C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - BOS GS1

CRL Document No. **C300-BFK-C4-RGN-CRT00_ST005-51211**

Contract MDL reference: C14.020

1. Contractor Document Submittal History

Revision	Date	Prepared by	Checked by	Approved by	Reason for issue
3.0	02/02/17	[redacted]	[redacted]	[redacted]	For acceptance

2a. Stakeholder Review Required? YES ☐ NO ☒

Stakeholder submission required: LU ☐ RfL ☐ NR ☐ LO ☐ DLR ☐ Other: _____

Purpose of submission: For no objection ☐ For information ☐

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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☐	[redacted]	Received fo[redacted]ed

Reviewed/Ac[redacted] Print Name[redacted] Position: [redacted] Date: 30/1/17

by: (signatur[redacted]

Acceptance [redacted] the designer/supplier from full compliance with their contractual [redacted] constitute *Crossrail* approval of design, details, calculations, analyses, test methods or materials developed or selected by the designer/supplier.

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 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 1

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 (SCoGM, 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 Bond Street Station Grout Shaft 1 were completed by June 2015. An abridged version of this report was issued in July 2015 (C300-CCM-10766), about 1 month 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 1 at Bond Street Station and includes manual monitoring up to October 2015 when the manual monitoring within the GS1 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. A separate close out report is provided for the ATS prisms (C300-BFK-C4-RGN-CRT00_ST005-51208).

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

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

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

- Updated as-built record and status for all instrumentation

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 separate “close out” report is not required. Example plots of HLC data are provided in Appendix B. Other instrumentation within the Grout Shaft 1 area comprises:

- Crackmeters - TA Centre, 56 Davies Street
- Piezometers – Around WTH to monitor recovery following cessation of de-watering by C411

Data from these instruments is also included in Appendix B.

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

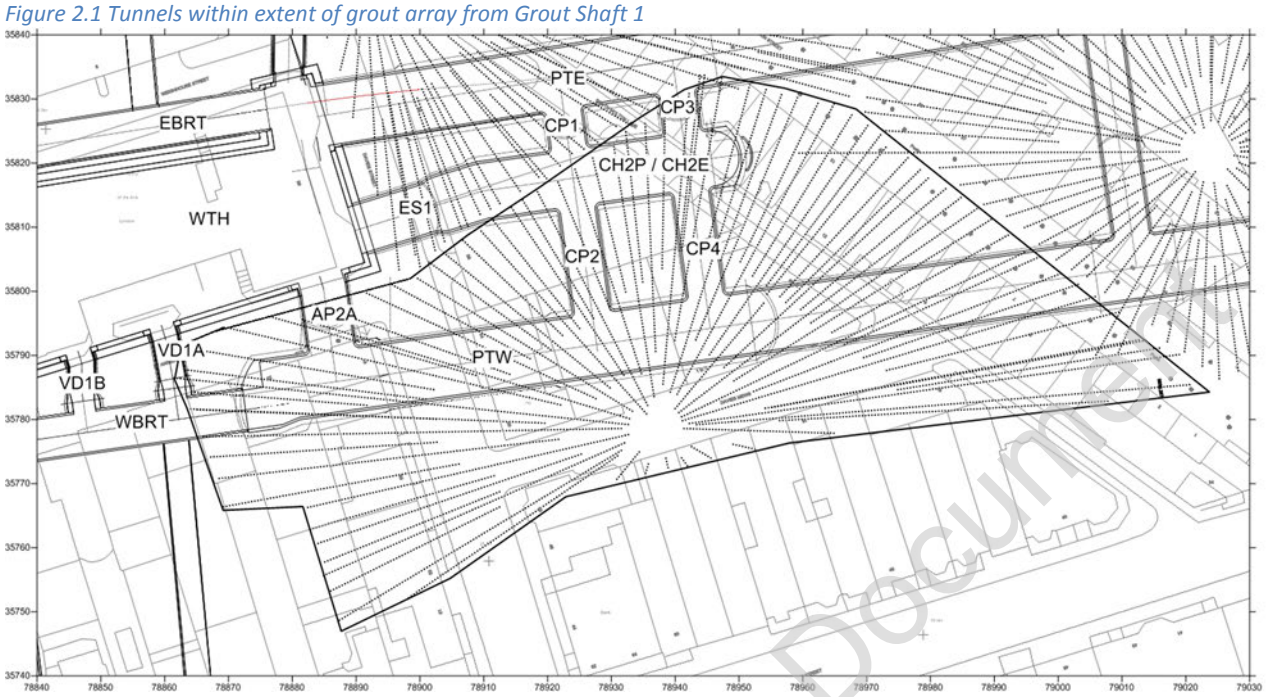
2.1. Tunnels

Table 2.1 and Figure 2.1 show the tunnel construction works undertaken within the footprint of the compensation grouting arrays installed from Grout Shaft 1 at Bond Street Station. Tunnel excavation commenced with the Westbound TBM (WBRT) in March 2013 and was completed with the excavation of the cross passage junctions from CH2 in June2015. To facilitate comparison of monitoring data with construction activities 7 periods (A to G) have been assigned. Tunnelling was completed in 4 of these periods (B, D, E & F) as shown in Table 2.1. The main construction activities in each period are summarised in Table 2.2.

Table 2.1 Progress of C300/C410 tunnelling works in BOS GS1 area.

	TUNNEL	ABB.	START DATE	NOTES	END DATE
Period B	Westbound Running Tunnel	WBRT	20/03/2013		02/04/2013
	Eastbound Running Tunnel	EBRT	17/05/2013		08/06/2013
Period D	Platform Tunnel Westbound (Enlargement)	PTW (West)	21/01/2014		19/04/2014
	Access Passage 2A	AP2A	26/03/2014		09/04/2014
	Vent Duct 1A	VD1A	28/03/2014		02/04/2014
	Vent Duct 1B	VD1B	26/04/2015		05/05/2014
Period E	Platform Tunnel Eastbound Enlargement (west)	PTE (west)	11/06/2014 10/07/2014		18/06/2014 27/07/2014
	Cross Passage 1	CP1	08/09/2014	~4m length excavated from PTE	10/09/2014
	Cross Passage 2	CP2	15/09/2014	~4m length excavated from PTW	17/09/2014
	Cross Passage 3	CP3	10/09/2014	~4m length excavated from PTE	12/09/2014
	Cross Passage 4	CP4	12/09/2014	~4m length excavated from PTW	14/09/2014
Period F	Escalator tunnel 1	ES1	04/02/2015		20/02/2015
	Lower Concourse Tunnel 2 Pilot	CH2P	27/02/2015		13/03/2015
	Lower Concourse Tunnel 2 Enlargement	CH2E	15/03/15		14/05/15
	Cross Passage 1 (Junction)	CP1	26/05/2015	To completion from CH2	27/05/2015
	Cross Passage 2 (Junction)	CP2	28/05/2015	To completion from CH2	03/06/2015
	Cross Passage 3 (Junction)	CP3	11/06/2015	To completion from CH2	12/06/2015
	Cross Passage 4 (Junction)	CP4	07/06/2015	To completion from CH2	11/06/2015

Figure 2.1 Tunnels within extent of grout array from Grout Shaft 1



2.2. Other construction works

Works by Others prior to the start of tunnelling included:

- Sinking of Grout Shaft 1
- Demolition for WTH
- Preparatory works for WTH (sheet piling, obstruction removal etc.)
- Diaphragm walling and Piling for WTH
- Excavation of WTH

Works by BFK prior to the commencement of tunnelling in GS1 area included:

- Drilling for installation of TaMs
- Pre-treatment grouting
- Pre-TBM grout jacking

Works by Others during tunnelling with the potential to generate ground movements comprised:

- Excavation of WTH: Handed over to BFK in November 2014 (Period E)
- De-watering of Lambeth Group Sand Channel (January to September 2013)

2.3. Compensation Grouting

The volume of grout injected from BOS GS1 is plotted against time on Figure 2.2 together with a plot of when each of the tunnels was constructed. Figure 2.2 shows that pre-treatment comprised approximately 70m^3 injected prior to tunnelling, concurrent grouting approximately 310m^3 and grout jacking almost 110m^3. Concurrent grouting was undertaken with all tunnels except the Cross Passages 1 to 4, VD1a, AP2A, WBRT, EBRT and ES1. A VE proposal was implemented to avoid any delays to the running tunnel drive which allowed grouting to be undertaken pre- and post- tunnelling (C300-PMI-00434) – the volume of grout associated with this is included under grout jacking. CP1 to CP4, VD1a, and AP2A are short length tunnels and the extent of the exclusion zones over the tunnel face (and adjacent to the WTH), as defined in the SCoGM, rendered concurrent grouting impractical. VD1b and VD1c are outside the plan extent of the GS1 arrays. The crown

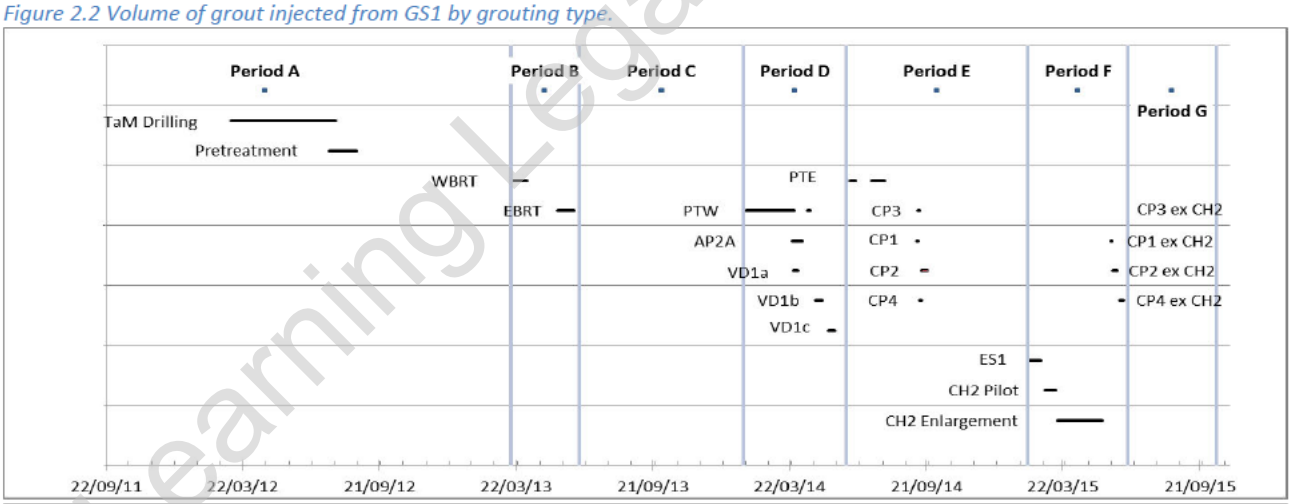
elevation of the inclined ES1 tunnel was too high to allow concurrent grouting to be undertaken. In additional a pipe arch was installed which was at the same elevation as the compensation grouting TaMs.

Figures 2.3 to 2.5 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 GS1 is shown in Figure 2.6. 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. The exclusion zone adjacent to the WTH and a similar 3m exclusion zone around the grout shaft are clearly evident in the contours.

Table 2.2 Construction Periods for BFK works in BOS GS1 area.

Periods	Start Date	End Dates	Main Works
A	07/03/12	15/03/13	Tam drilling, Pre-treatment
B	15/03/13	15/06/13	WBRT, EBRT, Grout Jacking
C	15/06/13	20/01/14	No tunnelling, Grout Jacking
D	20/01/14	06/06/14	PTW, AP2A, VD1a (VD1b, VD1c – outside the grouting zone), Concurrent Grouting, Grout Jacking
E	06/06/14	04/02/15	PTE, CP1, CP2, CP3, CP4, Concurrent Grouting, Grout Jacking
F	04/02/15	17/06/15	ES1, CH2P, CH2E, CP1-4 junctions, Concurrent Grouting, Grout Jacking
G	17/06/15	13/10/15	Post construction

Figure 2.2 Volume of grout injected from GS1 by grouting type.



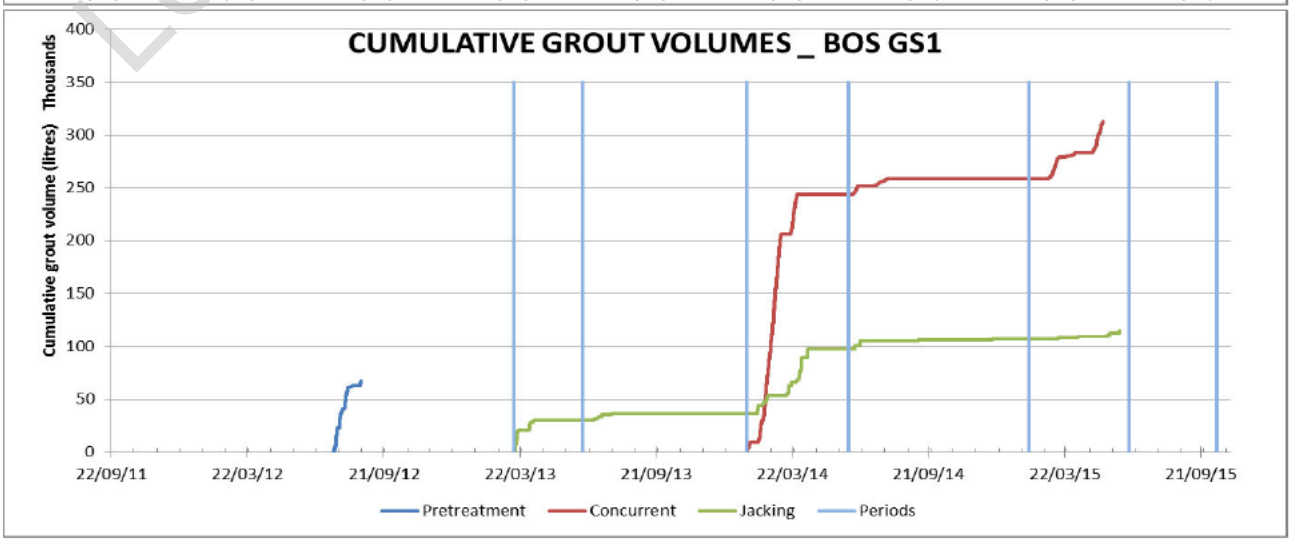


Figure 2.3 Distribution of grout injected from GS1: Pretreatment grouting. Grout Intensity (l/m2).

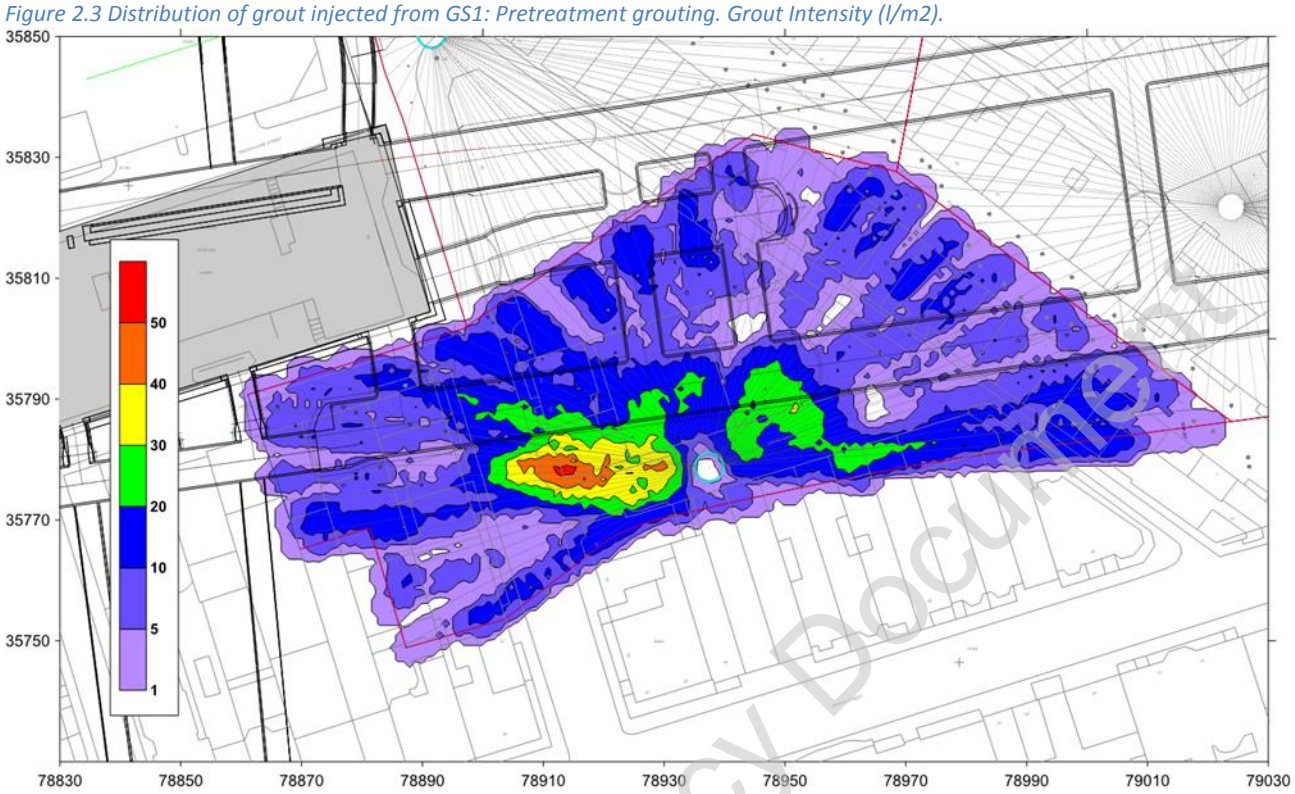


Figure 2.4 Distribution of grout injected from GS1: Concurrent grouting. Grout Intensity (l/m^2).

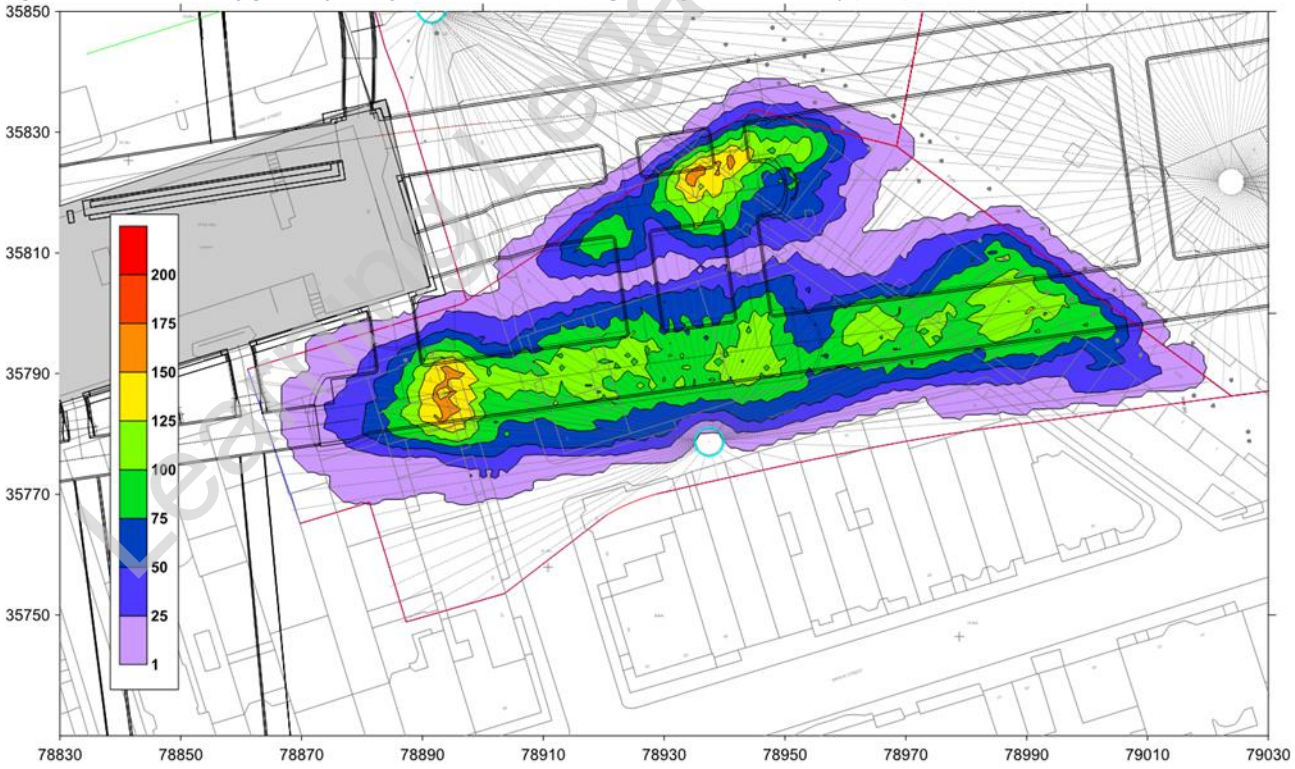


Figure 2.5 Distribution of grout injected from GS1: Jack grouting. Grout Intensity (l/m^2).

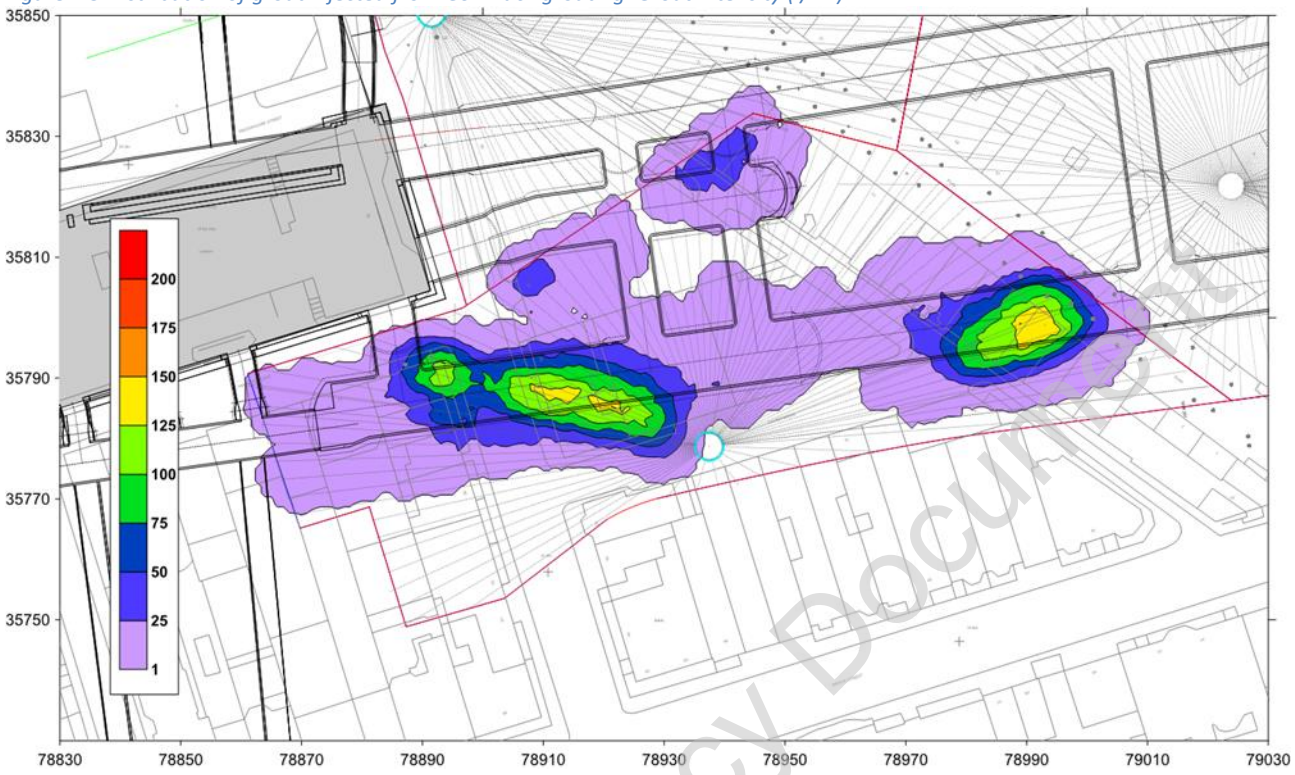
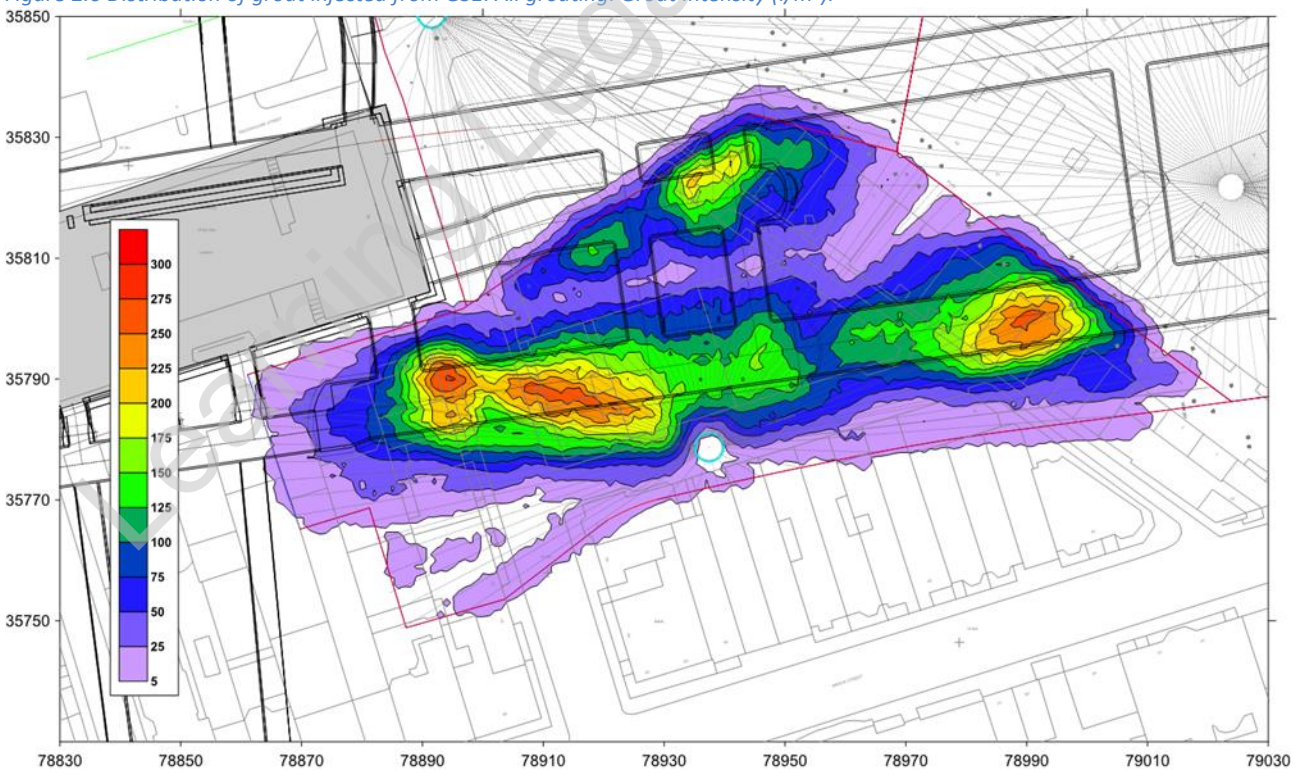


Figure 2.6 Distribution of grout injected from GS1: All grouting. Grout Intensity (l/m^2).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. SETTLEMENT OVERVIEW

Settlement contours have been generated showing the total settlement at the end of each Construction Period and the change in settlement during the Period. The latter is compared to the calculated greenfield volume loss settlement contour generated using the specified maximum values. The effect of the WTH excavation has been calculated using simple empirical methods.

Contours of total predicted greenfield short term settlement (supplied on C122) are shown in Figure 3.1.1. The measured settlement at the end of excavation in June 2015, including consolidation settlement during the period of construction in the GS1 area, is shown in Figure 3.1.2.

