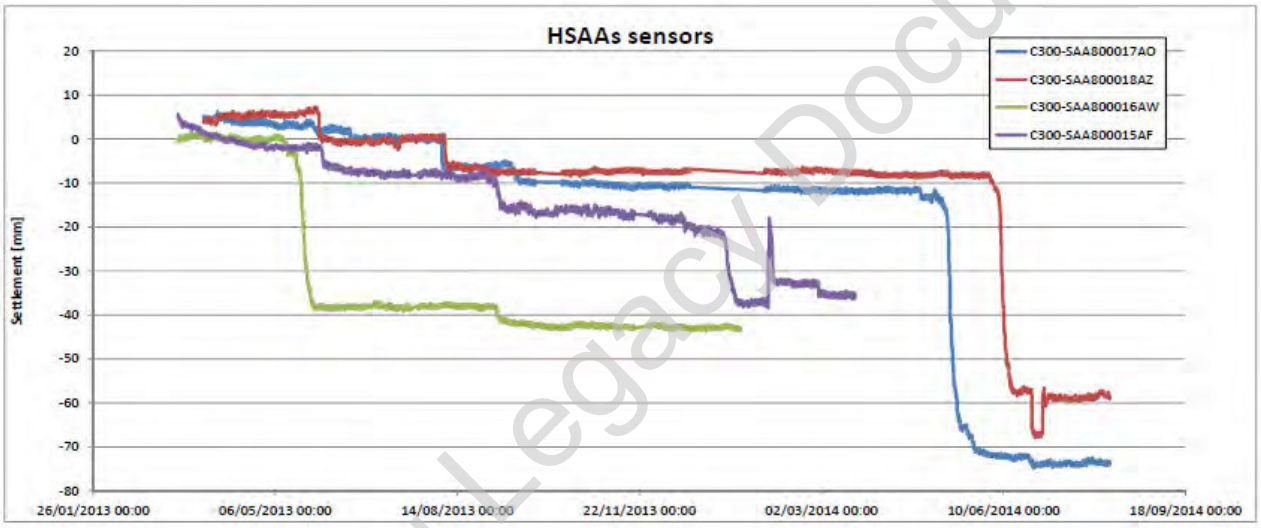












Scatter observed in HLC data during December 2014 and February 2015 was due to lack of maintenance as monitoring ceased with completion of excavation works by February 2014.

Appendix C

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