The following points are noted:

- Settlements are generally less than or similar to the predicted values, notwithstanding that the observed movements include a significant proportion of consolidation settlement over the 3 ½ year construction period.
- The most obvious differences between the greenfield predictions and the observations are:
    - The settlements in the GS1 area are generally slightly less than predicted (80mm maximum contour cf. 90mm)
    - There is an area in the east of the GS1 array, between the platform tunnels, where the measured settlement is greater than the volume loss values: The volume loss contour indicates less than 20mm whereas the actual settlement recorded was greater than 30mm.
    - Over the platform tunnel (PTW) the recorded magnitude of settlement is similar to that predicted (40 to 50mm), slightly less except at the eastern end of the GS1 area.
    - The extent of the zone of settlement on the southern boundary of GS1 is greater than predicted with 20mm settlement recorded at the 10mm predicted contour and 5mm to 10mm at the 1mm predicted contour;
    - The differences described above are attributed to a large contribution from consolidation during the construction period.

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

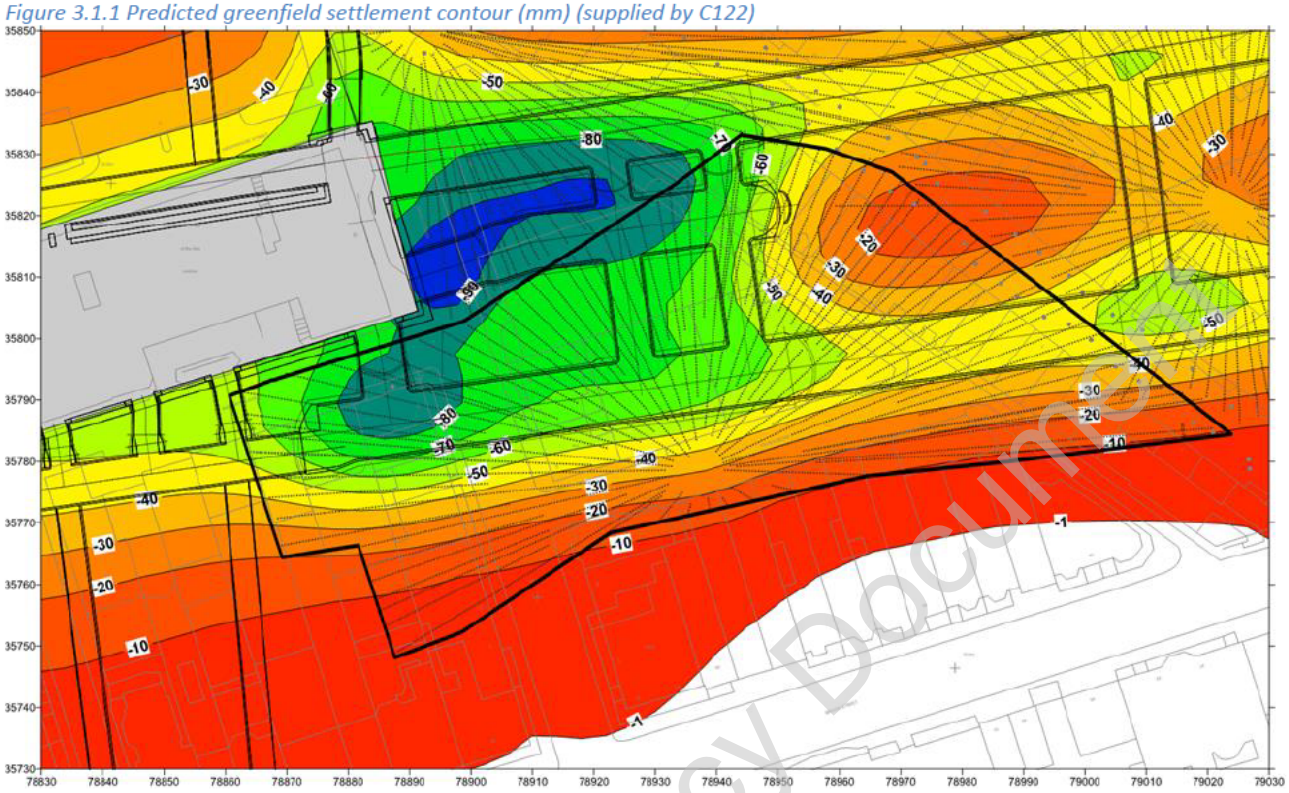
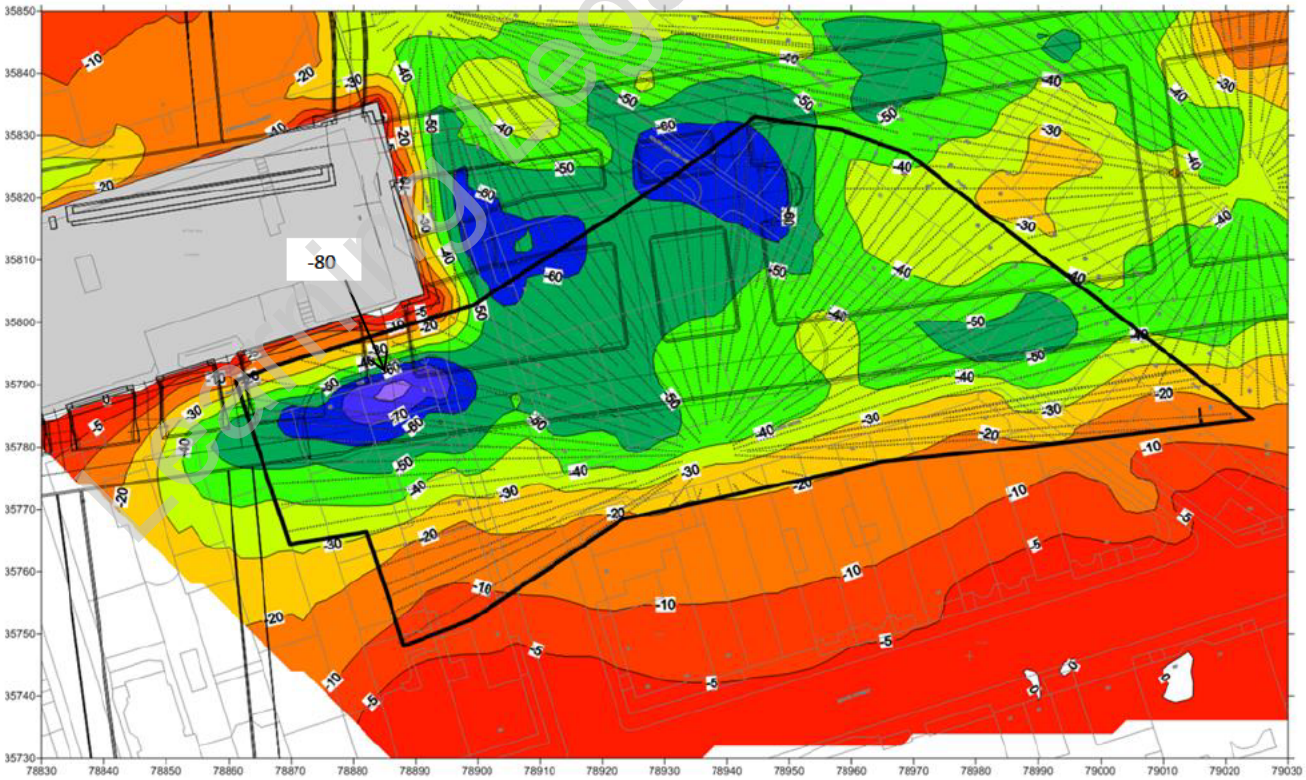


Figure 3.1.2 Observed settlement contour in June 2015 - end of Period F (mm)



In order to compare the predicted and actual movements at various stages of construction the overall monitoring period from September 2011 to October 2015 has been divided into a number of periods, based largely on tunnel excavation. The dates of each period and the associated construction activities are summarised in Table 2.2.

There were works by Others with the potential to generate ground movements, primarily C411 works at the WTH, prior to and during BFK monitoring. Since C411 works at the WTH preceded the commencement of monitoring by BFK, adjustments have been made to the monitoring data as described in report "Adjustment of BRE, PLP and Prisms in BOS area" C300-BFK-C4-RGN-CRT00_ST005-50758. The adjustments are evident in the time-settlement plots in Sections 4 and 5 where the initial settlement at the start of the data is non-zero. The WTH was constructed using a top-down sequence and consequently any ground movements associated with excavation took place slowly over an extended duration from Period A through to Period E. No particular "events" can be identified in the monitoring data and hence no specific reference to C411 works is made in the following sections.

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 – TaM drilling, Pre-treatment: 07/03/12 – 15/03/13

BFK works in Period A comprised the drilling and pre-treatment of TaMs from GS1. No calculated settlements are available for the permanent works completed in Period A.

The observed settlements (adjusted to allow for movements prior to the start of BFK monitoring) are shown on Figure 3.2.1. Pre-treatment was entirely completed in Period A and, consequently, the contours of grout intensity shown in Figure 3.2.2 are identical to those in Figure 2.3.

A maximum settlement of over 10mm was produced along the south wall of the WTH extending beyond the extent of the GS1 array. An area of over 10mm settlement is also shown adjacent to the grout shaft.

The contours of grout intensity show that, during pretreatment, effort was concentrated in the area of maximum settlement around the shaft where up to 50l/m^2 was injected to complete pre-treatment. Over the remainder of the area less than 20l/m^2 was required.

Figure 3.2.1 Period A: Total measured settlement (mm)

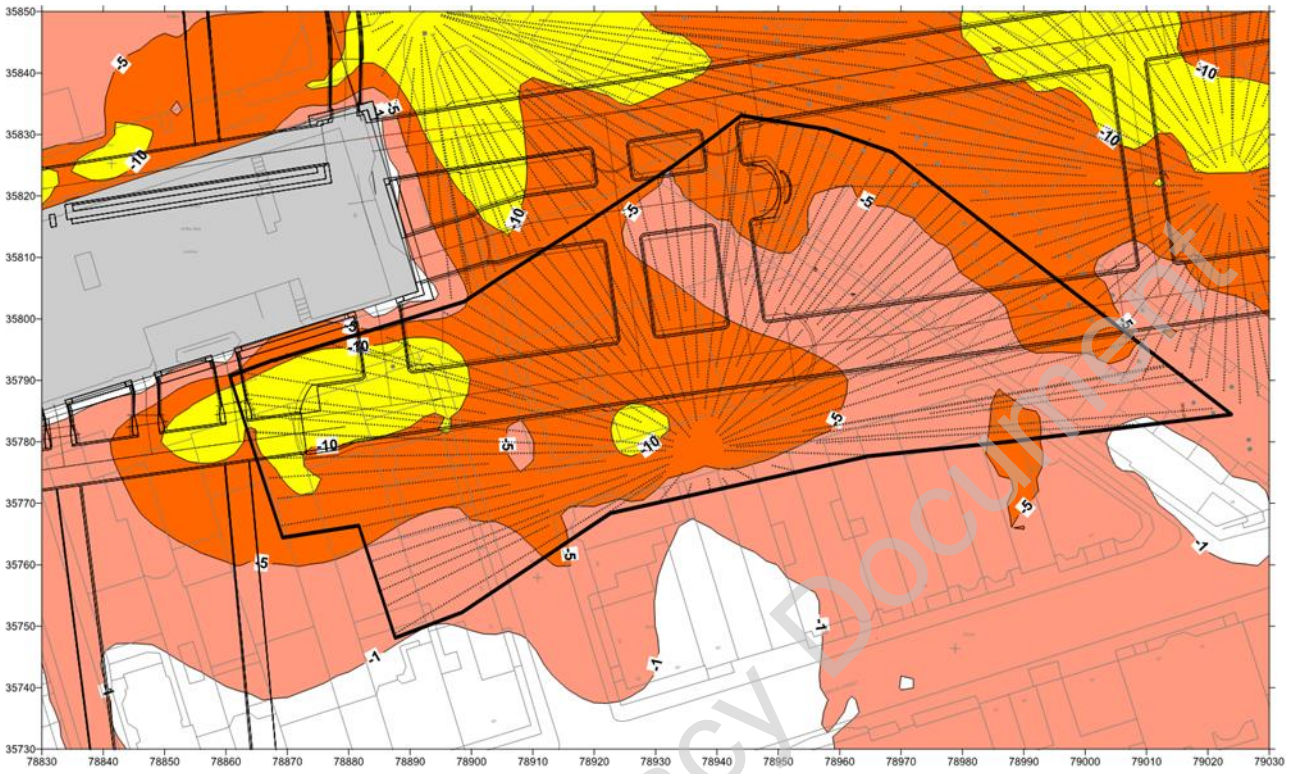
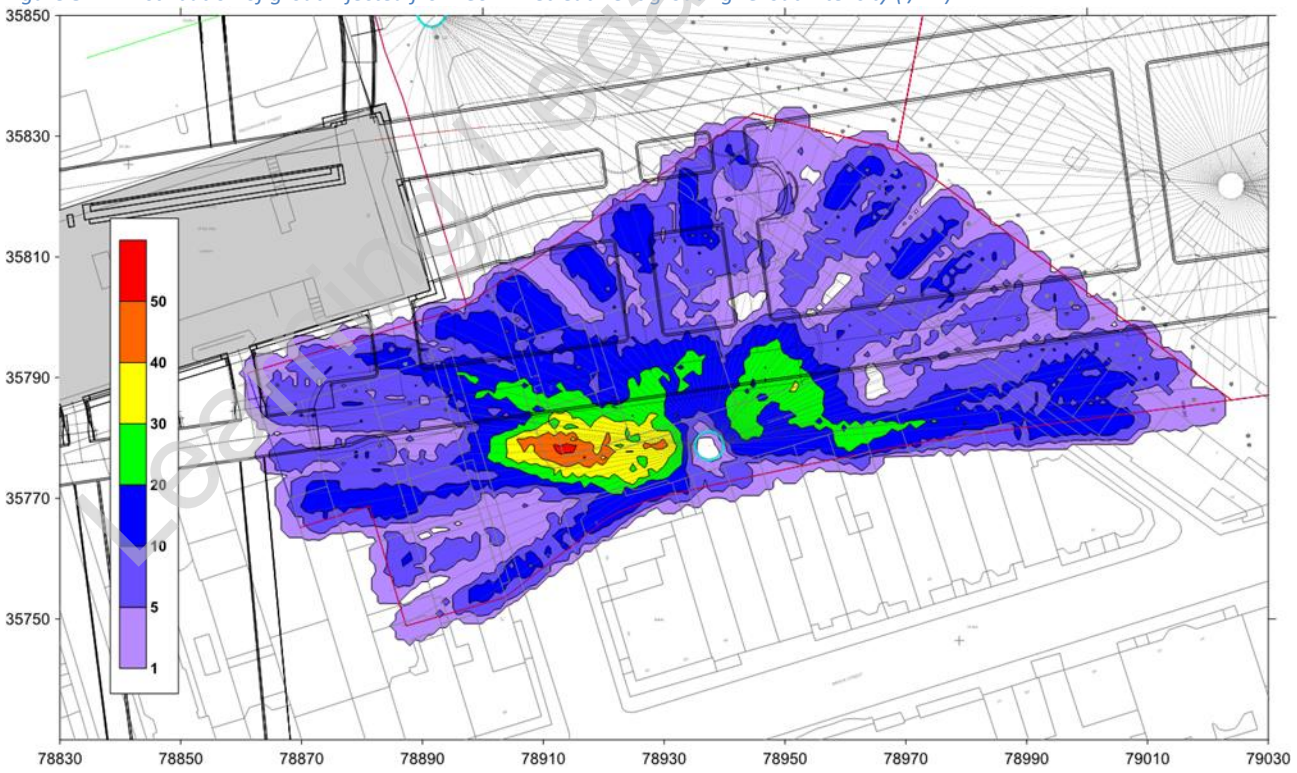


Figure 3.2.2 Distribution of grout injected from GS1: Pretreatment grouting. Grout Intensity (l/m^2).



3.3. Period B – WBRT, EBRT, Grout Jacking: 15/03/13 – 15/06/13

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

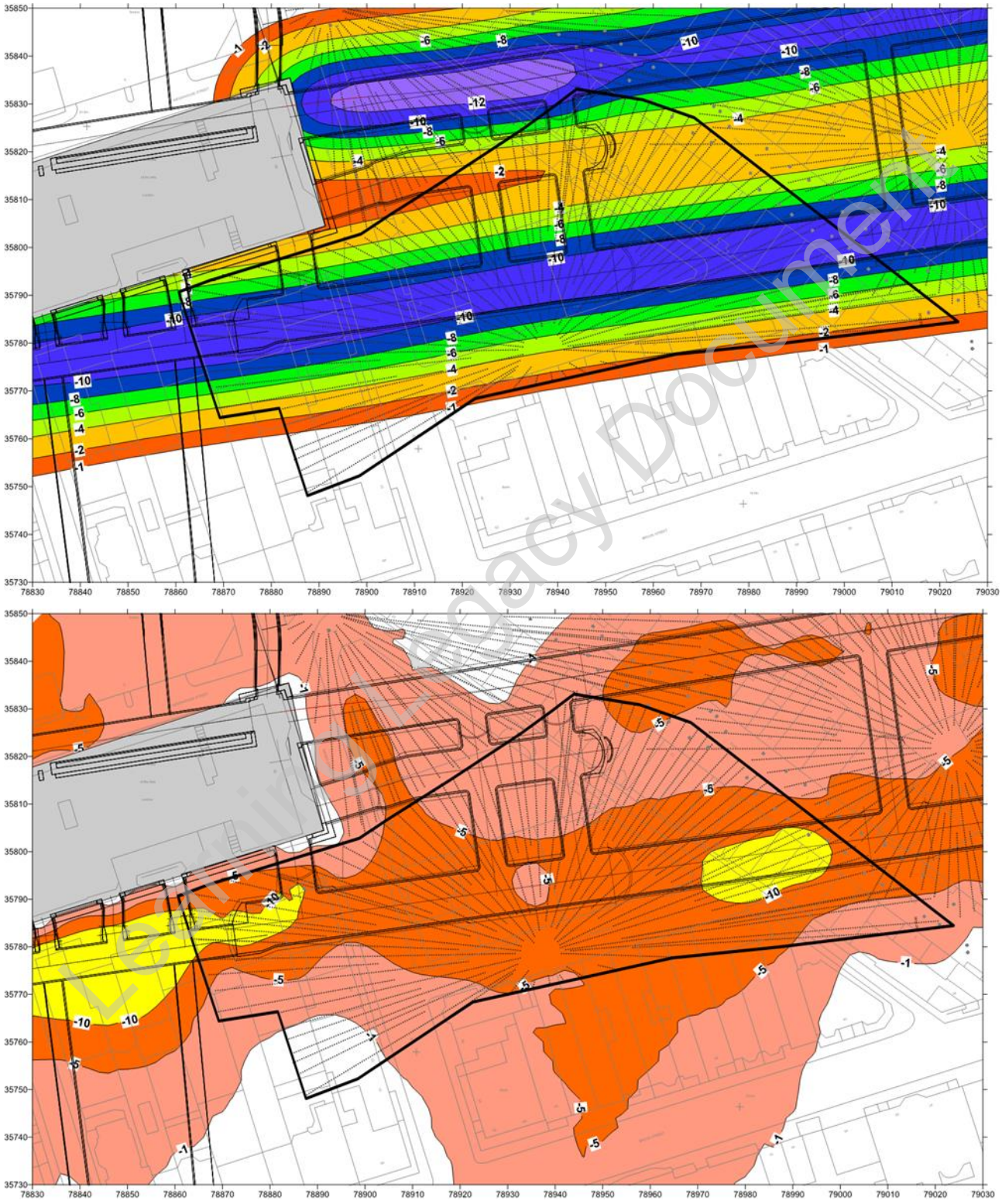


Figure 3.3.2 Period B: Total measured settlement (mm).

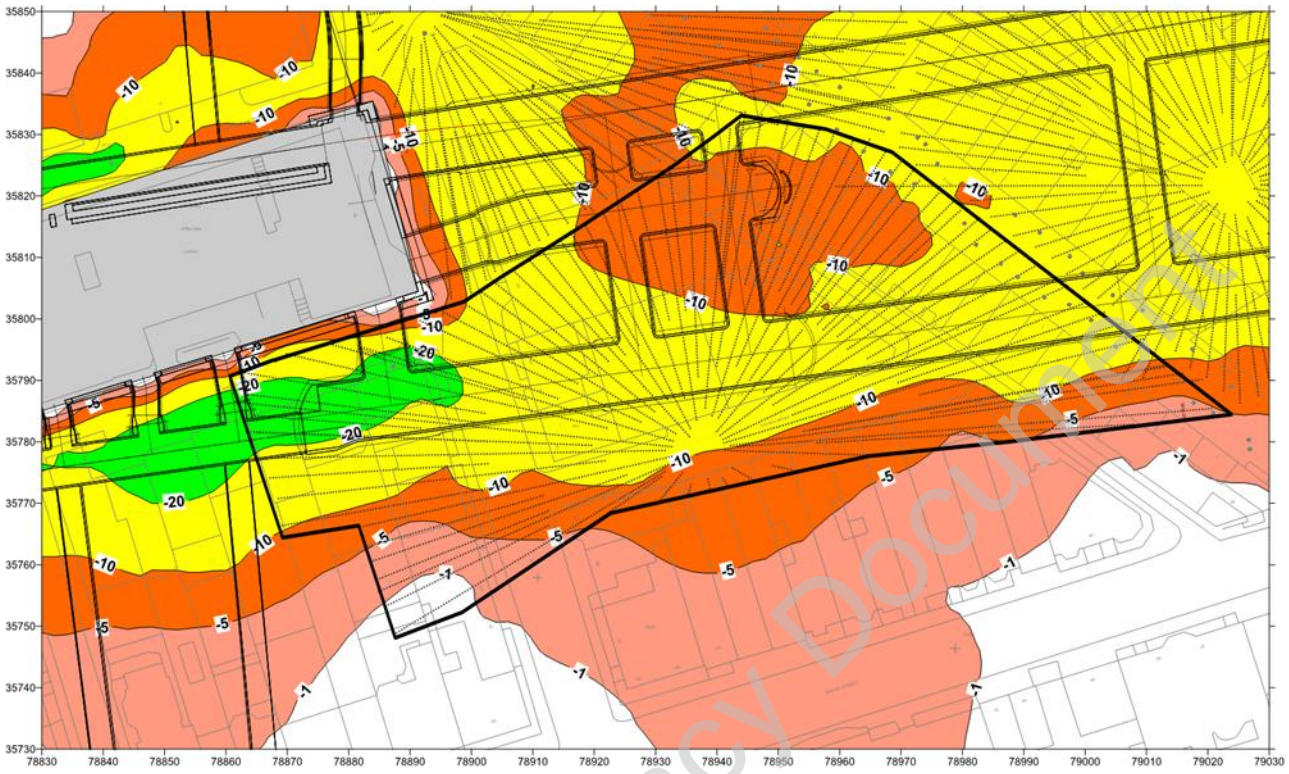


Figure 3.3.3 Period B: Distribution of grout injected from GS1: Jack grouting. Grout Intensity (l/m^2).

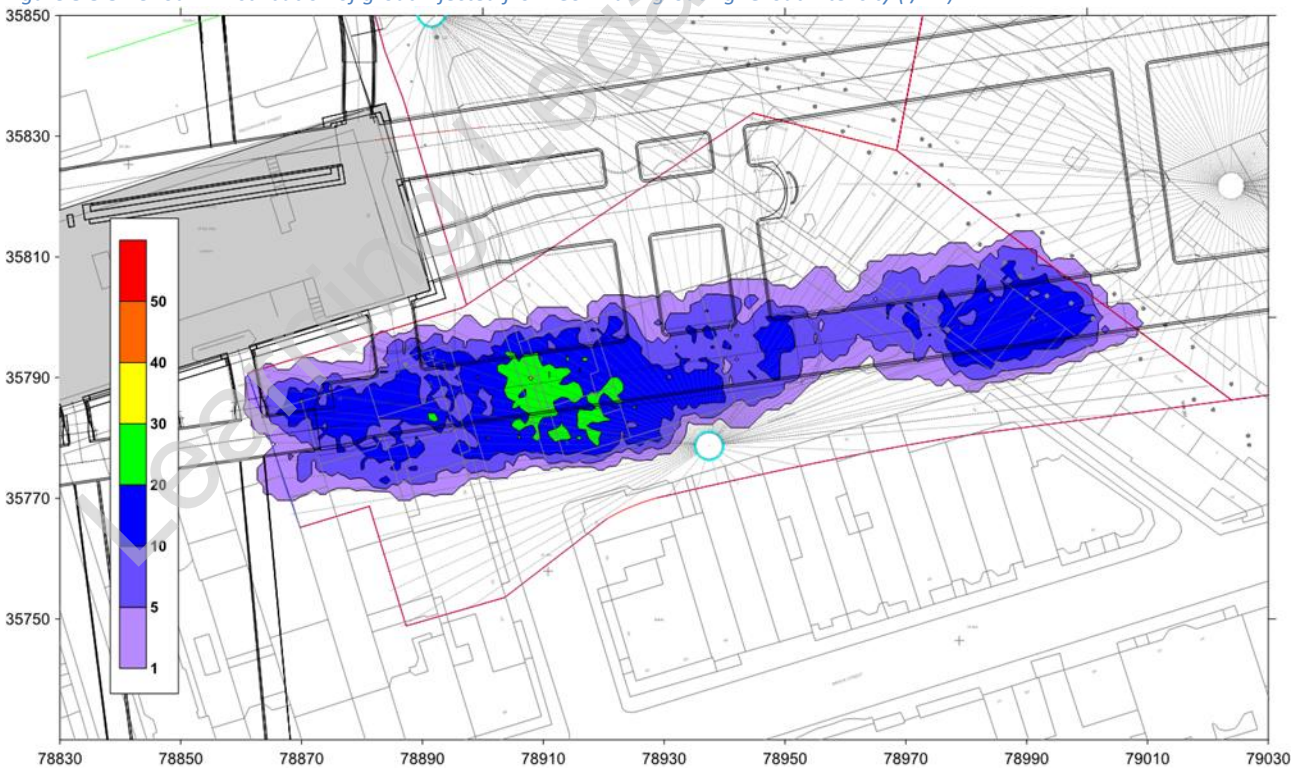


Figure 3.3.1(a) shows that just over 10mm volume loss settlement was anticipated for the WBRT drive and over 12mm for the EBRT drive. Figure 3.3.1(b) shows that maximum recorded settlement was over the WBRT where just over 10mm at the western and eastern boundaries of the GS1 arrays. Over the remainder of the WBRT in the GS1 area the settlement was about 8mm maximum. Much smaller movements were recorded from the EBRT with a maximum of just over 5mm.

At the end of Period B the cumulative movements (Figure 3.3.2) show a maximum of more than 20mm over the WBRT adjacent to the WTH decreasing to the east of the GS1 area.

No concurrent grouting was undertaken with the WBRT. Instead pre- and post- jacking was undertaken and the distribution of grout injected in shown in Figure 3.3.3. The grout volumes were varied to account for existing settlements, potential impact on the WTH and to minimise distortion on the façade of St. Alselm's Place.

3.4. Period C – No tunnelling, Grout Jacking: 15/06/13 – 20/01/14

Figure 3.4.1 Period C: Change in measured settlement (mm).

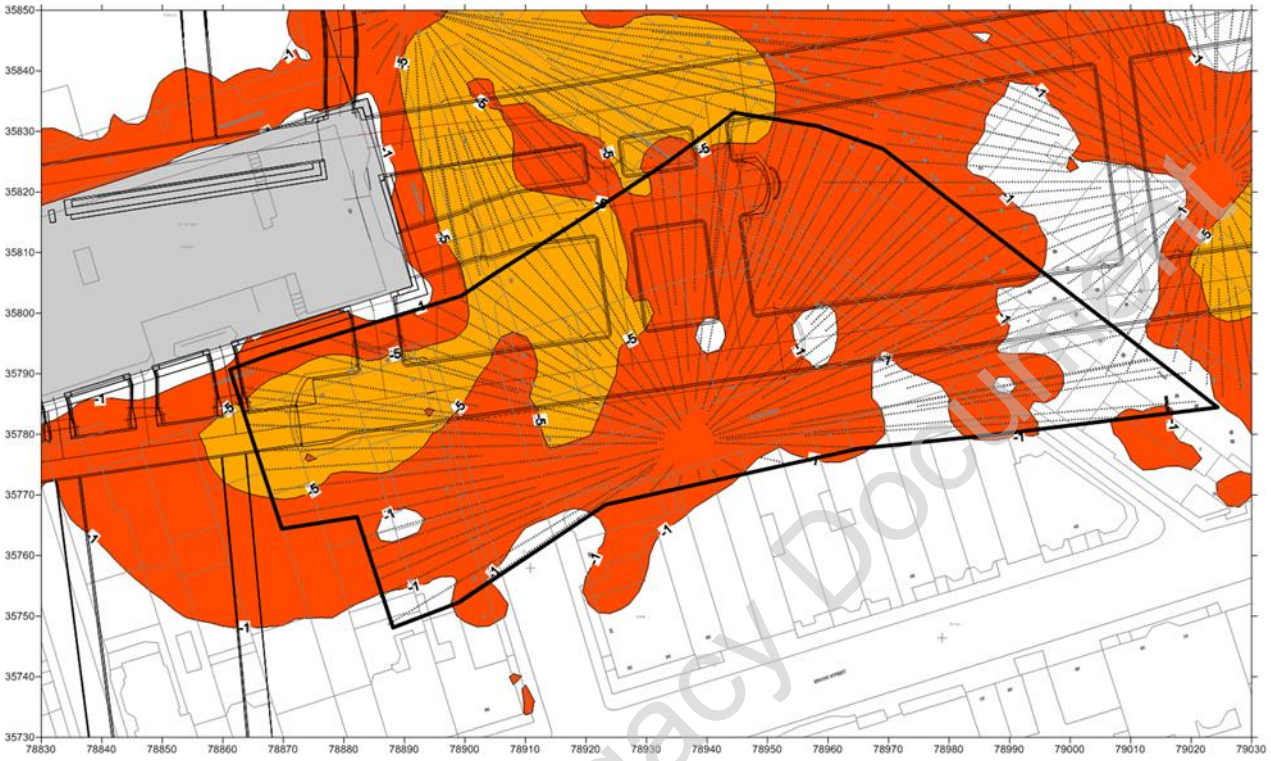


Figure 3.4.2 Period C: Total measured settlement (mm).

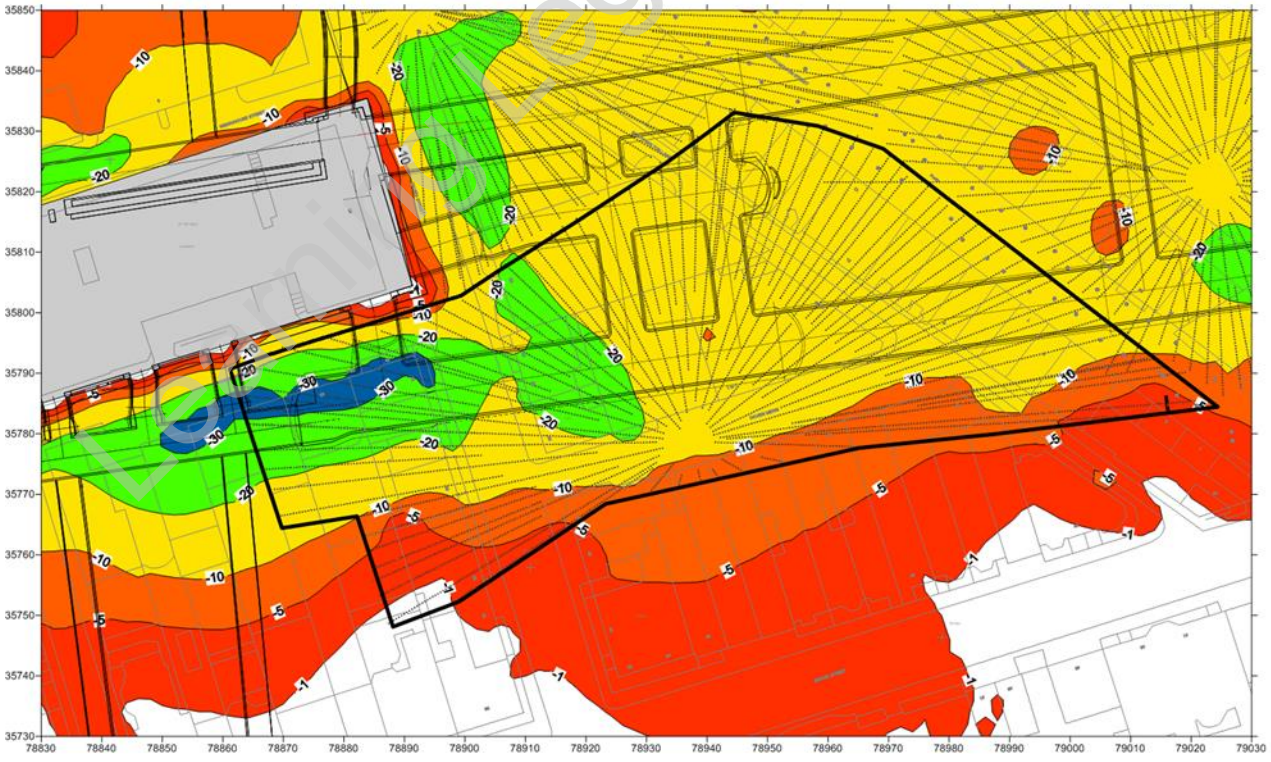


Figure 3.4.3 Period C: Distribution of grout injected from GS2: Grout jacking. Grout Intensity (l/m^2).

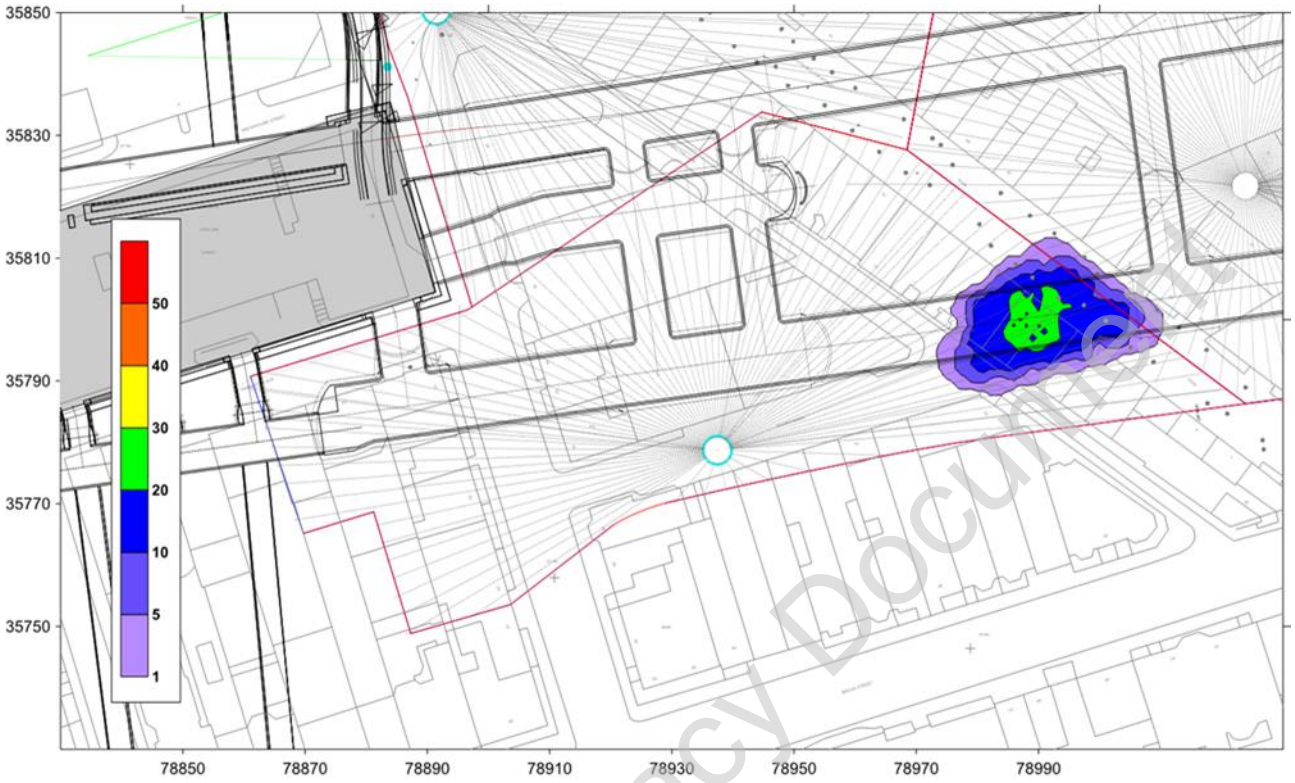


Figure 3.4.1 shows the recorded increase in settlement in Period C was between 5 and 10mm centred around the WTH. At the end of Period C the cumulative movements (Figure 3.4.2) show that the maximum settlement had reached 30mm locally adjacent to the WTH south wall.

Figure 3.4.3 shows the grout jacking undertaken from GS1 over the WBRT at the eastern end of the area, where a localised maximum of over 15mm settlement was recorded. The grout intensity had a maximum of ~20 l/m^2.

3.5. Period D – PTW, AP2A, VD1 (a, b, c), Concurrent & Grout Jacking: 20/01/14 – 06/06/14

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

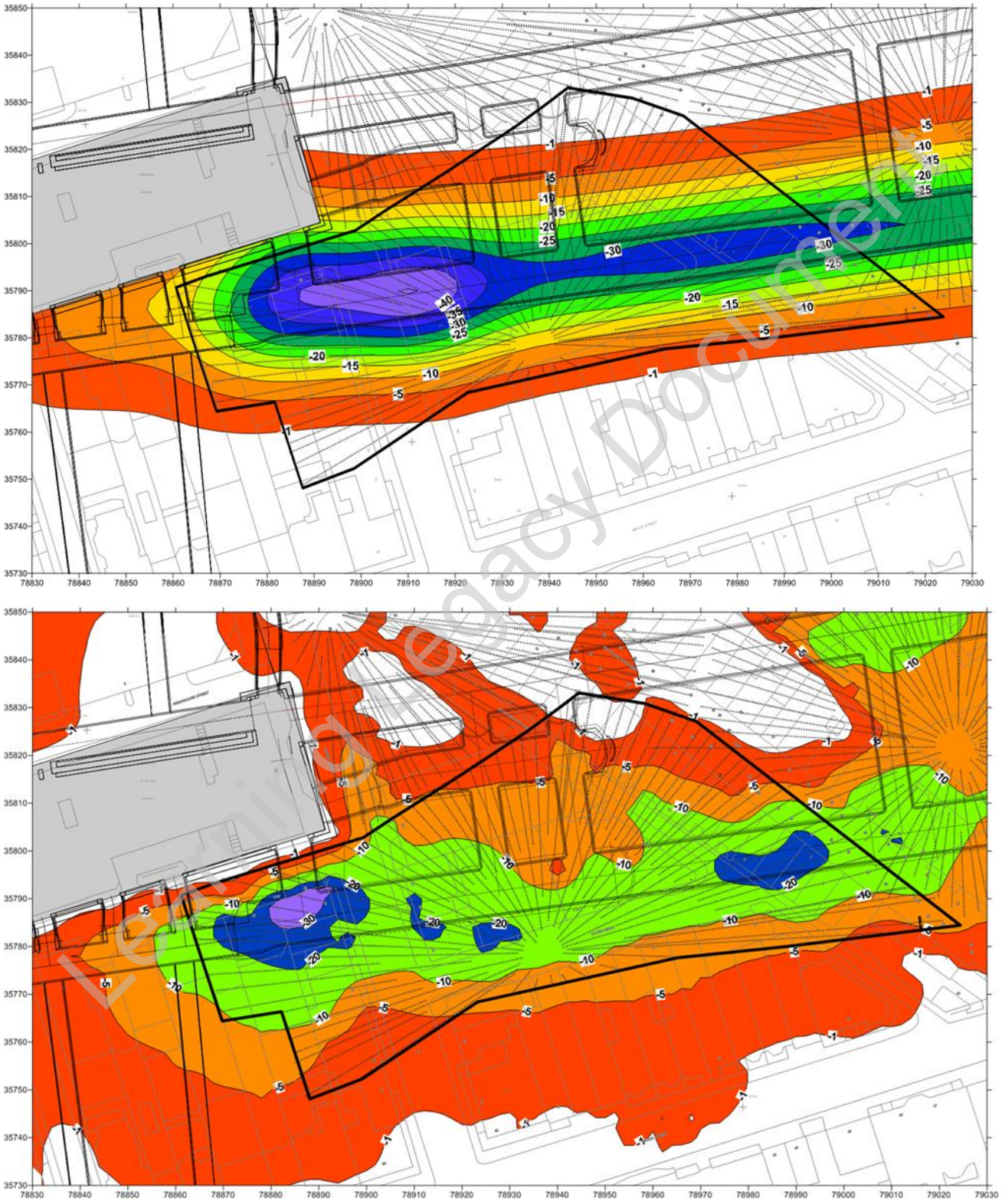


Figure 3.5.2 Period D: Total measured settlement (mm).

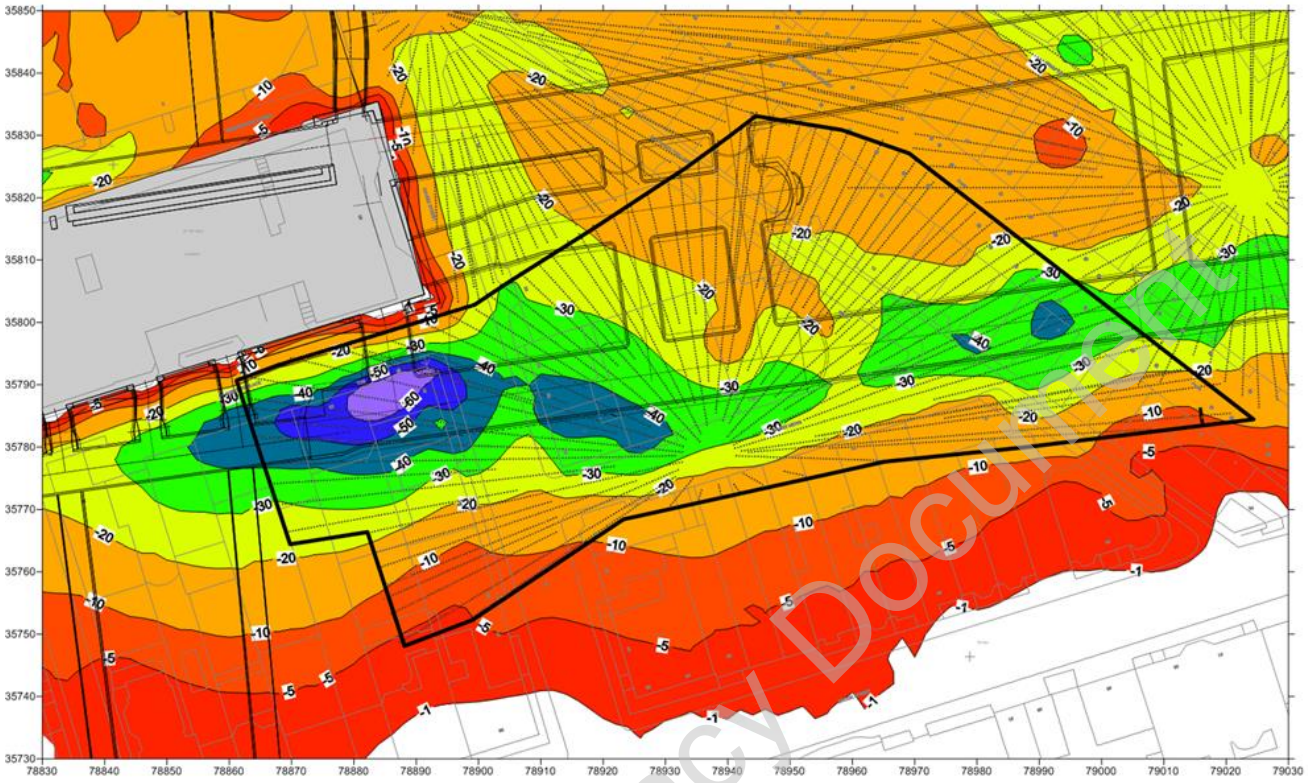


Figure 3.5.3 Period D: Distribution of grout injected from GS2: Concurrent Grouting. Grout Intensity (l/m^2).

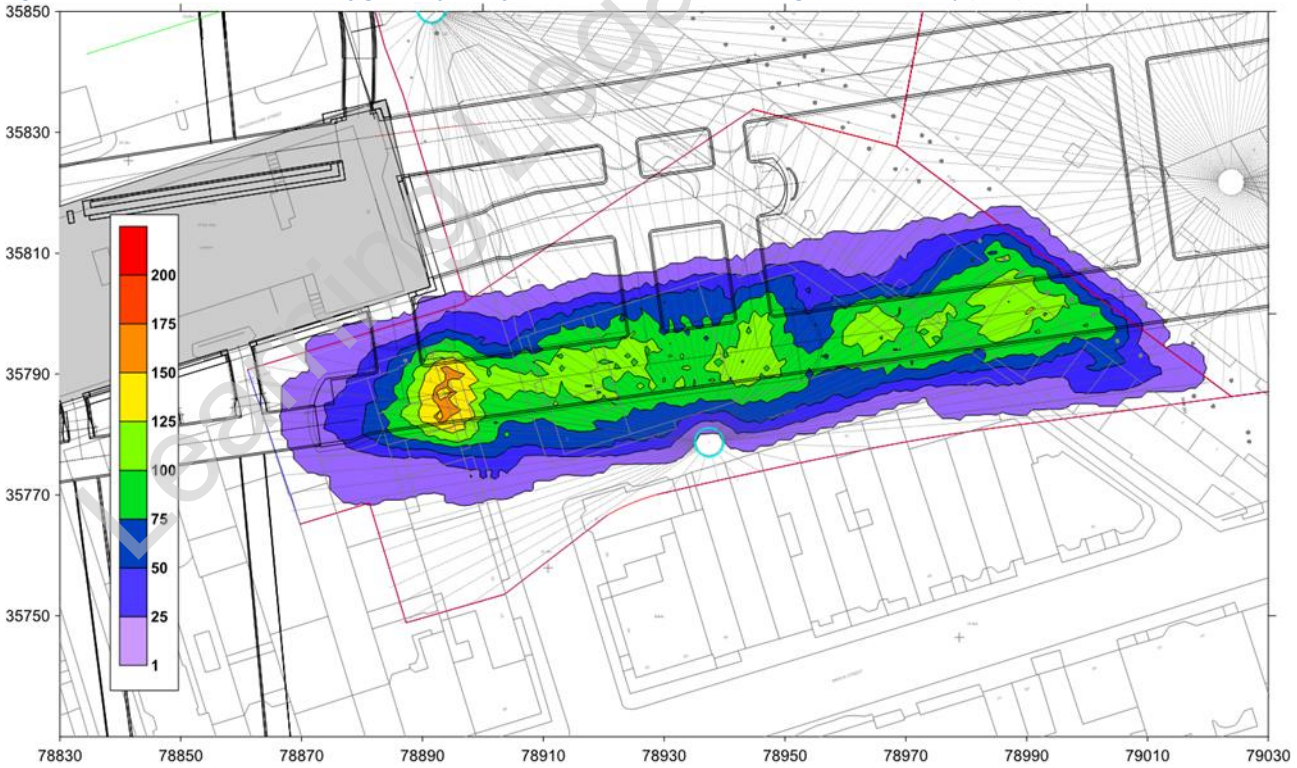
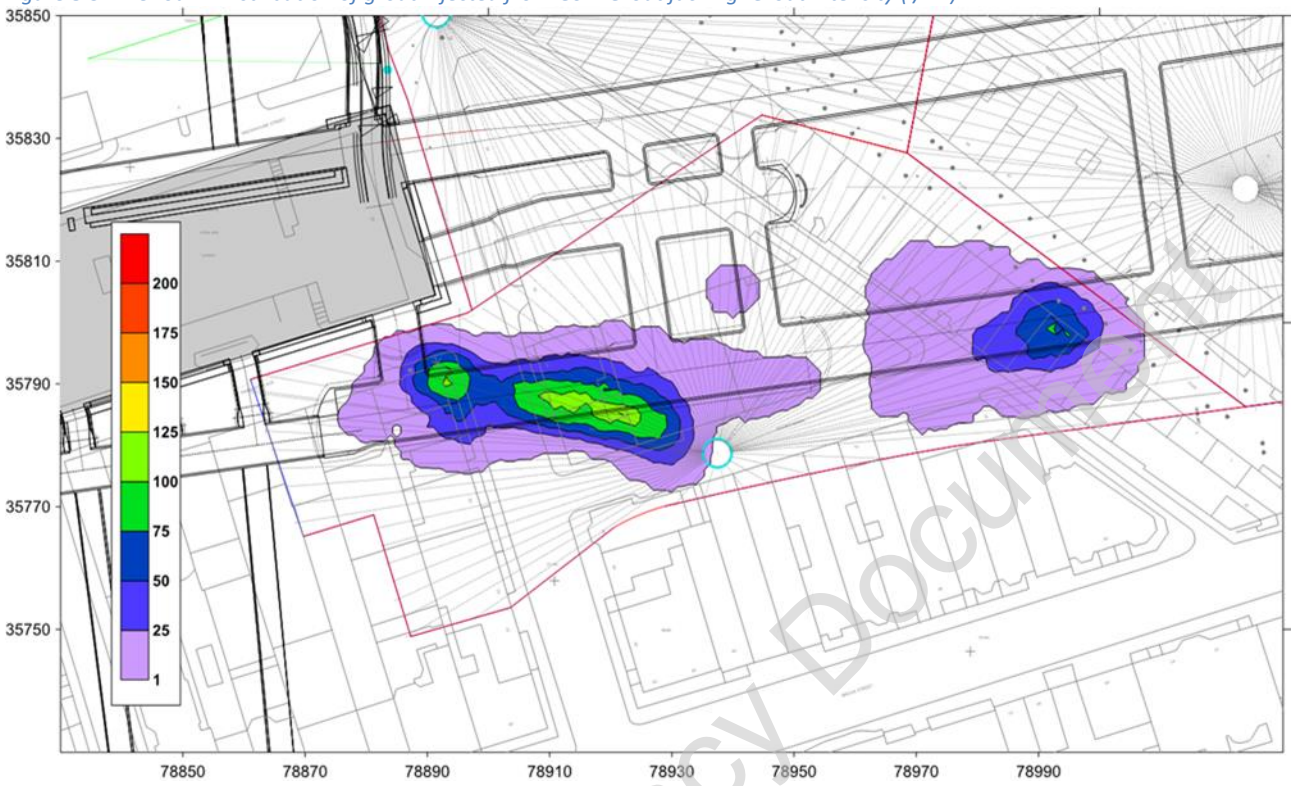


Figure 3.5.4 Period D: Distribution of grout injected from GS2: Grout jacking. Grout Intensity (l/m^2).



The PTW was constructed in Period D together with connections to the WTH (AP2A and VD1a, VD1b and VD1c). The specified compensation area extends only just beyond the end of PTW and consequently concurrent grouting could not be undertaken for the three vent tunnels. Concurrent grouting was also impractical for AP2A due to the extent of the exclusion zones over the tunnel face and around the WTH. specified in the SCoGM.

The maximum volume loss settlement for all tunnels constructed in Period D is over 40mm, as shown in Figure 3.5.1(a). The maximum observed settlement was locally greater than 30mm over AP2A but more generally was 20mm or less above PTW. Grout jacking was targeted based on the pre-existing settlements to control slopes and distortions.

Figure 3.5.2 shows that the maximum total settlement exceeded 60mm locally over the PTW / AP2A junction, with more generally 30 to 40mm over the PTW. The contour of grout intensity in Figures 3.5.3 and 3.5.4 shows that a large amount of grouting was undertaken centred directly over the PTW / AP2A junction. A maximum intensity of 150 l/m^2 was injected with concurrent grouting for PTW and a further 100 l/m^2 in grout jacking episodes.

3.6. Period E – PTE, CP1, CP2, CP3, CP4, Concurrent & Grout Jacking: 06/06/14 – 04/02/15

Figure 3.6.1 Period E: (a) Volume loss settlement (mm). (b) Change in measured settlement (mm).

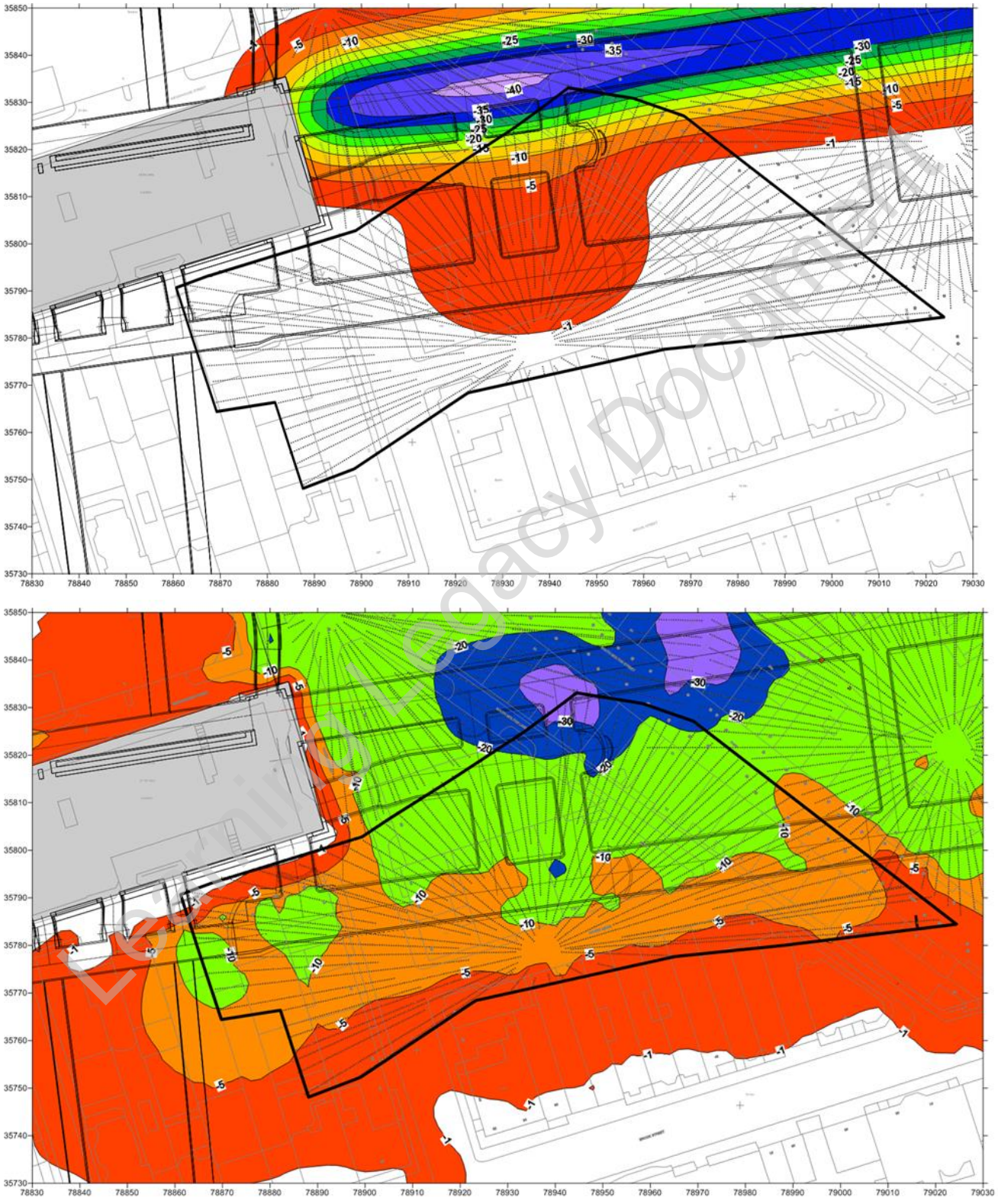


Figure 3.6.2 Period E: Total Measured Settlement (mm)

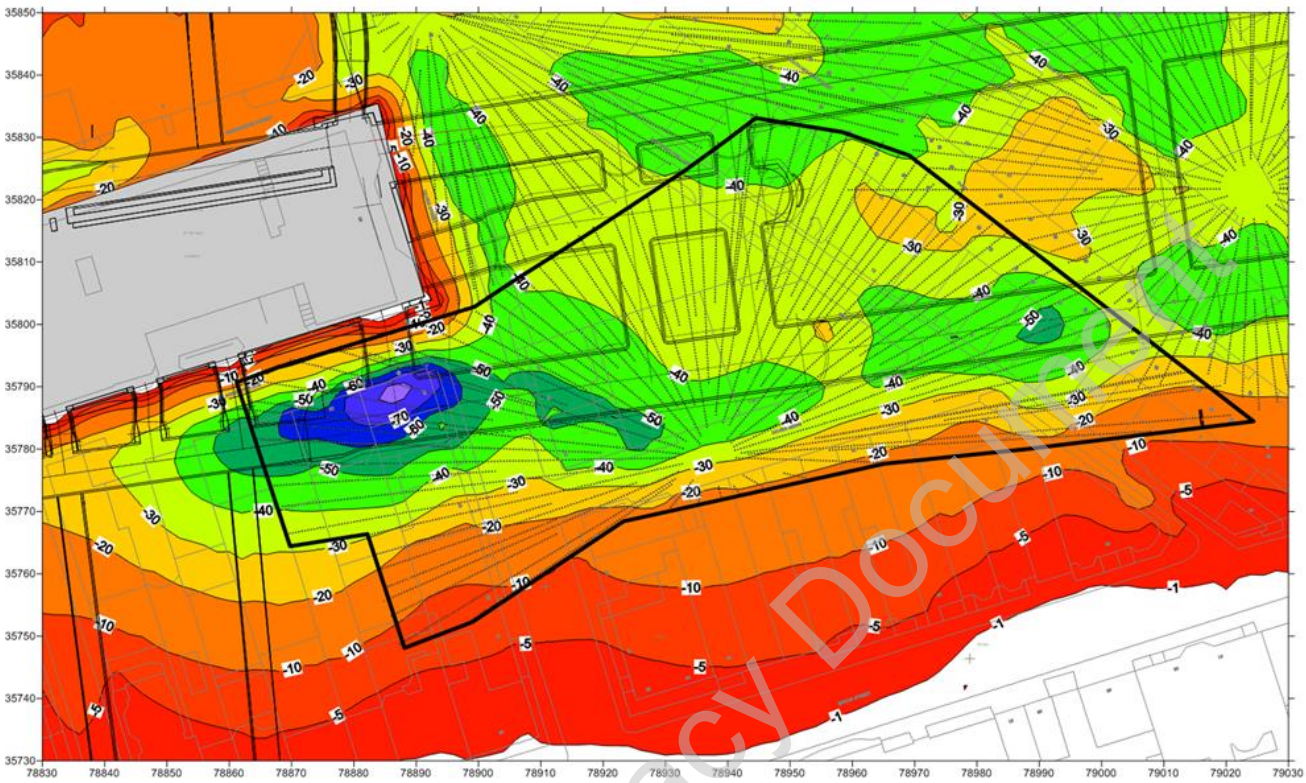


Figure 3.6.3 Period E: Distribution of grout injected from GS1: Concurrent grouting. Grout Intensity (l/m^2).

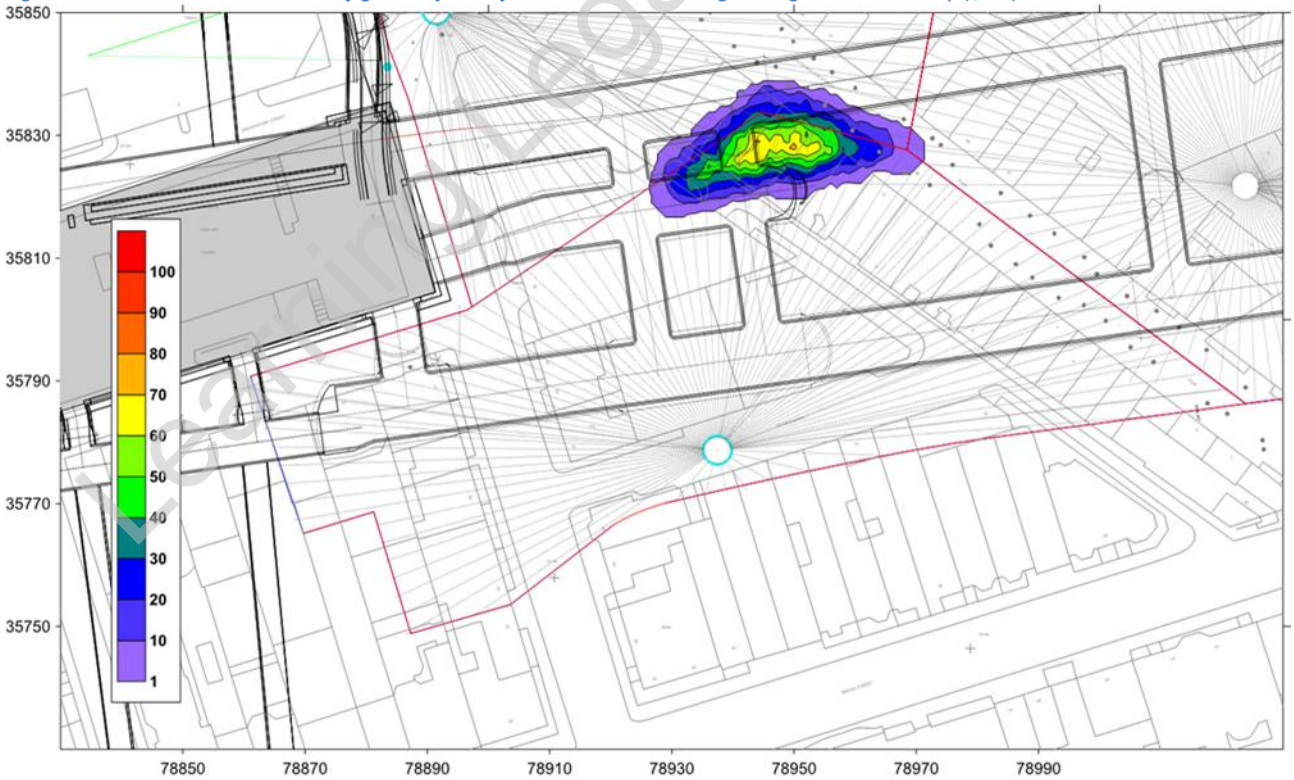
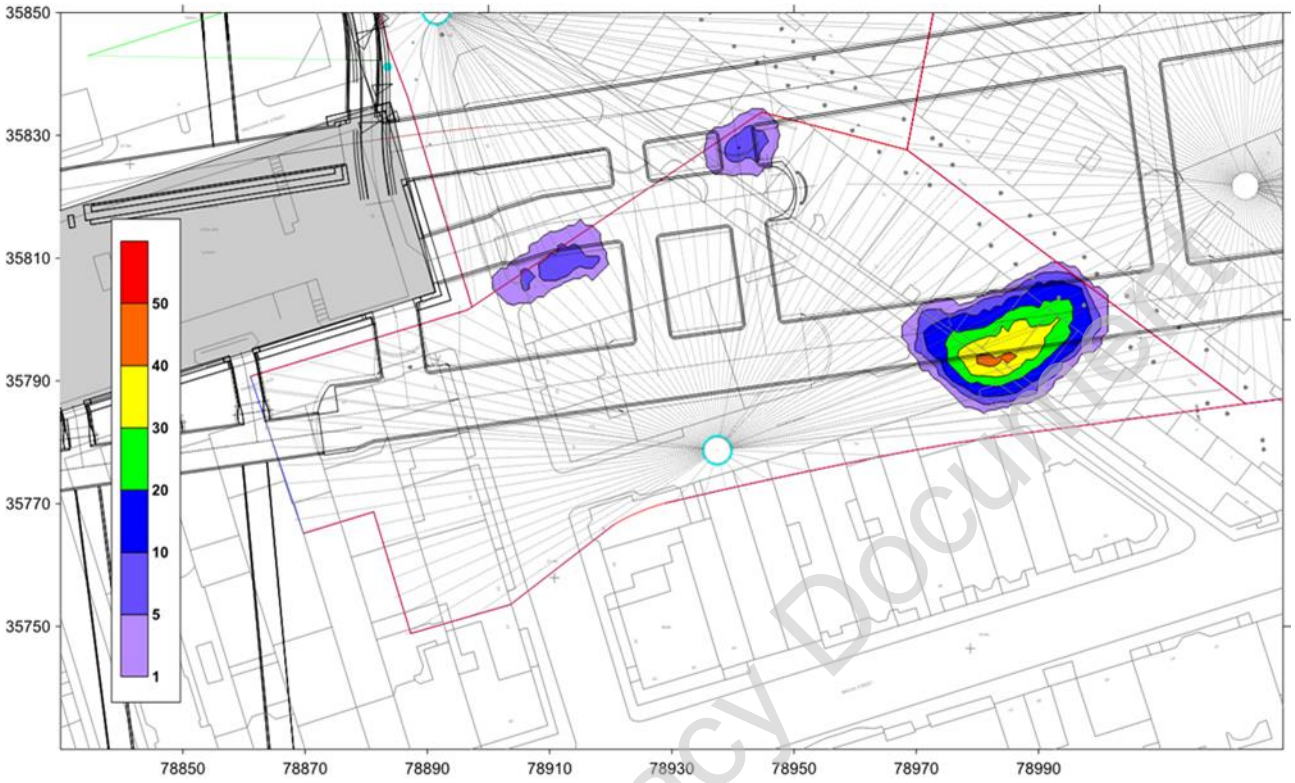


Figure 3.6.4 Period E: Distribution of grout injected from GS1: Grout jacking (l/m^2).



During Period E, C411 completed excavation at the WTH and the site was handed over to BFK in November 2014 for construction of AP1 and ES1/ CH2. The main activity in Period E is the PTE, which is located at and beyond the northernmost extent of the GS1 arrays. Stub tunnels commencing the for crosspassages were also excavated in Period E. The maximum calculated volume loss settlement over PTE is ~40mm.

The actual settlements are shown in Figure 3.6.1(b) and give a maximum over 30mm locally above the PTE / CP3 junction. It is noted that the 10mm contour extends over the full plan extent of the SCL tunnel indicating significant consolidation over the 8 month duration of Period E.

Only a minor amount of concurrent grouting and grout jacking was undertaken in Period E, as illustrated in Figures 3.6.3 and 3.6.4.

3.7. Period F – ES1, CH2P, CH2E, CP1-4, Concurrent & Grout Jacking: 04/02/15 – 17/06/15

Figure 3.7.1 Period F: (a) Volume loss settlement (mm). (b) Change in measured settlement (mm).

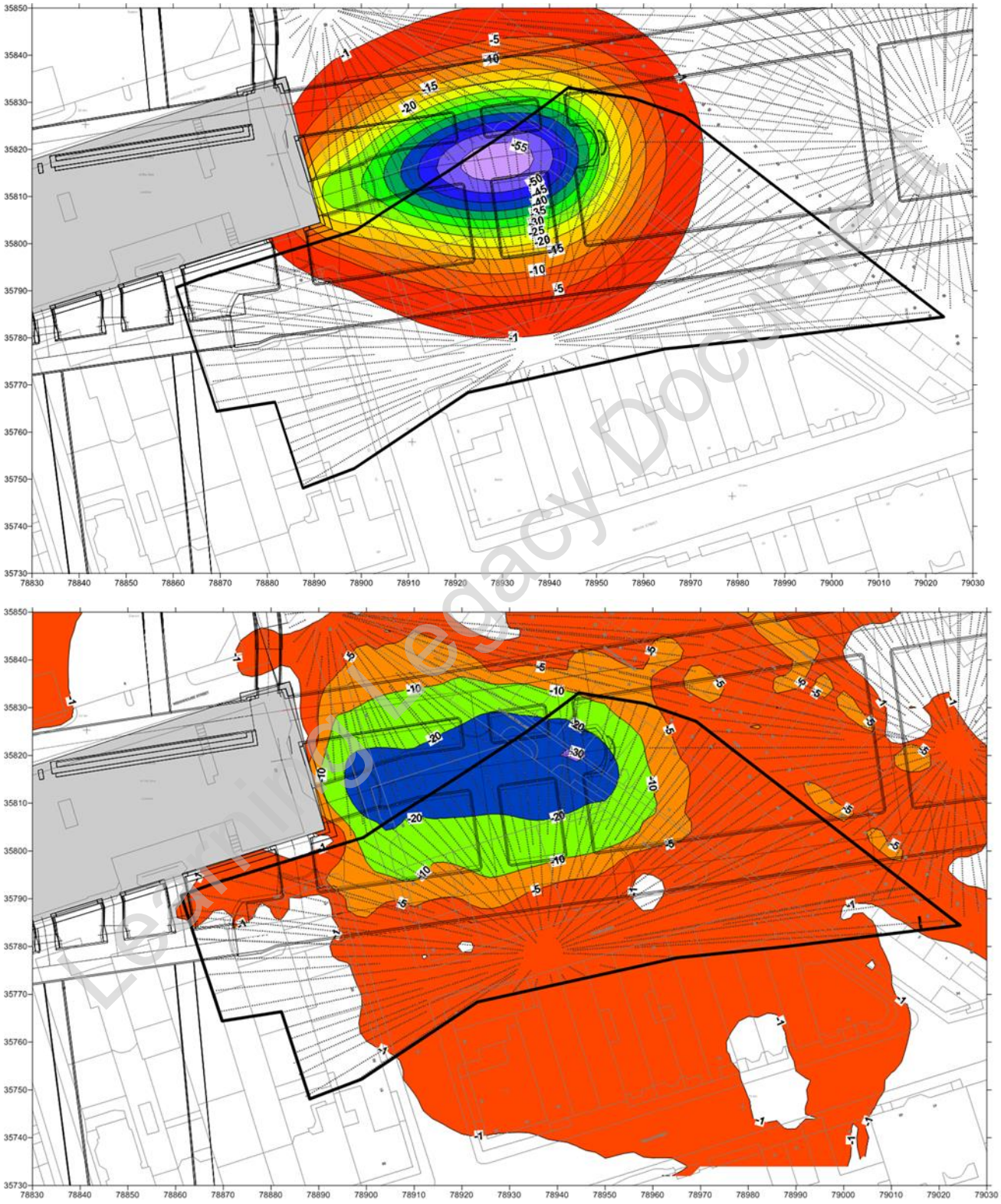


Figure 3.7.2 Period F: Total measured settlement (mm)

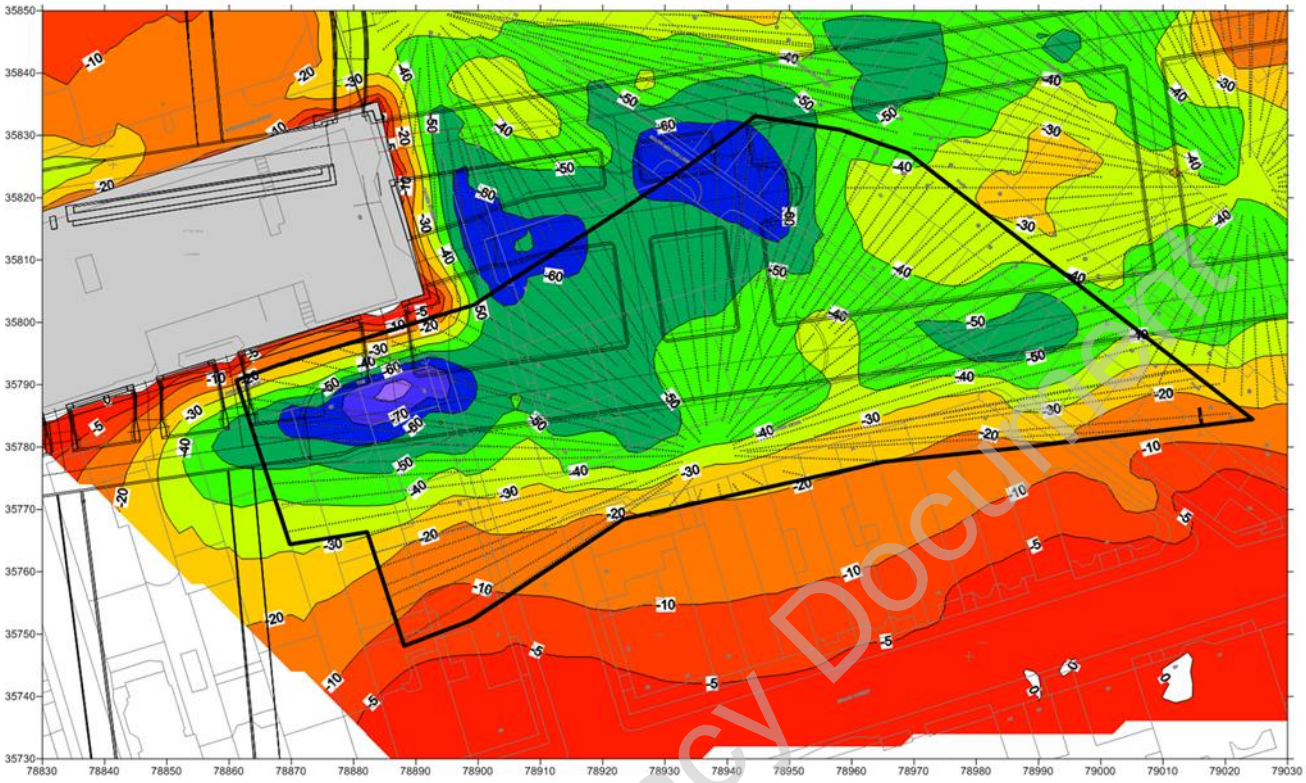


Figure 3.7.3 Period F: Distribution of grout injected from GS1: Concurrent grouting. Grout Intensity (l/m^2).

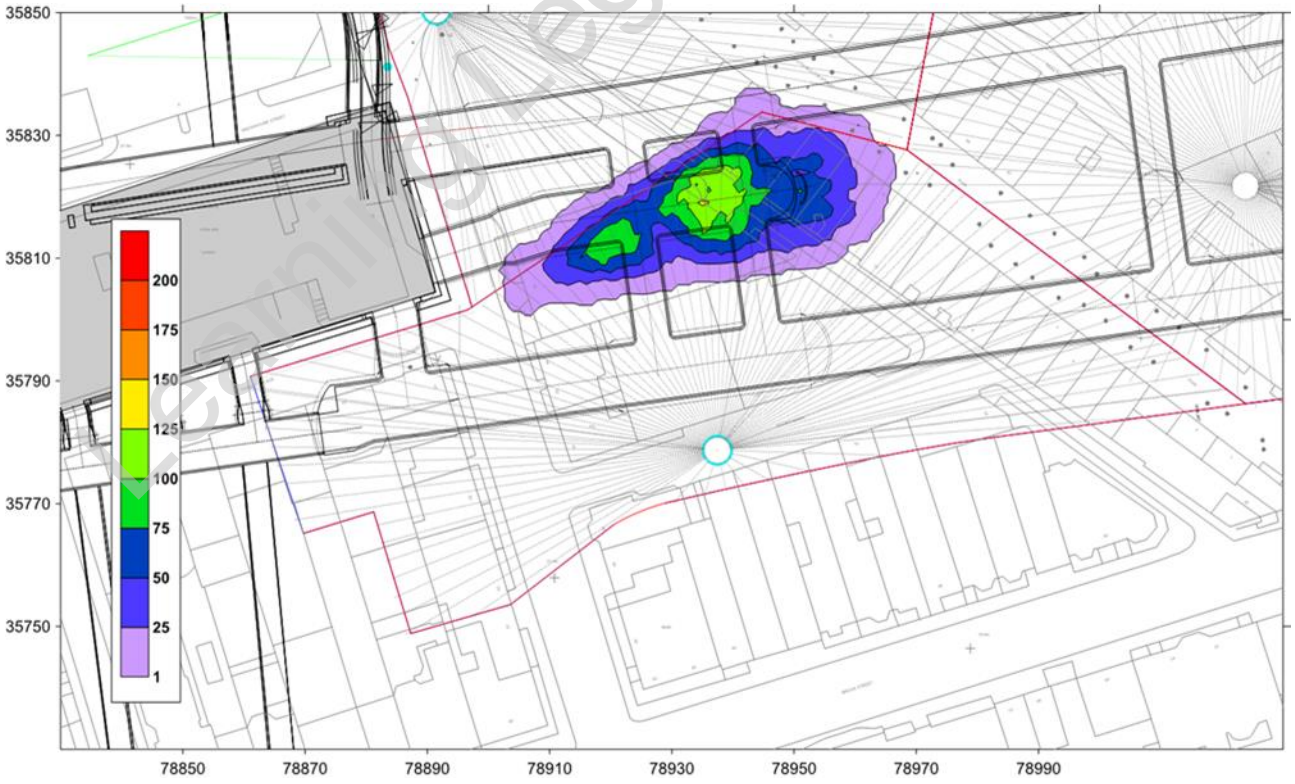
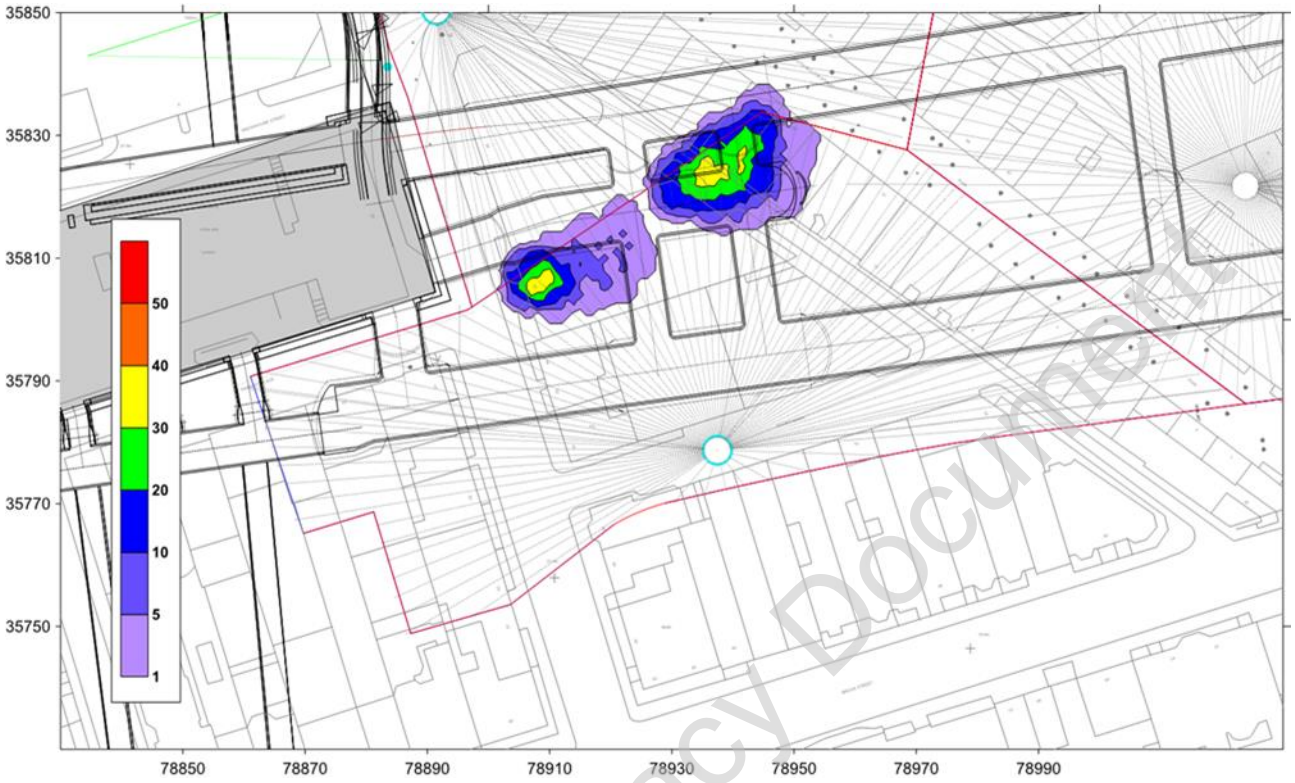


Figure 3.7.4 Period F: Distribution of grout injected from GS1: Grout jacking. Grout Intensity (l/m^2).



ES1 and CH2 were constructed in Period F along with the connections of CP1, CP2, Cp3 and CP4 to CH2. The maximum calculated volume loss settlement (Figure 3.7.1(a)) is over 55mm above the centre of CH2.

The actual settlements are shown in Figure 3.7.1(b) and show less than 25mm (20mm maximum contour). It is noted that the 5mm contour is at a similar location to that given in the prediction.

The maximum total settlement increased but remained located over the PTW/ AP2A junction. Over CH2 the maximum settlement was between 50 and 60mm, as shown in Figure 3.7.2.

No concurrent grouting was possible for ES1 since its crown is located within the vertical exclusion zone from the TaM array. The concurrent grouting for CH2 is illustrated in Figure 3.7.3 and shows a maximum intensity of over 100 l/m^2. Grout jacking was undertaken in Period F as shown in Figure 3.7.4, which targeted control of crack widths within the TA Centre, 56 Davies Street which were perceived to be related primarily to horizontal movements (see Appendix B for crack width data). A maximum intensity of ~40 l/m^2 was injected.

3.8. Period G - No tunnelling: 17/06/15 – 13/10/15

Figure 3.8.1 Period G: Change in measured settlement, (mm)

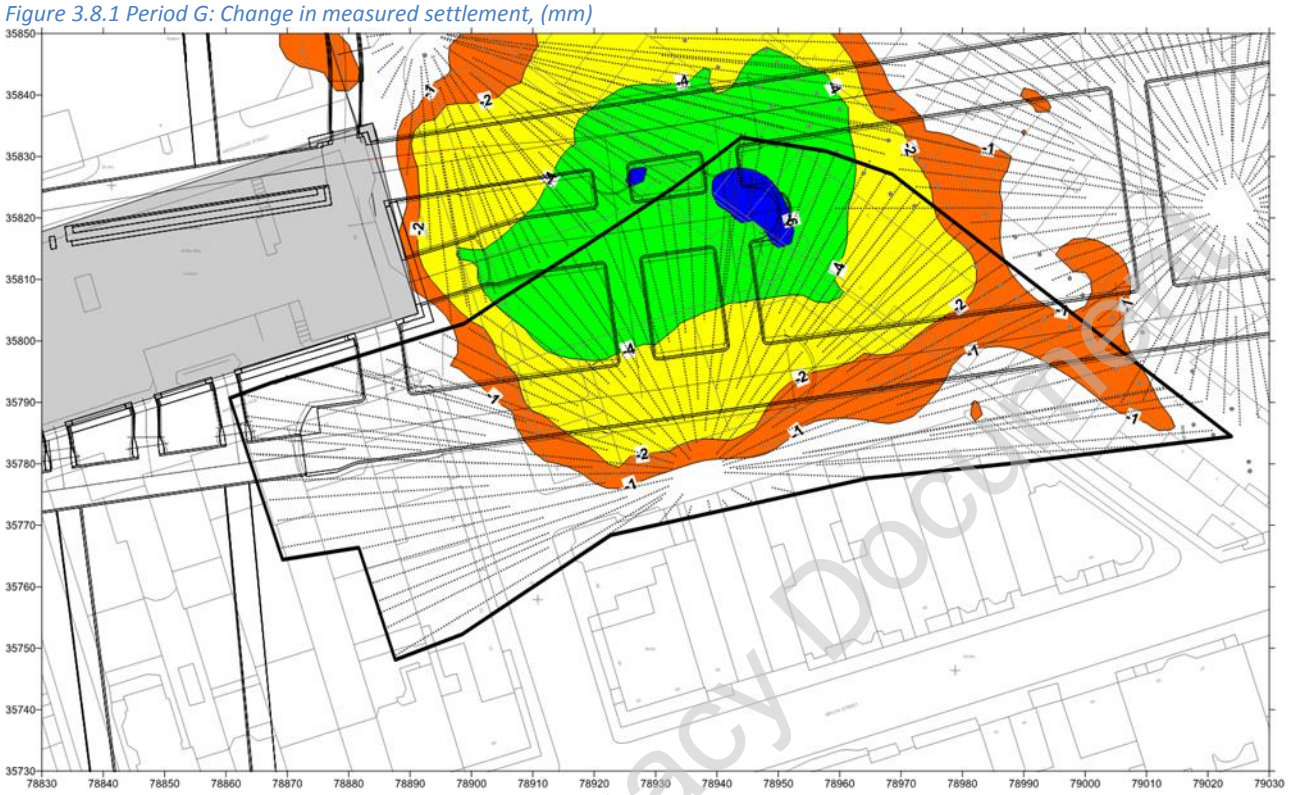


Figure 3.8.2 Period G: Total measured settlement, (mm)

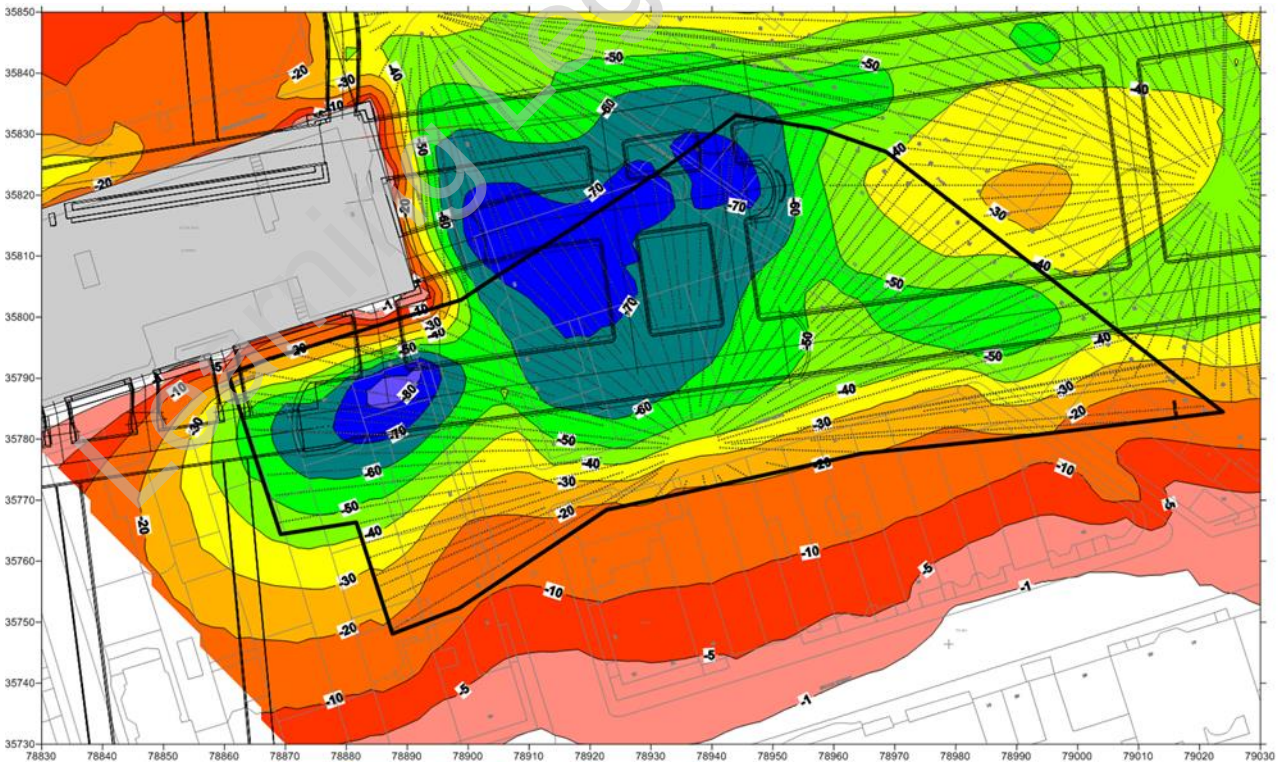


Figure 3.8.1 shows an increase of settlement of up to 6mm during the 4 months following the completion of tunnelling. The maximum movement is located above the east end of CH2. The contours are centred over CH2 and the crosspassages which were the final excavations in this area.

The total settlement at the end of Period G is shown on Figure 3.8.2.

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. A larger version of Figure 4.1 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

Figure 4.1. Locations where building slope triggers have been exceeded.

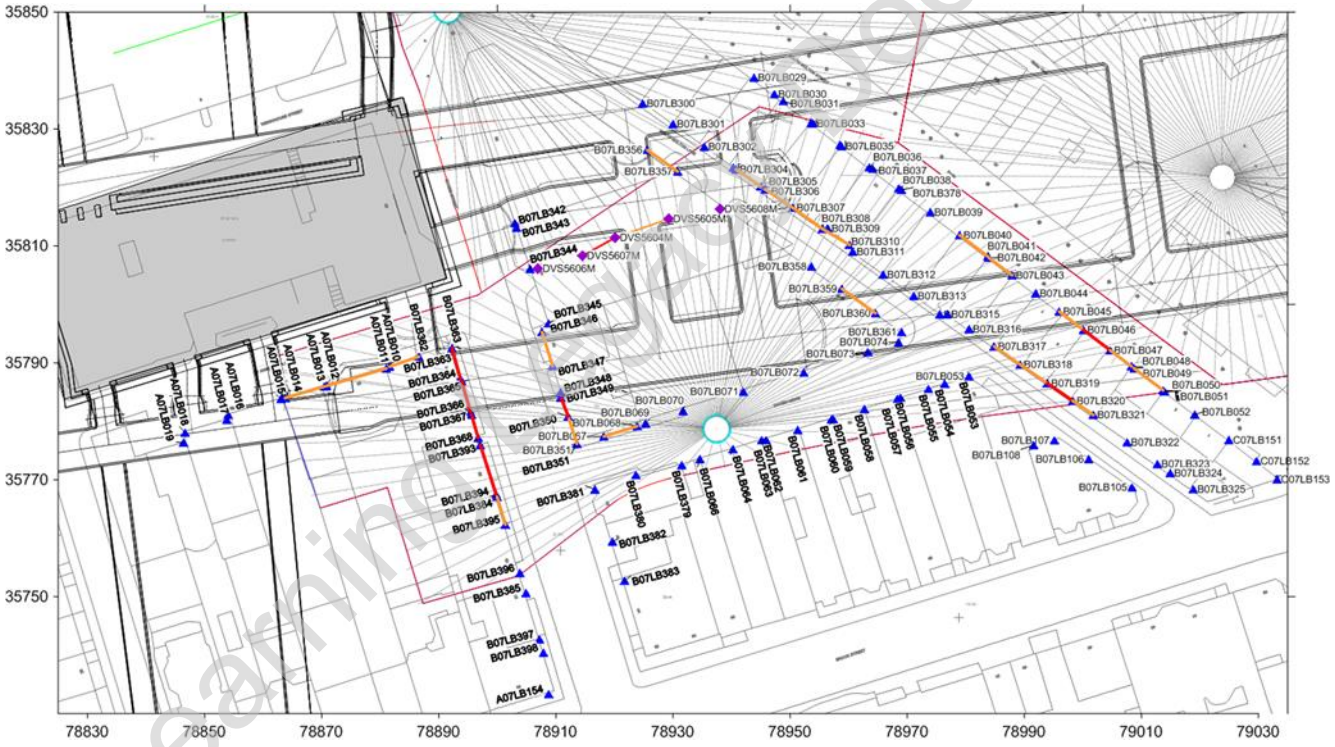


Table 4.1 **Details of trigger breaches on Building Facades**

BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Davies Mews – South: NONE					
Davies Mews - North					
B07LB067-B07LB068	Amber	PTW	02/04/2014	1.61	1.58
St Anselm's Place					
A07LB010-A07LB362	Amber	Transitory during PTW / AP2A to 24/03/14	21/03/2014	1.16	0.45
A07LB011-A07LB012	Amber	Transitory during PTW / AP2A to 26/04/14	07/04/2014	1.36	1.07
A07LB013-A07LB014	Amber	PTW / AP2A	18/04/2014	1.55	1.53
Davies Street (SW)					
B07LB363-B07LB364	Red	Post PTW / AP2A	15/05/2014	2.13	1.98
B07LB365-B07LB366	Red	Post PTW / AP2A	07/05/2014	2.32	2.31
B07LB367-B07LB368	Red	PTW / AP2A	25/03/2014	3.08	2.91
B07LB393-B07LB394	Red	Post PTW / AP2A	14/08/2014	2.25	2.25
B07LB384-B07LB395	Amber	Post PTW / AP2A	15/10/2014	1.23	1.21
Davies Street (E)					
B07LB346-B07LB347	Amber	Transitory to 23/03/14	05/03/2014	1.4	0.07
B07LB349-B07LB350	Red	PTW Amber 05/03/14	25/03/2015	2.78	2.43
B07LB350-B07LB351	Amber	PTW	08/03/2014	1.58	1.58
South Molton Lane (West)					
B07LB359-B07LB360	Amber	Transitory due to PTW to 13/09/14	24/04/2014	1.14	0.08
B07LB356-B07LB357	Amber	Marginal in Period G	16/06/2015	1.07	0.85
South Molton Lane (East)					
B07LB304-B07LB305	Amber	CH2	09/03/2015	1.62	0.37
B07LB306-B07LB307	Amber	CH2	10/05/2015	1.26	1.11
B07LB307-B07LB308	Amber	CH2	14/05/2015	1.62	1.76
B07LB317-B07LB318	Amber	PTW	26/03/2014	1.61	1.61
B07LB318-B07LB319	Amber	PTW	09/02/2014	1.98	1.95
B07LB319-B07LB320	Red	PTW & CH2 (Amber 10/02/14)	19/02/2015	2.04	2.04
B07LB320-B07LB321	Amber	Post PTW	08/05/2014	1.53	1.53
South Molton Street (West)					
B07LB040-B07LB041	Amber	Post PTW	25/02/2014	1.57	1.33
B07LB042-B07LB043	Amber / Red	Transitory peak into Red during PTW followed by gradual increase	08/02/2014	2.12	1.89
B07LB045-B07LB046	Amber / Red		09/02/2014	2.02	1.92
B07LB046-B07LB047	Red	Amber PTW peak ~1.9 post ~1.1 - post construction increase to Red.	09/09/2014	2.27	2.12
B07LB047-B07LB048	Amber	Amber from PTW peak ~1.2 post ~0.8 - post construction increase.	31/01/2014	1.78	1.68
B07LB049-B07LB050	Amber	Post PTW movement	21/03/2014	1.45	1.35
TA Centre (HLC)					
DVS5607M-DVS5604M	Amber / Red	Transitory due to CH2 to 27/05/15	14/02/15	2.05	0.43
DVS5604M-DVS5605M	Amber	Transitory due to CH2 to 05/05/15	11/03/15	1.62	0.47

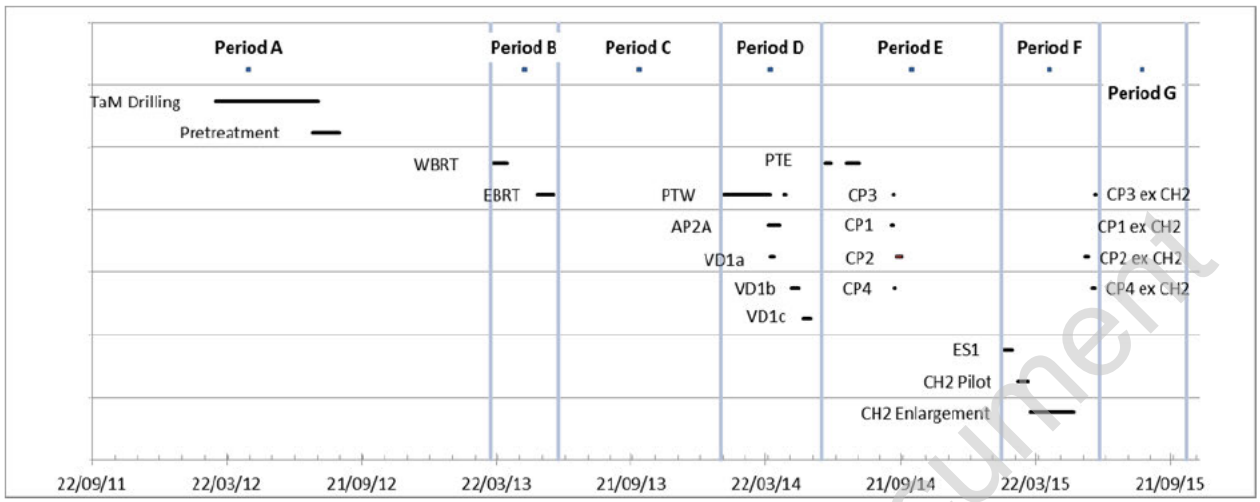
BRE monitoring data from the facades within the footprint of GS1 are presented in the following sections, namely South Molton Street west, South Molton Lane east and west, Davies Mews north and south, Davies Street east and west and St. Anselm's Place south. HLC data is used where no BRE data is available; namely, across the TA Centre. The locations of the HLC are shown on Figure 4.1. All HLC data presented is based on daily means.

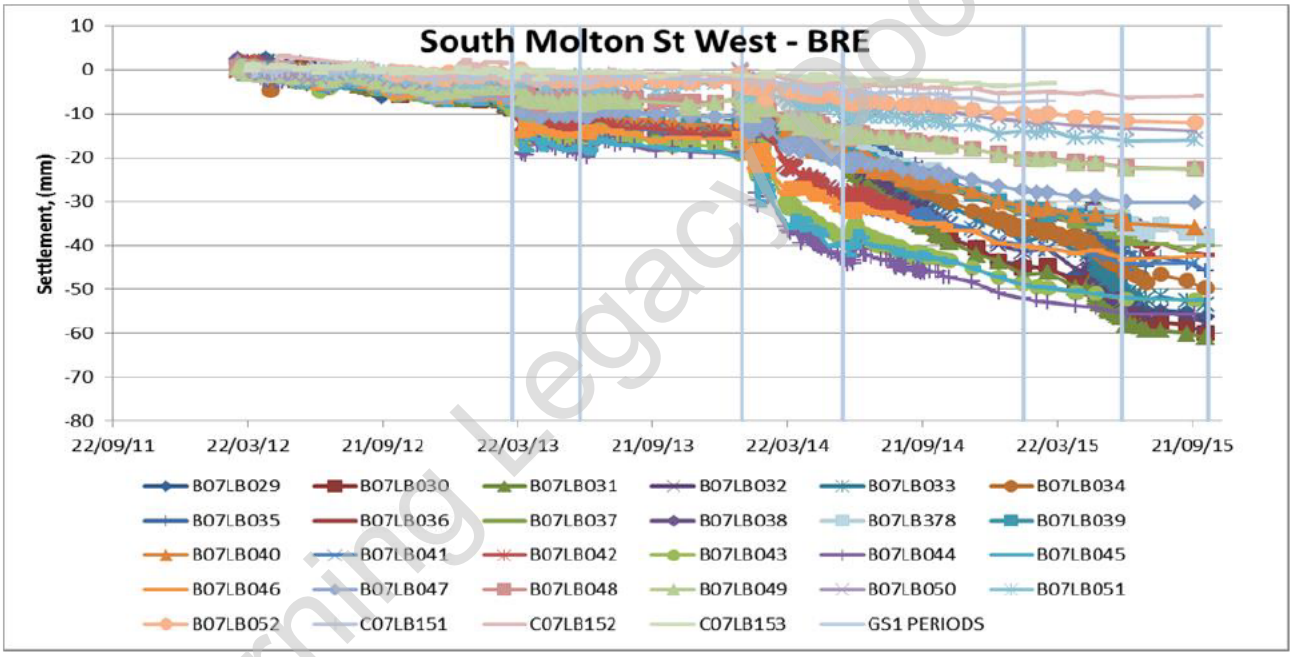
The plots presented, as appropriate, for each façade comprise:

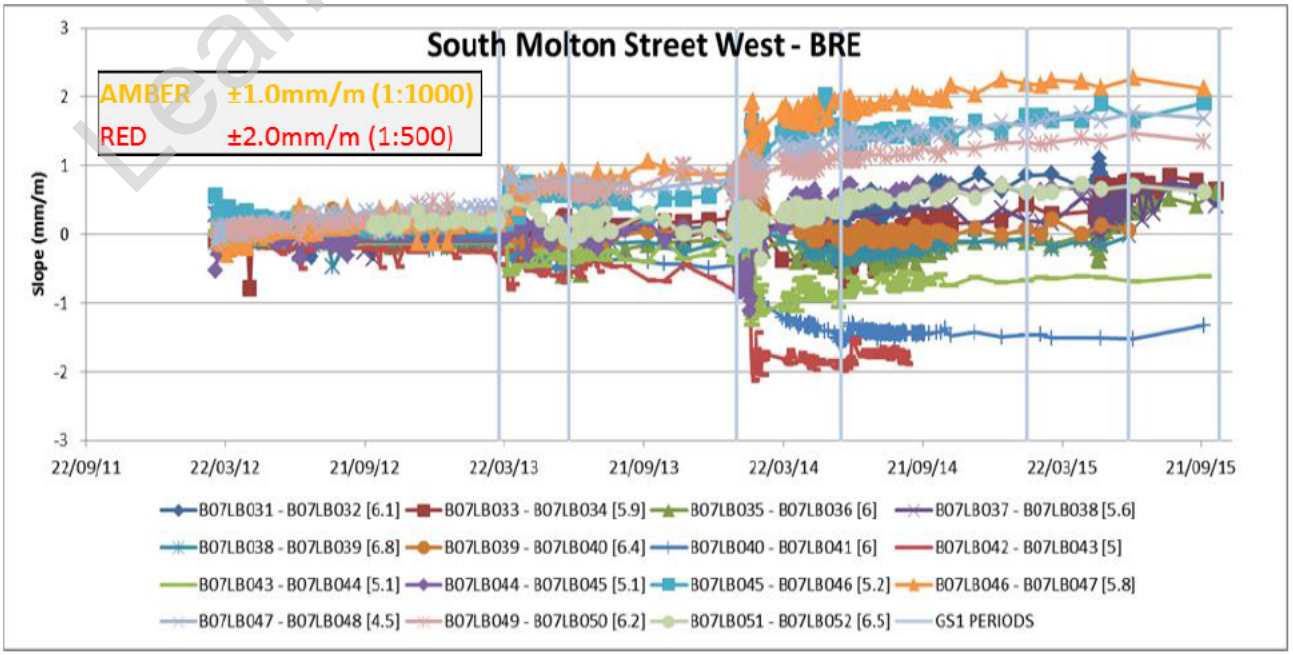
1. Summary of tunnel construction and associated construction periods.
2. Time settlement history.
3. Settlement profile plots with a series as close as possible to the date of the end of each construction period.
4. Time slope history over the full construction period with the distances between the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

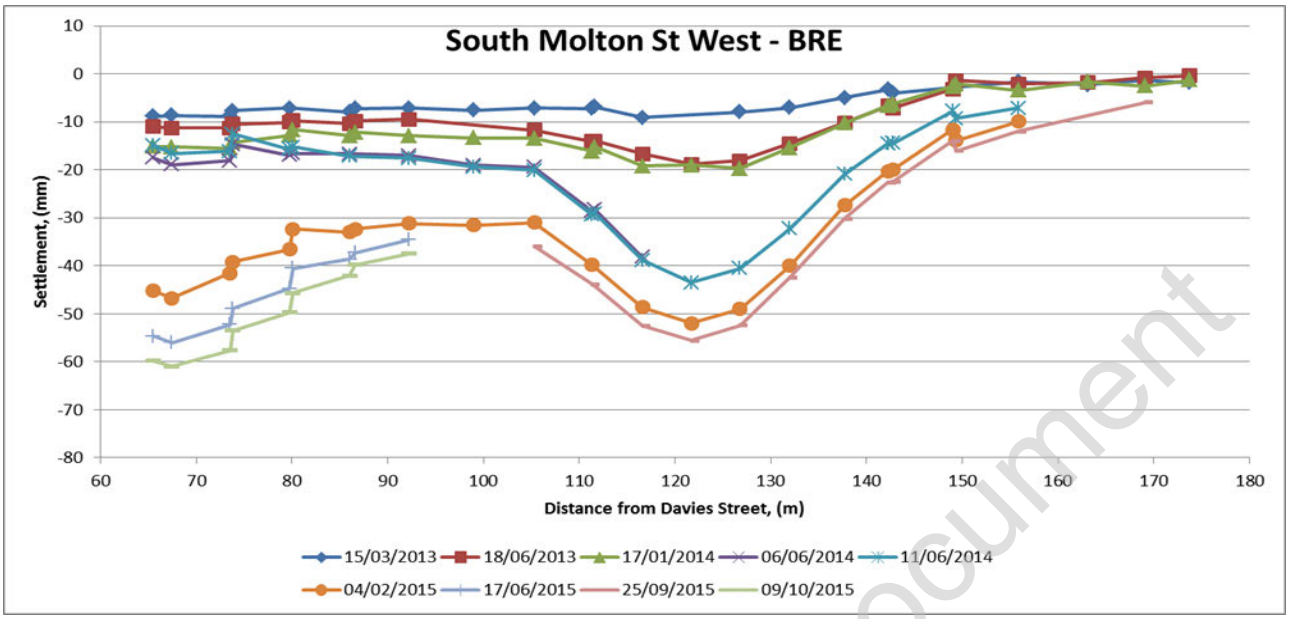
All available data is plotted in these figures.

4.2. South Molton Street - West





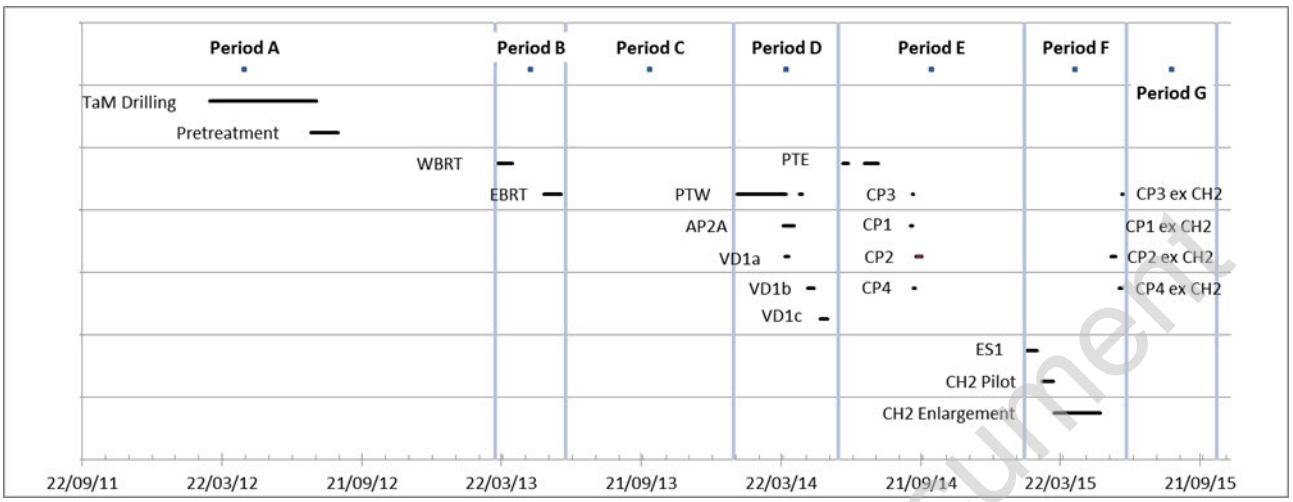


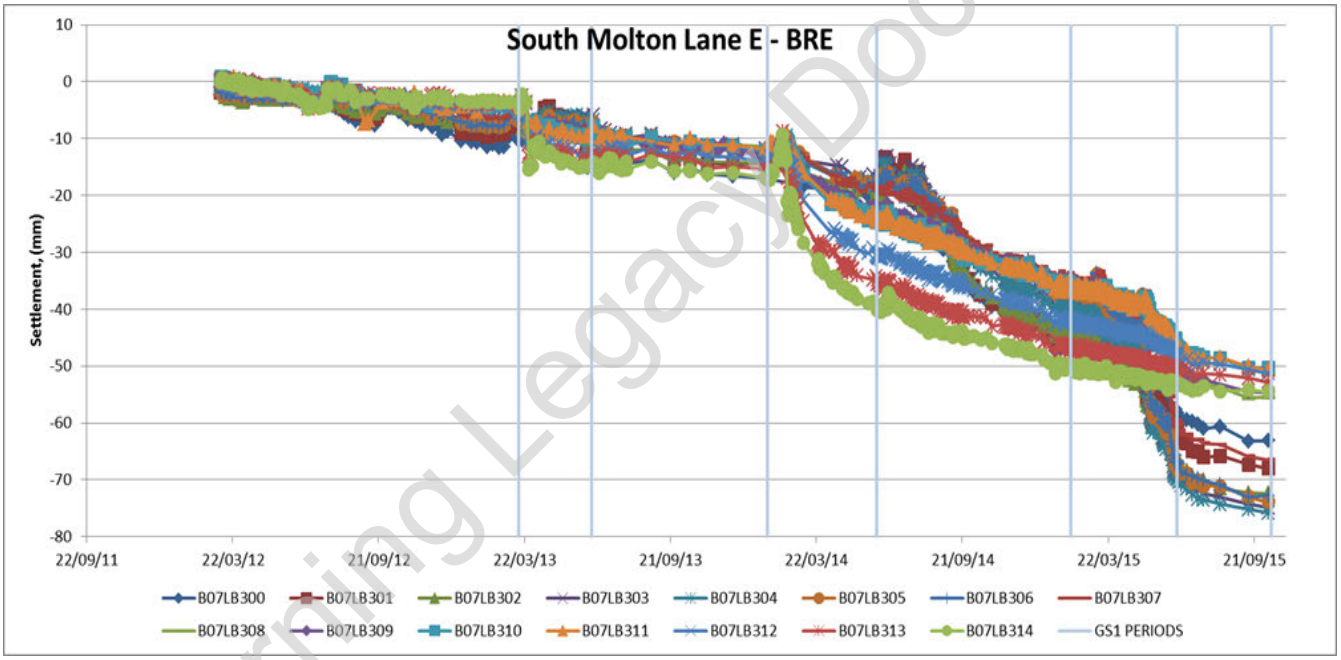


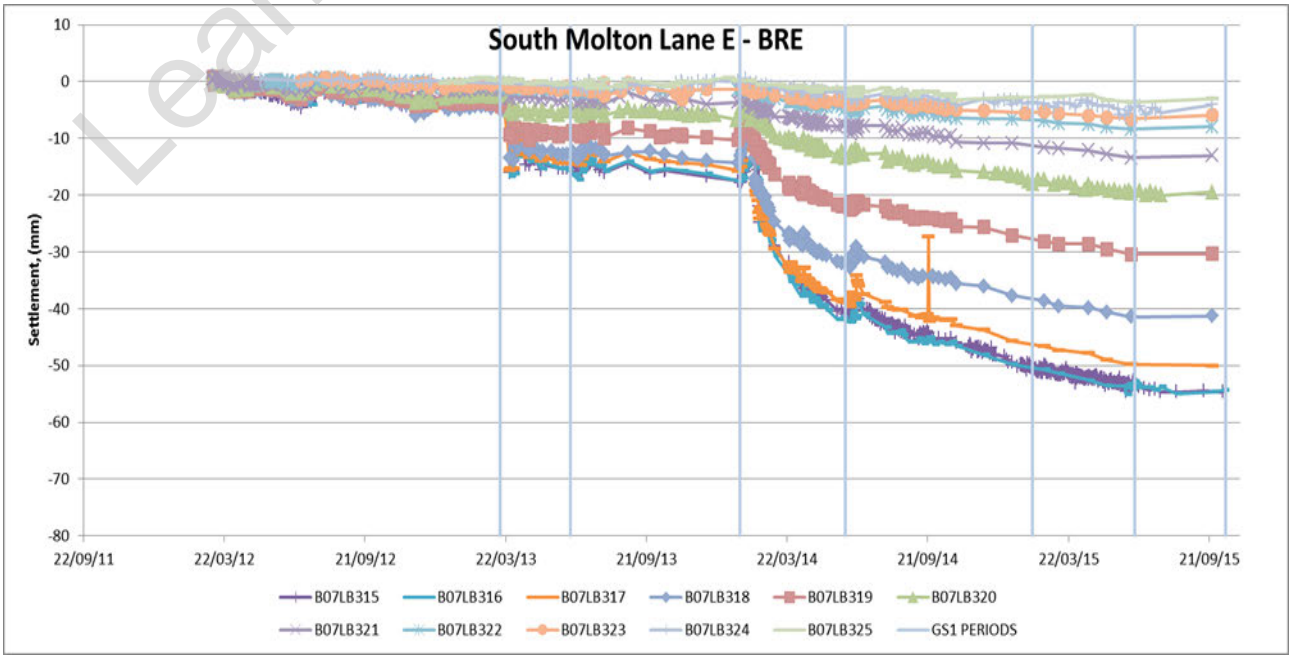
The following points are noted:

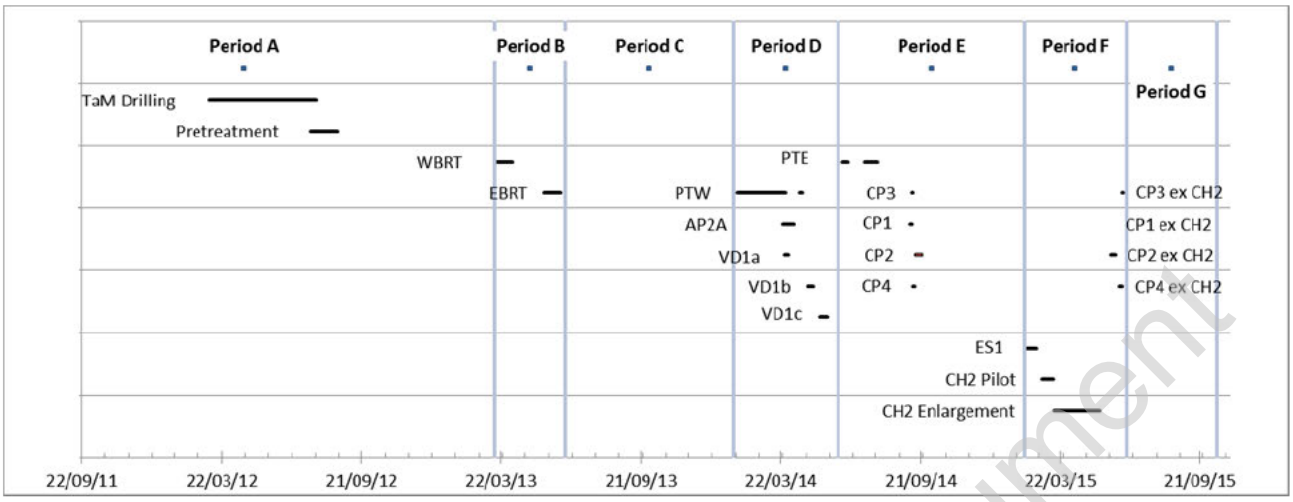
- The southern part of the South Molton Street west façade is within the GS1 array (from distance 75m): data from all points shown on Figure 4.1 are presented.
- The South Molton Street west façade traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable event was however the construction of PTW in Period D (see Section 3.6).
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm but there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a further 10mm settlement with a trough extending from distance 100m to 150m even though grout jacking was undertaken. No significant effect is evident from the EBRT.
- In Period C there was little change: grout jacking at the start of the Period reduced settlement slightly but time-related movement resulted in no or a small increase in settlement by the end of the Period.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement was controlled to ~10mm by concurrent compensation grouting, but also by large and rapid consolidation settlement which increased the total settlement within the Period to over 20mm, producing a total settlement of over 40mm. Despite a number of grout jacking episodes, 6 Amber triggers were generated, 2 of which were, for a short duration, in excess of the Red trigger, as detailed in Table 4.1.
- In Period E the construction of PTE with concurrent grouting had an immediate effect between distances 65m and 85m but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 50mm despite further grout jacking. The CP excavations had little apparent immediate effect. A Red trigger was generated due to the post construction movements (see Table 4.1)
- In Period F, there was a further increase in total settlement to ~60mm associated with the construction of CH2 and ongoing consolidation settlement. The magnitude of movement was mitigated by concurrent grouting and subsequent grout jacking.
- Post construction, in Period G, settlement has continued to increase. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, there are no Deflection Ratio trigger breaches.

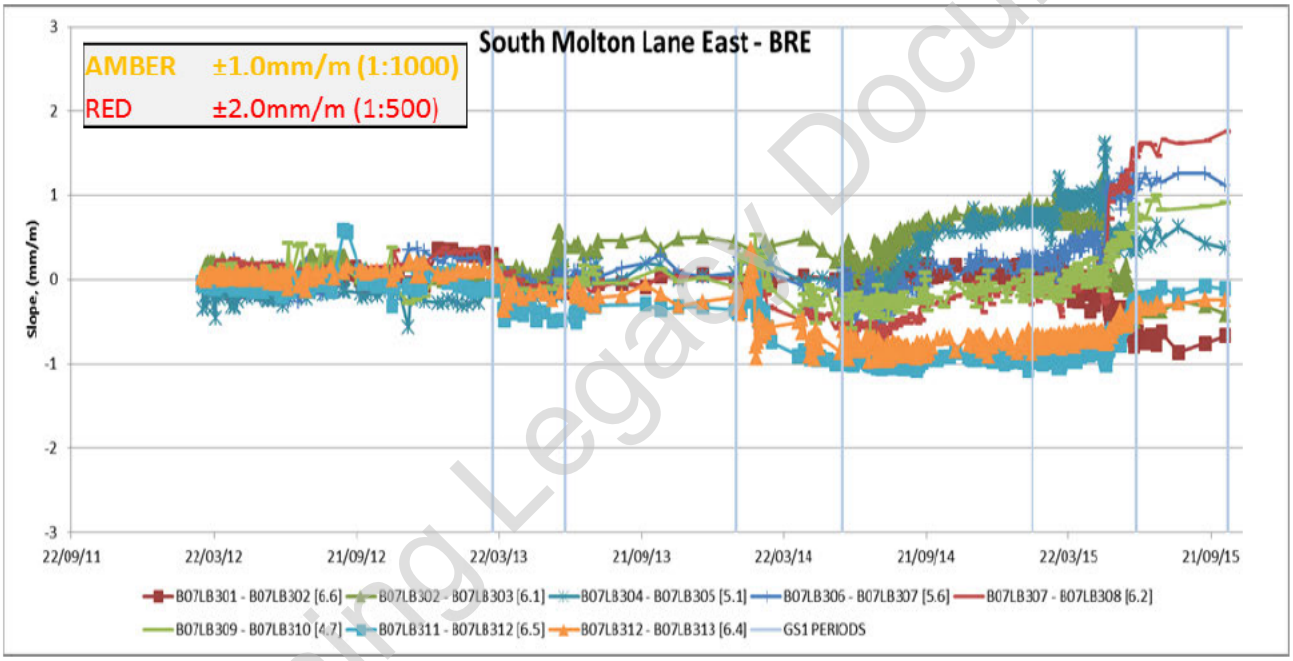
4.3. South Molton Lane East

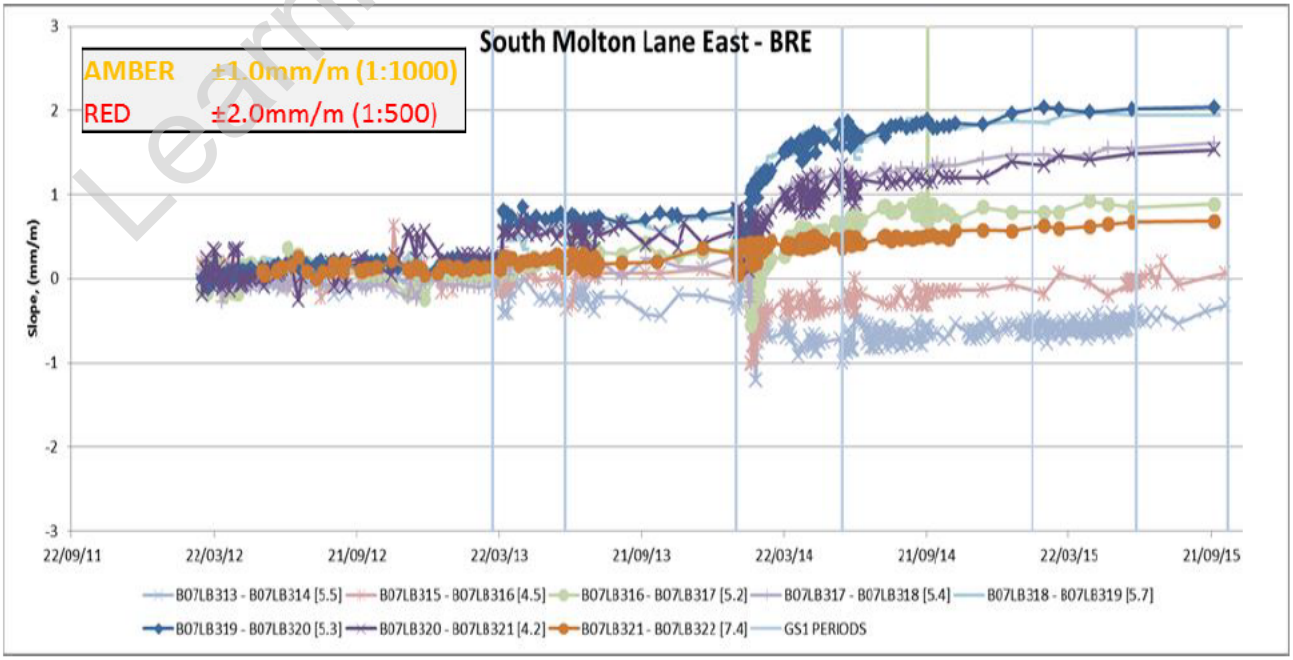


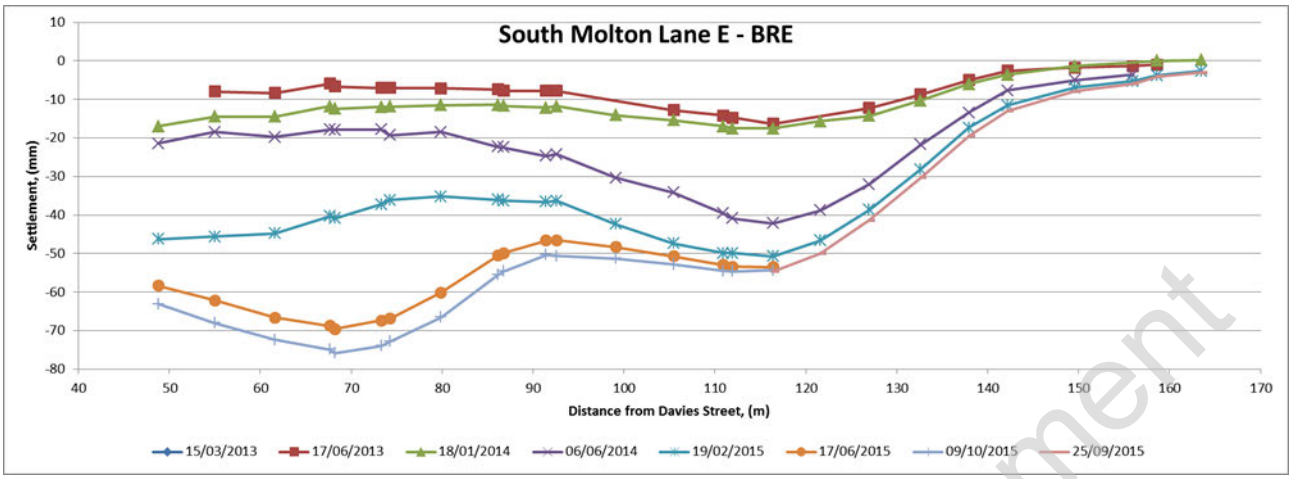








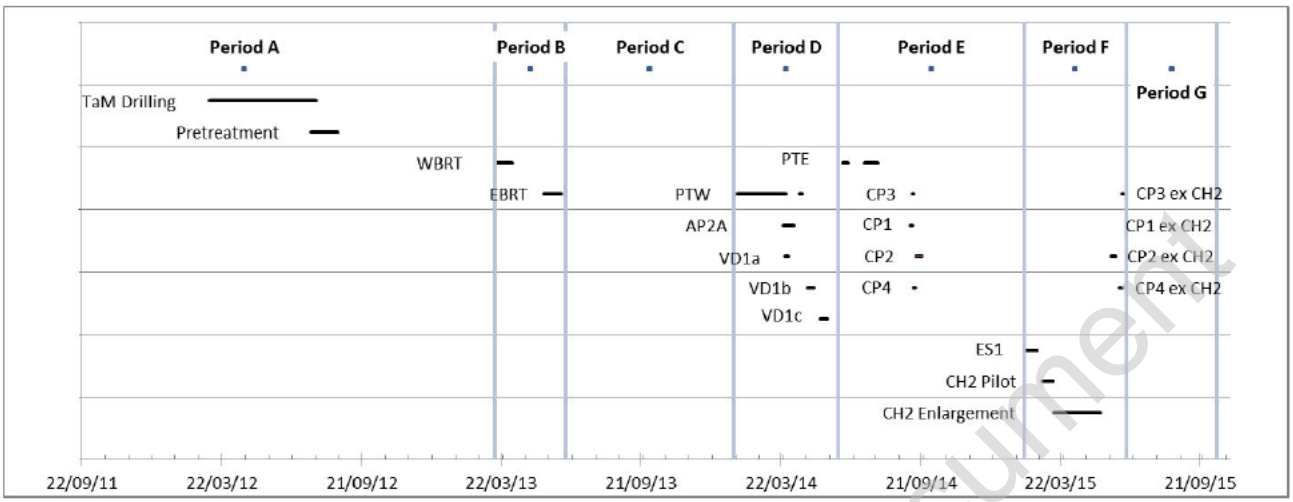


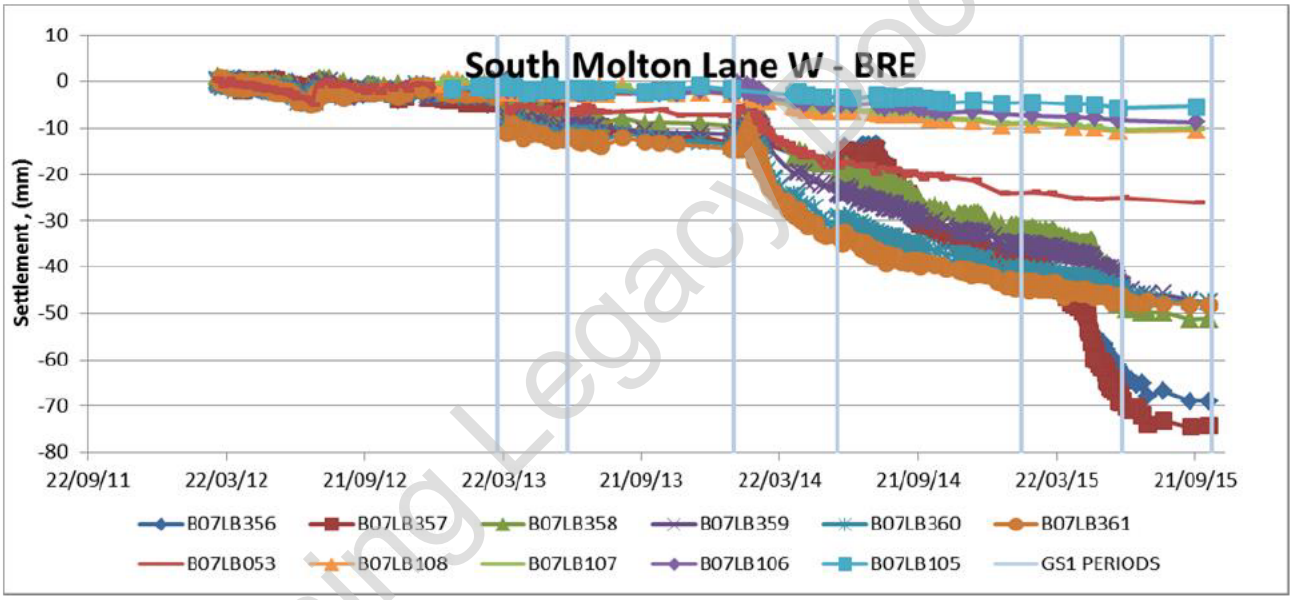


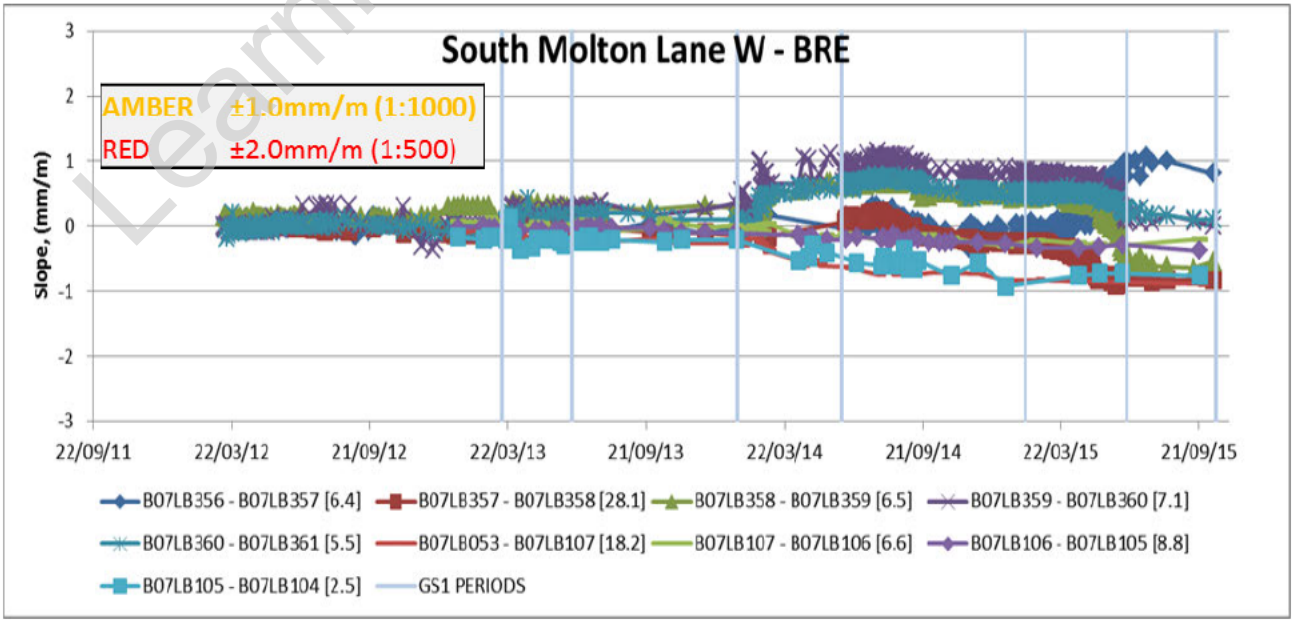
The following points are noted:

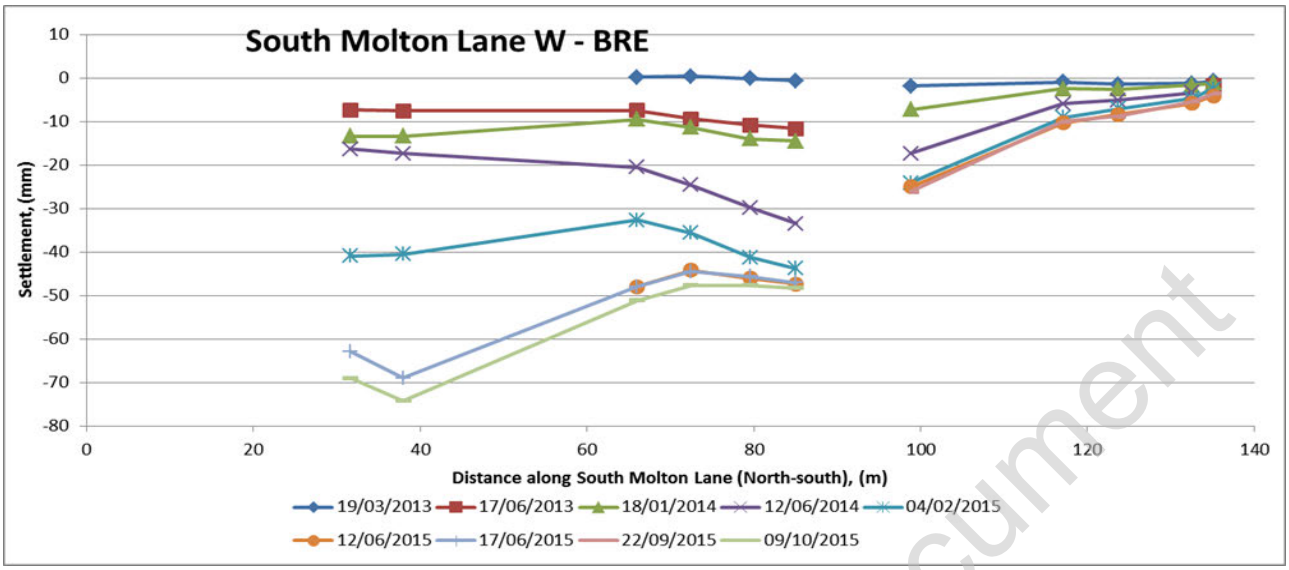
- The southern part of the South Molton Lane east façade is within the GS1 array (from distance 60m): data from all points shown on Figure 4.1 are presented.
- The South Molton Lane east façade is the rear of the buildings on South Molton Street West which are approximately 15m apart: consequently the behaviour is similar to that described in Section 4.2. The exception to this is that there is a greater impact from CH2 since the tunnel ends below the buildings.
- The South Molton Lane east facade traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTW in Period D and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm but there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a further 10mm settlement with a trough extending from distance 90m to 140m even though grout jacking was undertaken. No significant effect is evident from the EBRT.
- In Period C there was little change: grout jacking at the start of the Period reduced settlement slightly but time-related movement resulted in no or a small increase in settlement by the end of the Period.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement was controlled to ~10mm by concurrent compensation grouting, but also by large and rapid consolidation settlement which increased the total settlement within the Period to over 20mm, producing a total settlement of over 40mm. Despite a number of grout jacking episodes, 7 Amber triggers were generated, 2 of which were for a short duration only and a further 3 of which were due to post construction movements some time after the tunnelling. Details are given in Table 4.1.
- In Period E the construction of PTE had an immediate effect between distances 50m and 90m but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 50mm despite further grout jacking. The CP excavations had little apparent immediate effect.
- In Period F, there was a further increase in total settlement to ~70mm associated with the construction of CH2 and an increased rate of consolidation settlement. One marginal Red trigger occurred (max 2.04mm/m) prior to CH2 construction but this changed by a negligible amount due to CH2 movements. The magnitude of movement was mitigated by concurrent grouting and subsequent grout jacking.
- Post construction, in Period G, settlement has continued to increase. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, there are no Deflection Ratio trigger breaches.

4.4. South Molton Lane - West





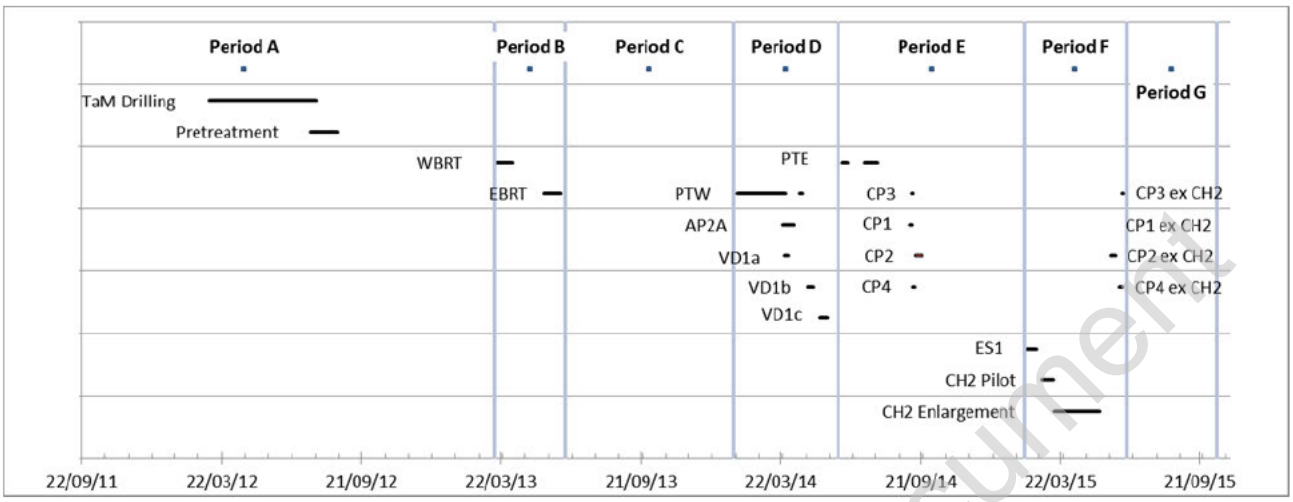


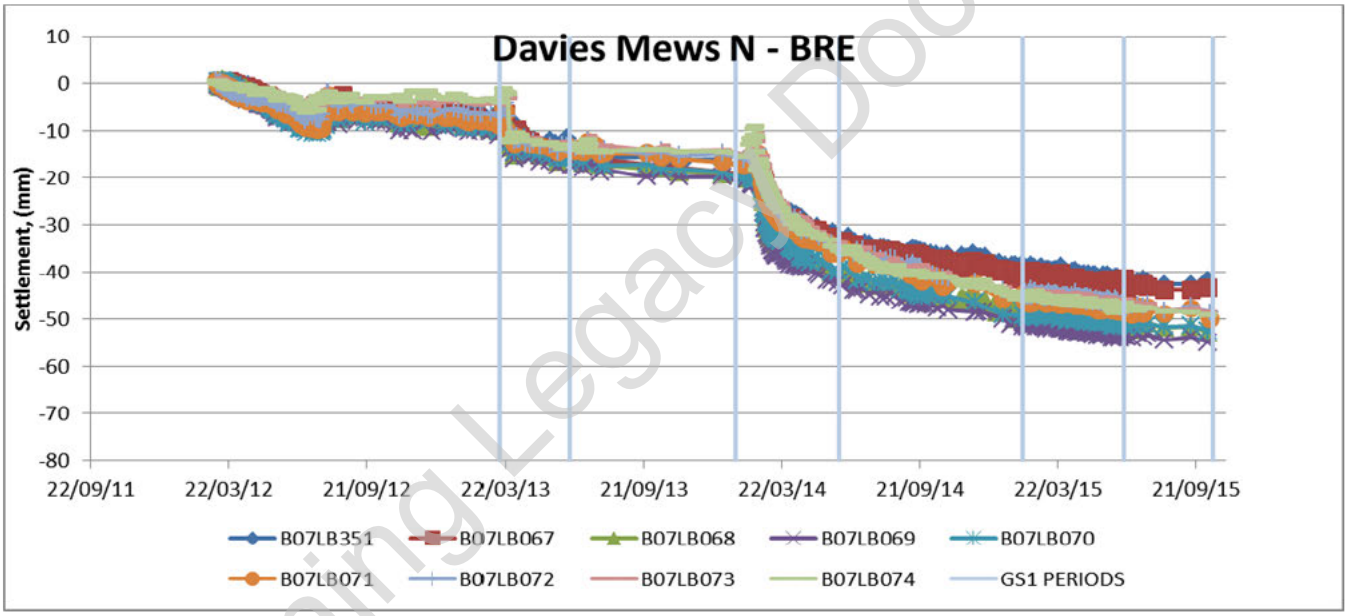


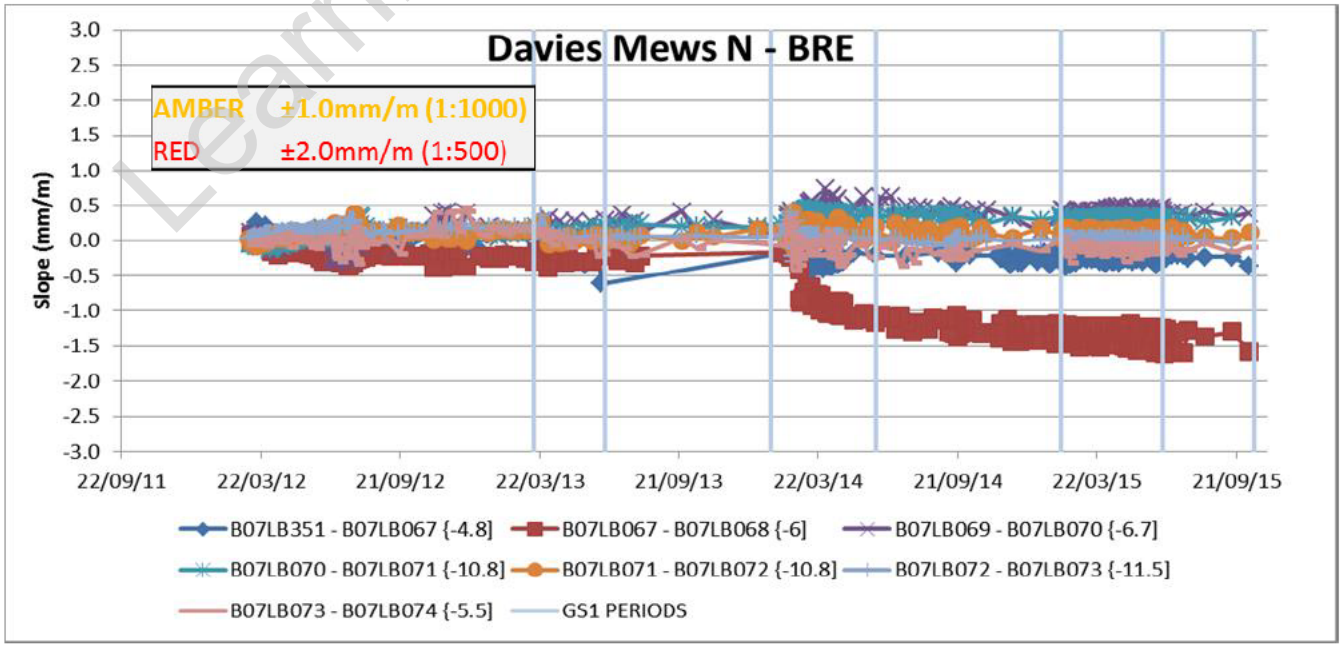
The following points are noted:

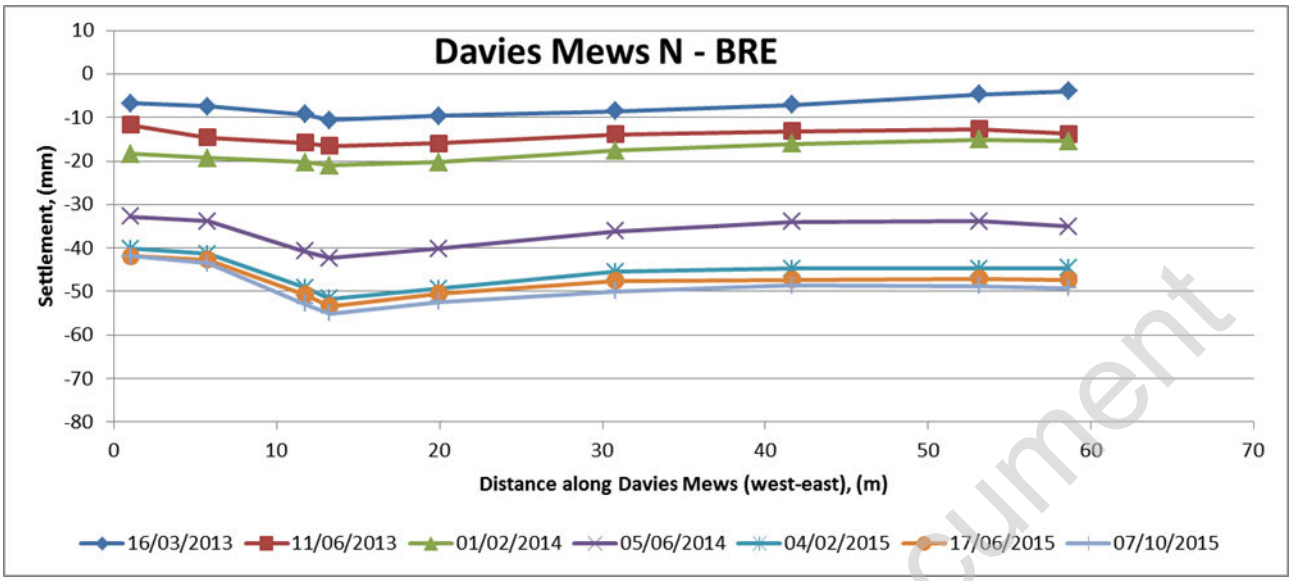
- The southern part of the South Molton Lane west façade is within the GS1 array (from distance 35m): data from all points shown on Figure 4.1 are presented.
- The South Molton Lane west façade is parallel to the east façade and separated by only about 6m: consequently the behaviour is similar to that described in Section 4.3, except that the continuity of the façade is broken by Davies Mews.
- The South Molton Lane west facade traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTW in Period D and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~5mm and there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a further 10mm settlement even though grout jacking was undertaken. No significant effect is evident from the EBRT.
- In Period C there was little change: grout jacking at the start of the Period reduced settlement slightly but time-related movement resulted in no or a small increase in settlement by the end of the Period.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement was controlled to ~10mm by concurrent compensation grouting, but also by large and rapid consolidation settlement which increased the total settlement within the Period to almost 20mm, producing a total settlement of 34mm. 1 Amber trigger was generated due to post construction movements some time after the tunnelling. Details are given in Table 4.1.
- In Period E the construction of PTE had an immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 40mm despite further grout jacking. The CP excavations had little apparent immediate effect.
- In Period F, there was a further increase in total settlement to ~70mm associated with the construction of CH2 and an increased rate of consolidation settlement. The magnitude of movement was mitigated by concurrent grouting and subsequent grout jacking.
- Post construction, in Period G, settlement has continued to increase. As expected the movements become relatively uniform and hence the impact on slopes becomes minor. 1 transitory Amber trigger was generated due to post construction movements some time after the completion of tunnelling. Details are given in Table 4.1.
- By inspection, there are no Deflection Ratio trigger breaches.

4.5. Davies Mews - North





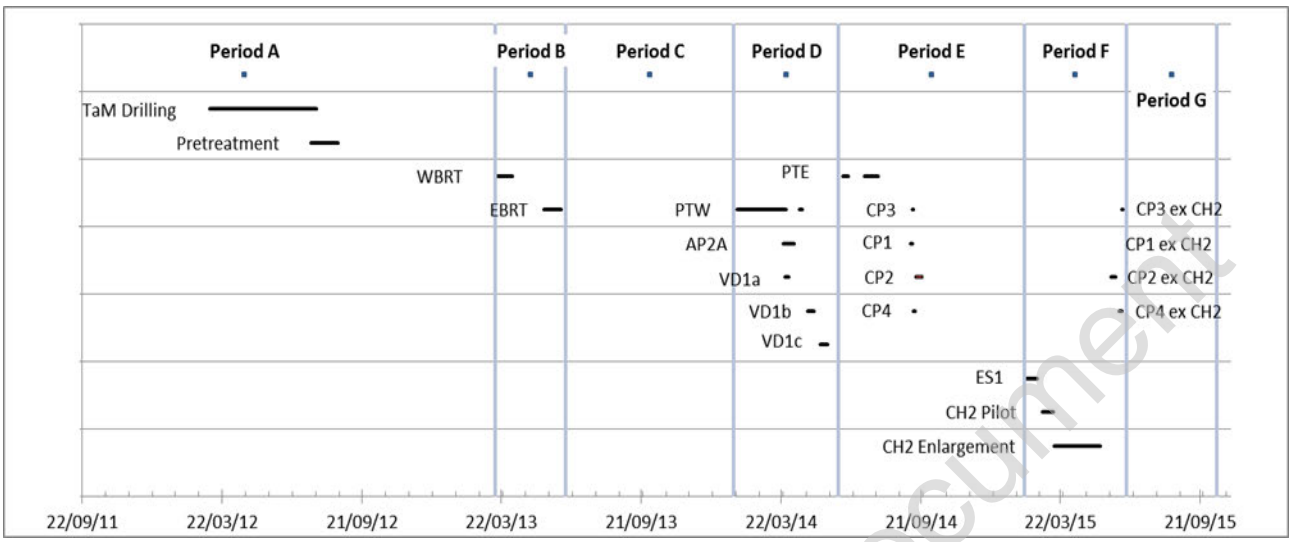


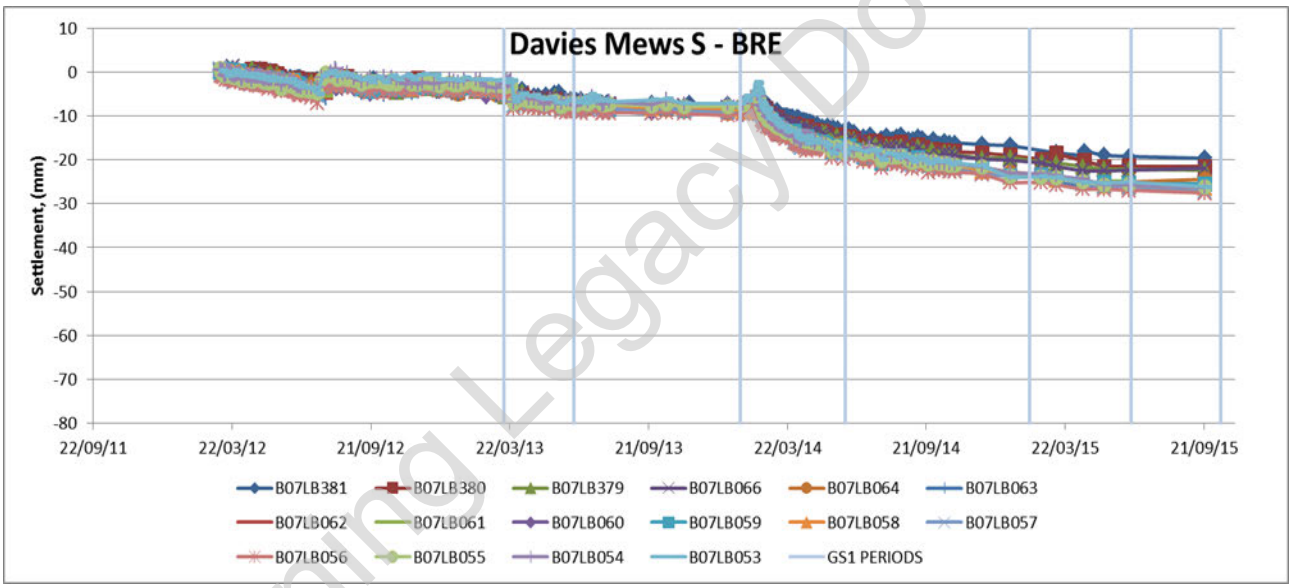


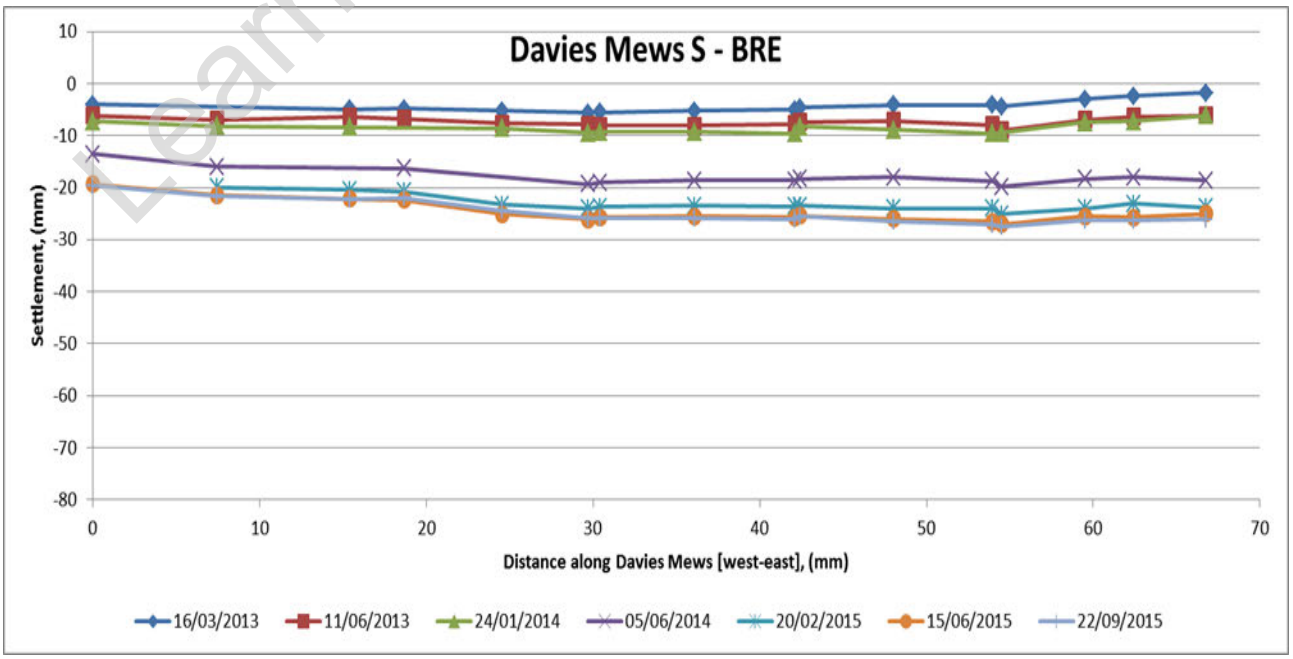
The following points are noted:

- The north façade of Davies Mews is sub-parallel to the PTW lying directly above the tunnel at its east end and gradually diverging to the west. The full extent of the façade is within the GS1 array.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm but there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a further 10mm settlement even though grout jacking was undertaken. No significant effect is evident from the EBRT. Maximum settlement was about 17mm at the end of Period B.
- In Period C there was a small increase in settlement giving a maximum of 20mm by the end of the Period.
- The construction of the PTW in Period D had a more significant effect, not just during construction where settlement was controlled to ~10mm by concurrent compensation grouting, but also by large and rapid consolidation settlement which increased the total settlement within the Period to about 20mm, producing a total settlement of up to 41mm. 1 Amber trigger was generated due a difference in response at the west end of the façade which resulted in lower movements. Details are given in Table 4.1.
- In Period E there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 50mm.
- In Period F, there was no direct impact from the construction of CH2 and continued consolidation settlement increased settlement uniformly by about 5mm.
- Post construction, in Period G, settlement has continued to increase. As expected the movements become relatively uniform and hence the impact on slopes becomes minor. The slopes are essentially constant within the repeatability of the data. By inspection, there are no deflection ratio triggers.

4.6. Davies Mews - South



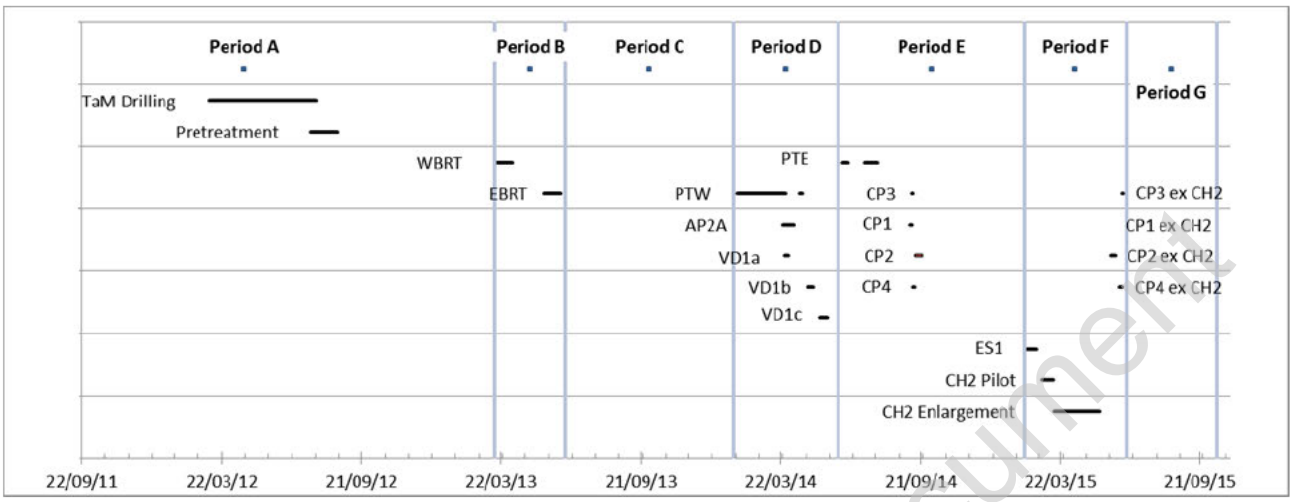


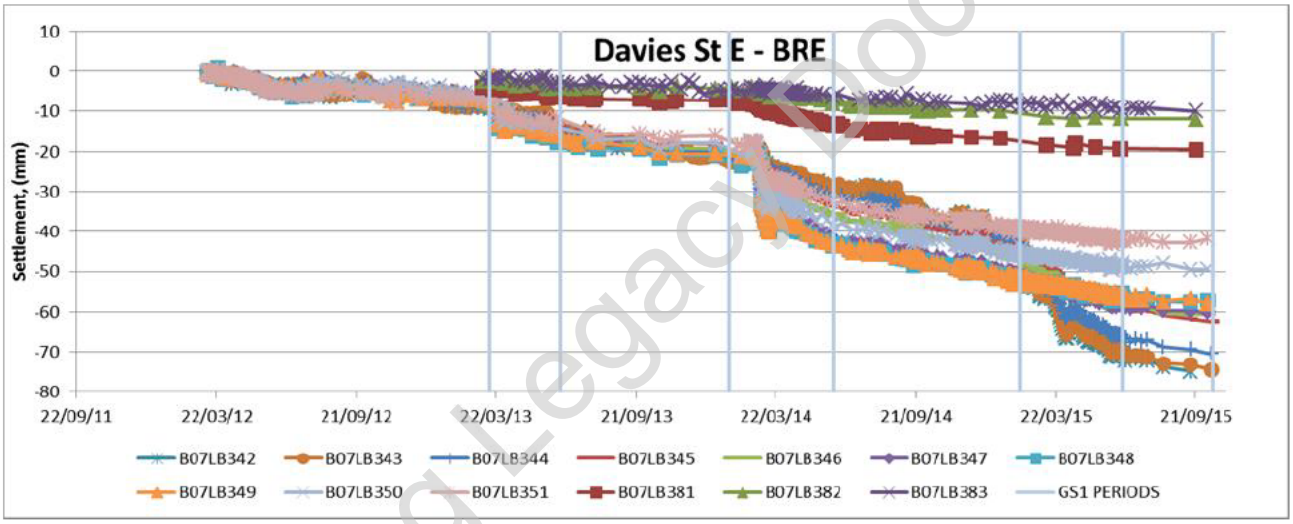


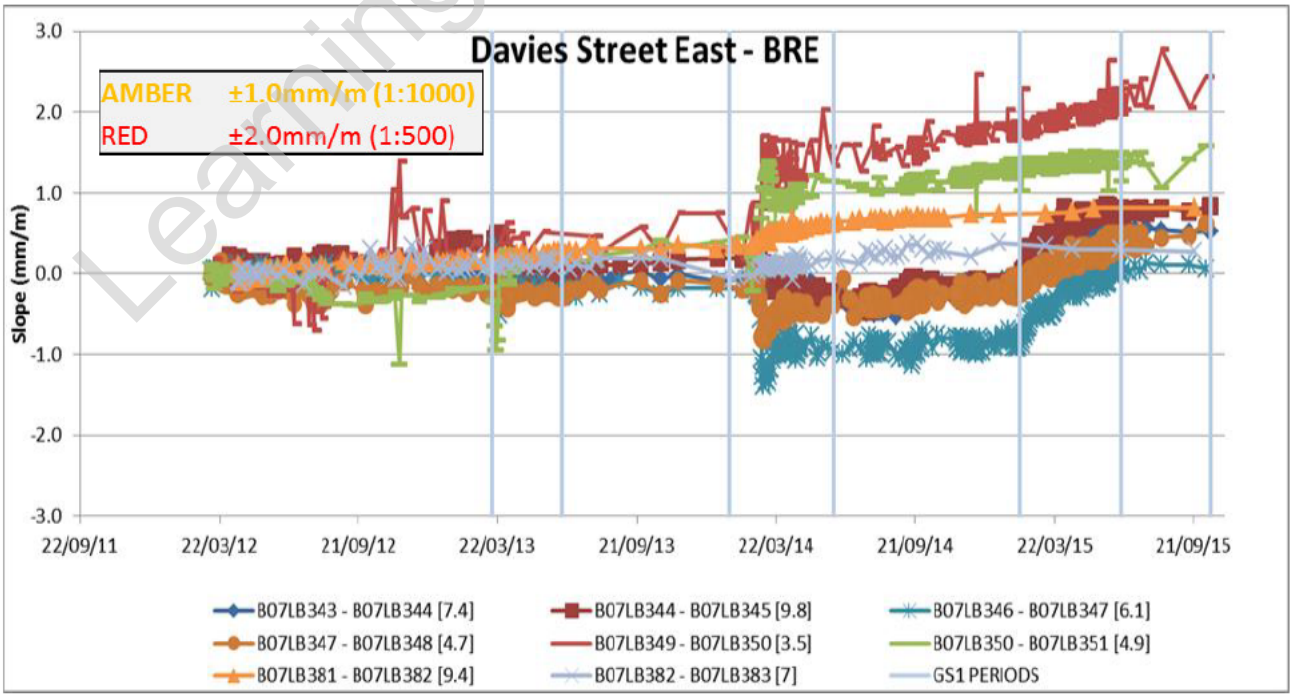
The following points are noted:

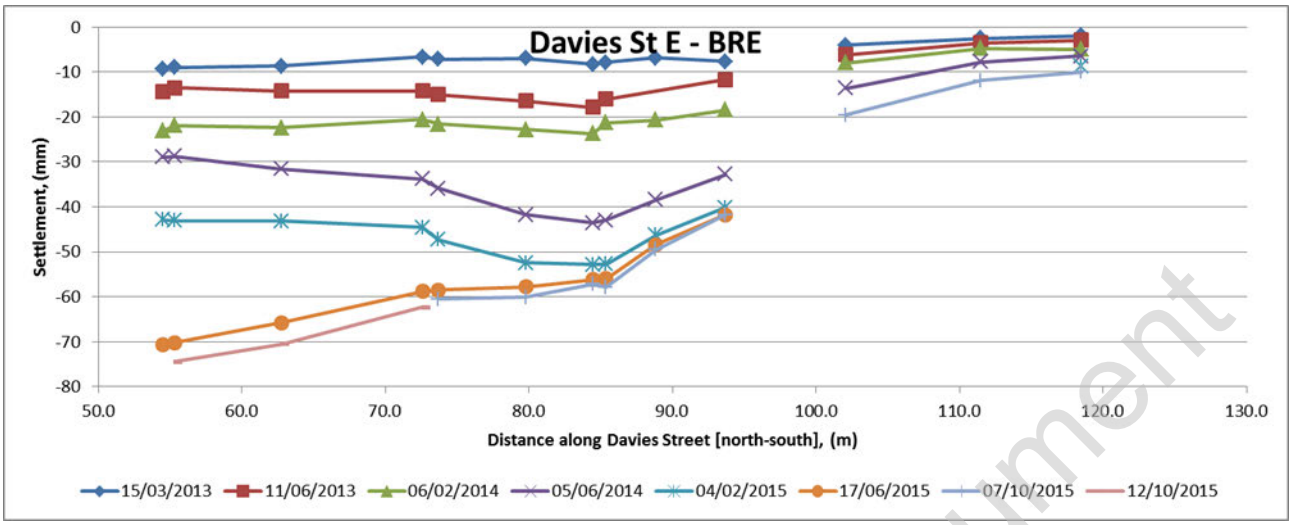
- The south façade of Davies Mews is parallel to north façade at an offset about 9m greater from the PTW gradually diverging to the west. The full extent of the façade is within the GS1 array.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~5mm and there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a further 5mm settlement even though grout jacking was undertaken. Maximum settlement was about 10mm at the end of Period B.
- In Period C there was a negligible increase in settlement giving a maximum of 11mm by the end of the Period.
- The construction of the PTW in Period D had a more significant effect, not just during construction where settlement was controlled to ~5mm by concurrent compensation grouting, but also by consolidation settlement which increased the total settlement within the Period to about 10mm, producing a total settlement of up to 20mm.
- In Period E, F and G there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 8mm to ~28mm.
- By inspection of the time and profile plots, there are no slope triggers.

4.7. Davies Street - East





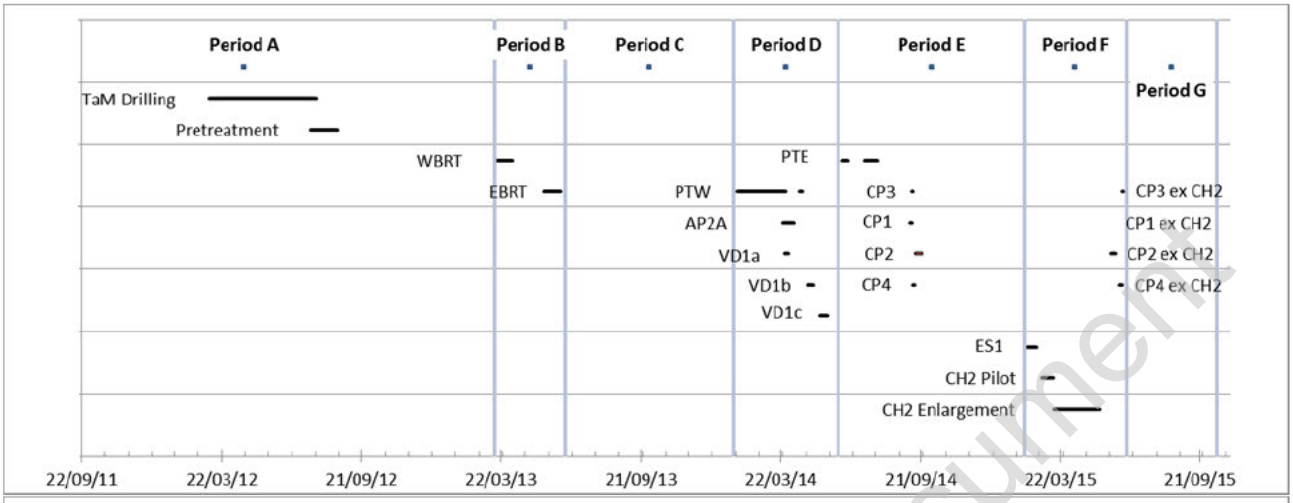


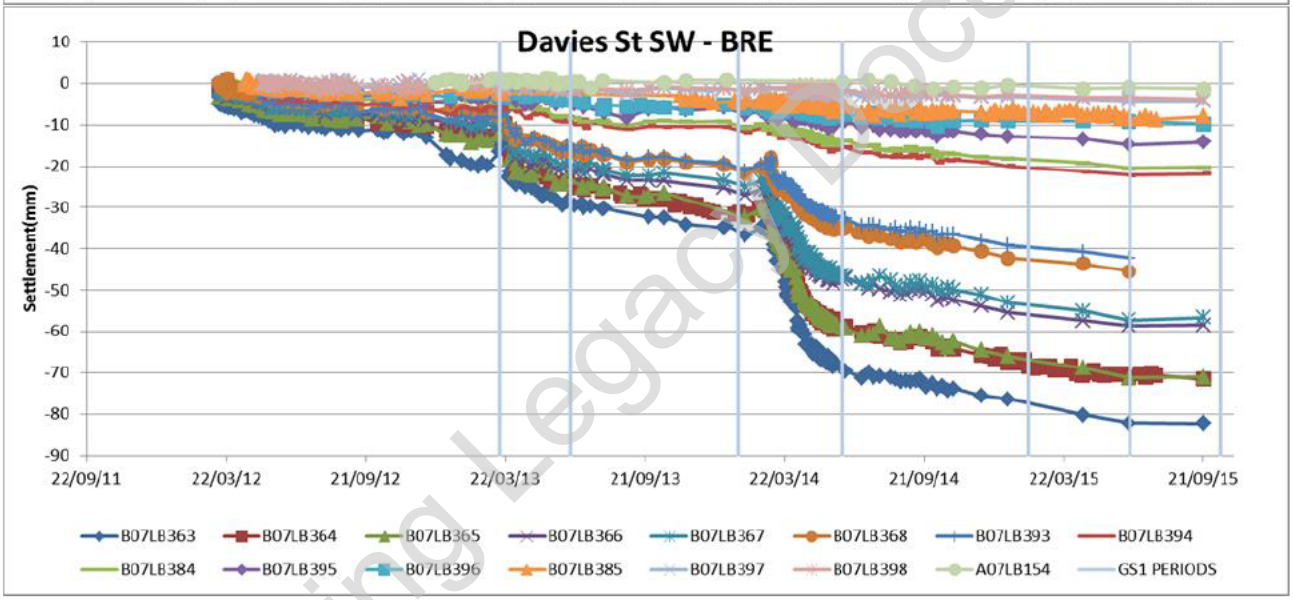


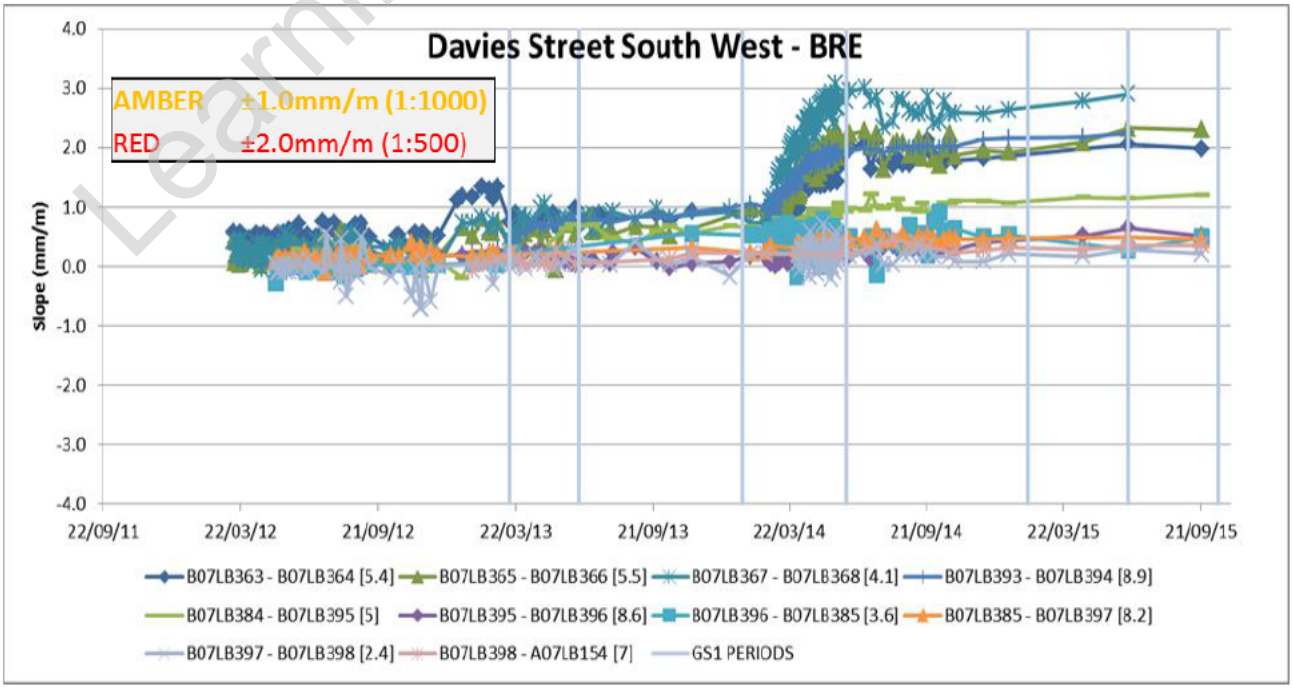
The following points are noted:

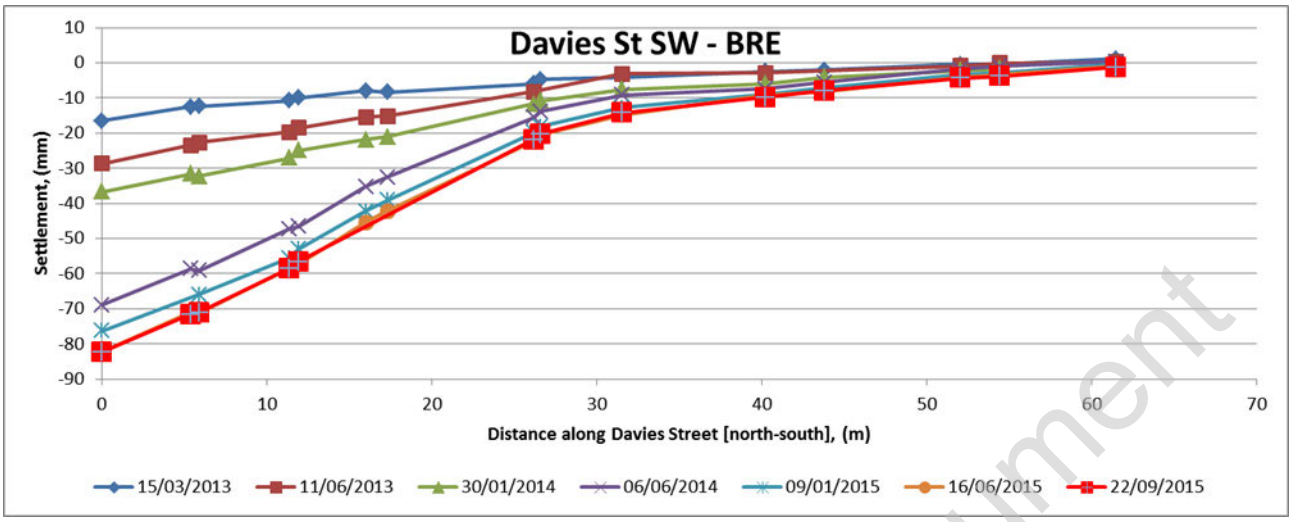
- The southern part of the Davies Street east façade is within the GS1 array (from distance 65m): data from all points shown on Figure 4.1 are presented.
- The Davies Street east façade traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTW in Period D and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm but there was only minor variation over the full length of the façade.
- In Period B, the WBRT and subsequent consolidation generated a further 10mm settlement even though grout jacking was undertaken.
- In Period C there was little change: time-related movement resulted in no or a small increase in settlement by the end of the Period.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement was limited to ~15mm by concurrent grouting, but also by significant consolidation settlement which increased the total settlement within the Period to about 20mm, producing a total settlement of 44mm. Despite a number of grout jacking episodes, 3 Amber triggers were generated. Details are given in Table 4.1.
- In Period E the construction of PTE had a minor immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 50mm despite further grout jacking. The CP excavations also had a minor immediate effect.
- In Period F, there was a further increase in the maximum total settlement to ~70mm associated with the construction of CH2 and an increased rate of consolidation settlement. The location of the greatest settlement moved from over PTW to the northern end of the transect adjacent to CH2. Associated with this change one slope reduced below the Amber trigger level but one of the others exceeded the Red trigger value. Details are given in Table 4.1.
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, there are no Deflection Ratio trigger breaches.

4.8. Davies Street - West





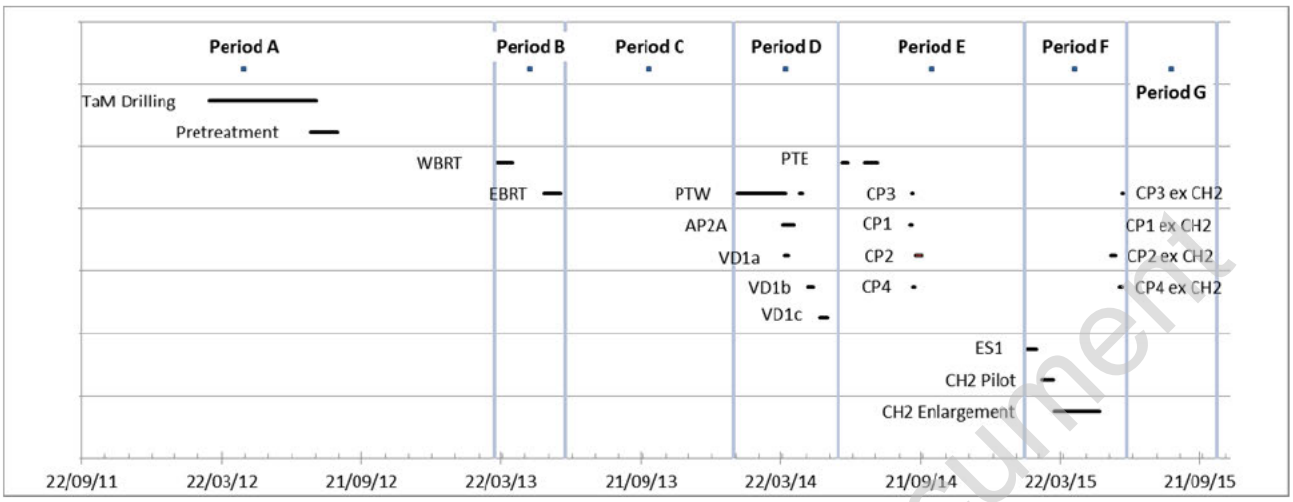


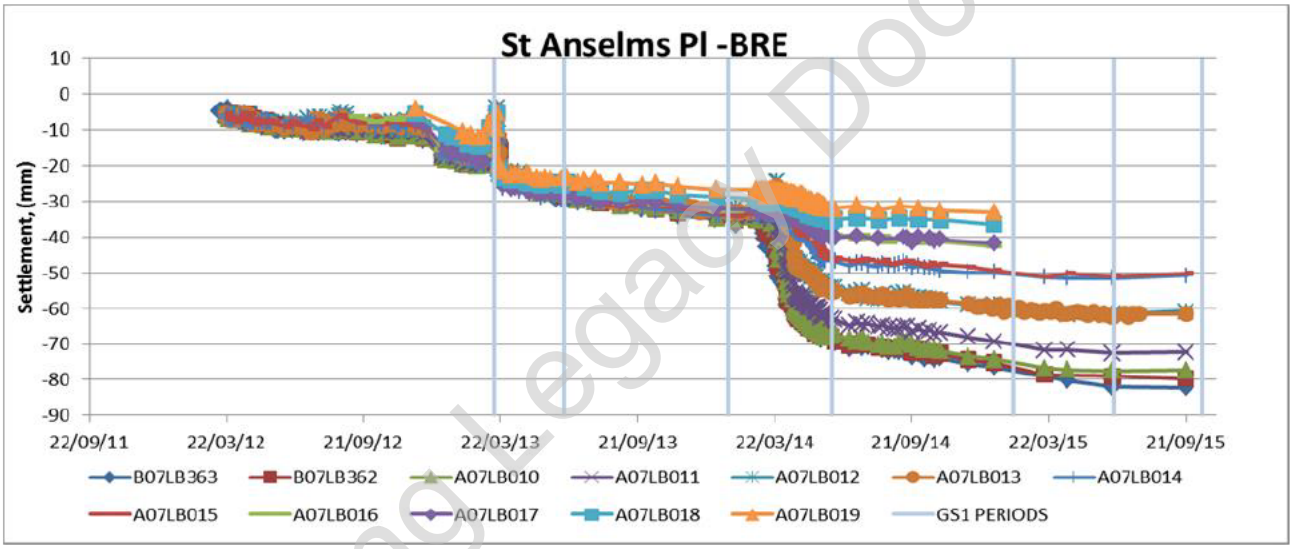


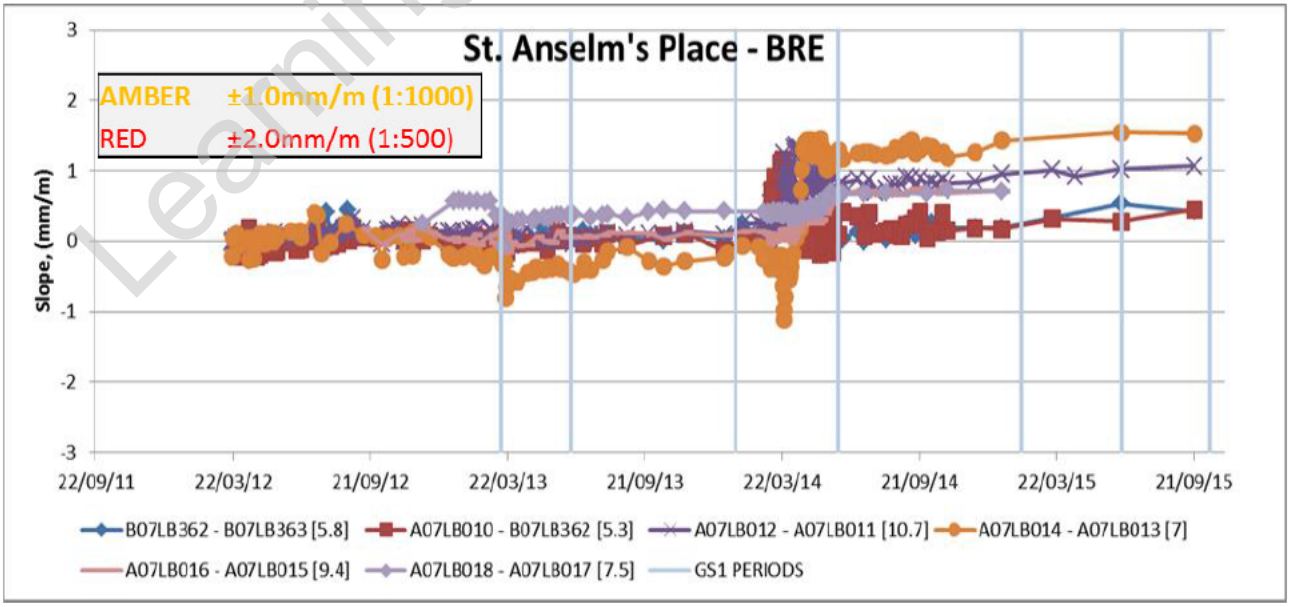
The following points are noted:

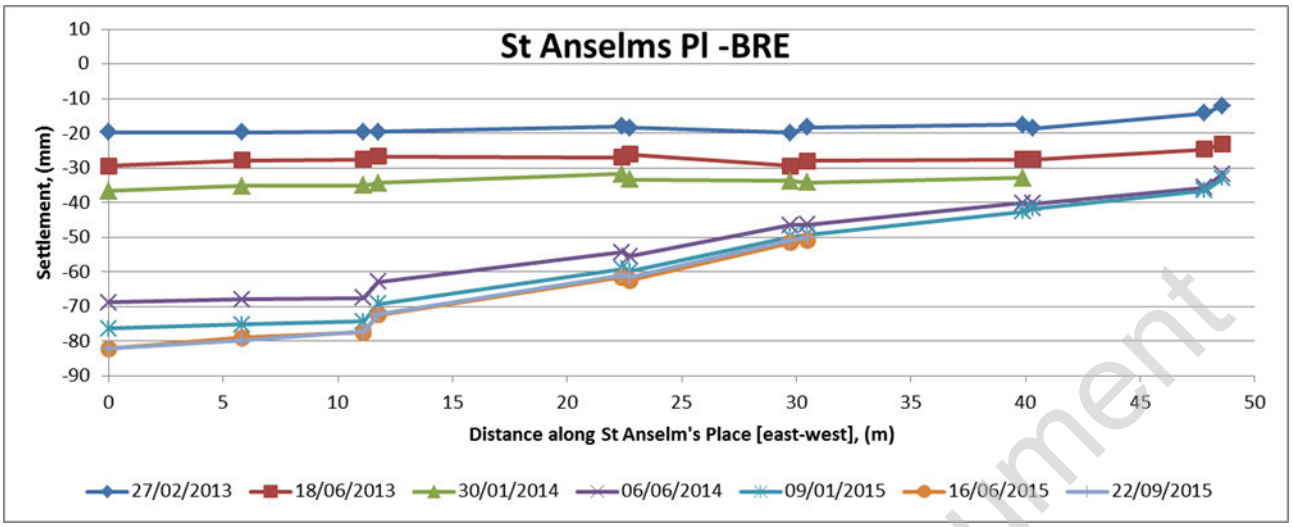
- The northern part of the Davies Street west façade (south of St. Anselm's Place) is within the GS1 array (up to distance 35m): data from all points shown on Figure 4.1 are presented.
- The Davies Street west façade extends from close to the PTW / AP2A junction to the south: the most notable events were the construction of WBRT in Period B and PTW and AP2A in Period D.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~18mm with the maximum value located at the north end of the façade, adjacent to the WTH.
- In Period B, the WBRT and subsequent consolidation generated a further 10mm settlement even though grout jacking was undertaken.
- In Period C time-related movement resulted in an increase in settlement of 9mm to a maximum of 38mm by the end of the Period.
- The construction of the PTW in Period D had a major effect but not just during construction at the start of the Period where the effect of concurrent grouting producing a small uplift is evident. Excavation was followed by significant consolidation settlement which increased the total settlement within the Period to over 30mm, producing a total settlement of 70mm, despite further grout jacking. 2 Red and 2 Amber trigger were generated. Details are given in Table 4.1.
- In Periods E and F the tunnelling had no immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 12mm to over 80mm. The slopes also continued to increase and at the end of Period F, there were 4 Red triggers and 1 Amber trigger.
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, there are no Deflection Ratio trigger breaches.

4.9. St Alselm's Place - South





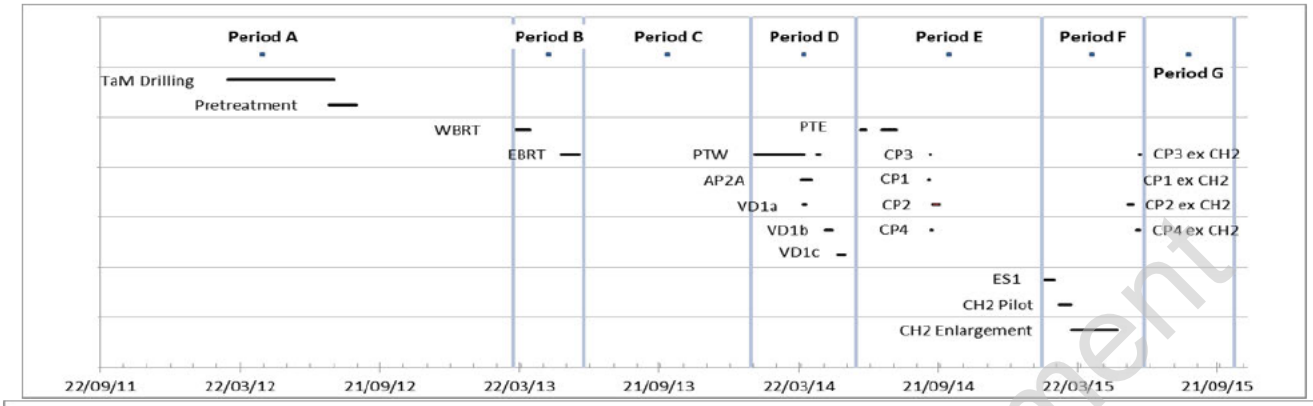


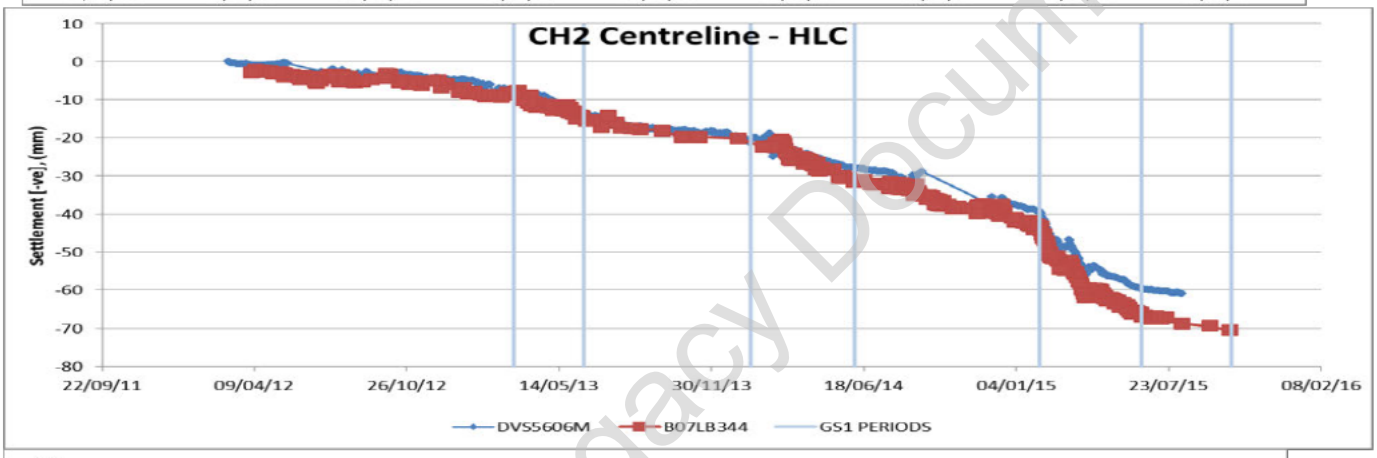


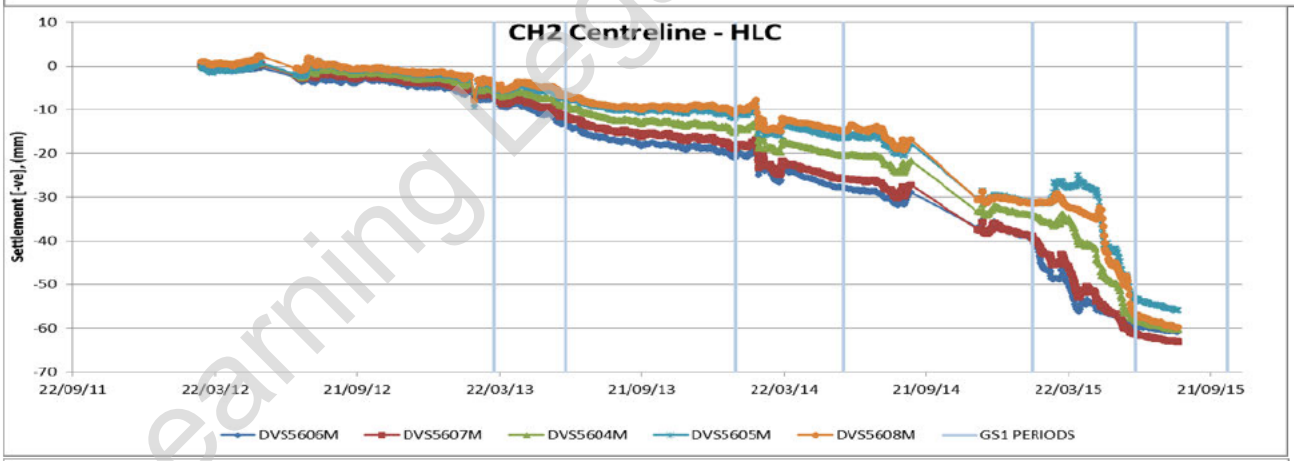
The following points are noted:

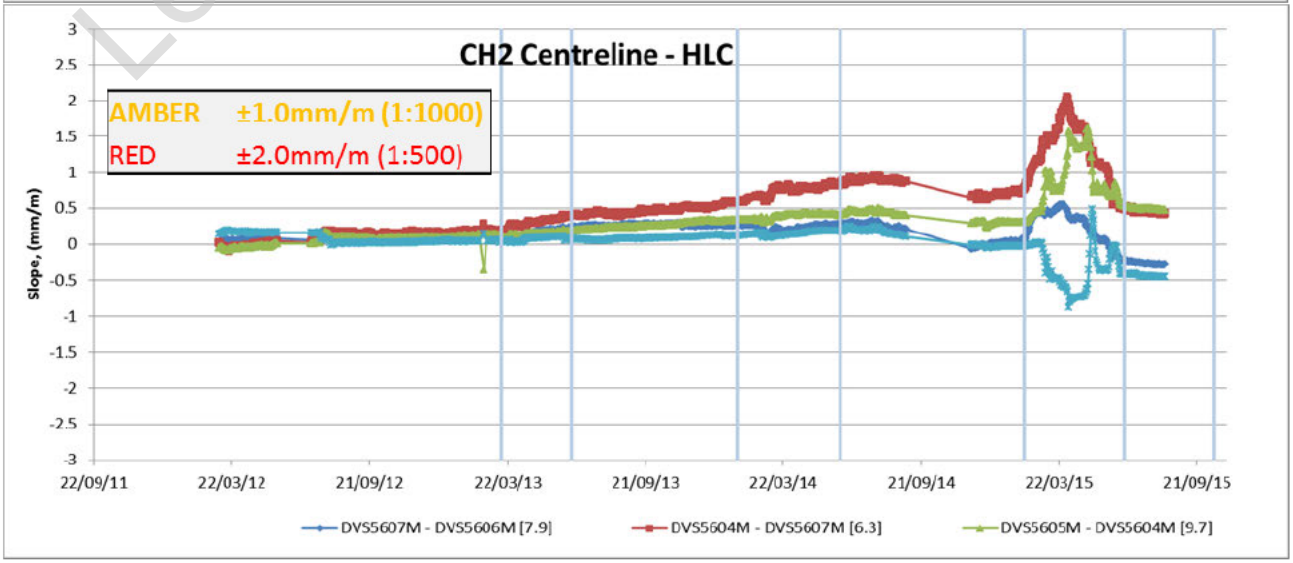
- The St Anselm's Place façade extends from the northern end of the Davies Street west façade (see Section 4.8) to the west approximately parallel to the WTH south wall and over the PTW and WBRT. The façade is within the GS1 array up to distance 30m: data from all points shown on Figure 4.1 are presented.
- The most notable events were the construction of WBRT in Period B and PTW and AP2A in Period D.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~20mm with the maximum value located at the west end of the façade, adjacent to the Davies Street.
- In Period B, the WBRT and subsequent consolidation generated a further 10mm settlement, despite uplift of 5mm generated by grout jacking.
- In Period C time-related movement resulted in an increase in settlement of 8mm to a maximum of 38mm by the end of the Period.
- The construction of the PTW in Period D had a major effect both during construction at the start of the Period and afterwards. The effect of concurrent grouting producing a small uplift is evident which generated a transitory (negative) Amber trigger at the extremity of the grout array (A07LB014-A07LB013). This slope reversed in direction and exceeded the Amber trigger value in the opposite sense (positive) as the tunnel excavation progressed and the amount of grouting was restricted by the extent of the arrays and the exclusion zone over the tunnel face.
- Excavation of PTW was followed by significant consolidation settlement which increased the total settlement within Period D to over 30mm, producing a total settlement of 70mm, despite further grout jacking. 3 Amber triggers were generated, albeit 2 of these were transitory, leaving 1 remaining Amber trigger at the end of the Period. Details are given in Table 4.1.
- In Periods E and F the tunnelling had no immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 12mm to over 80mm. The slopes also continued to increase and at the end of Period F, there were 2 Amber triggers.
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, there are no Deflection Ratio trigger breaches.

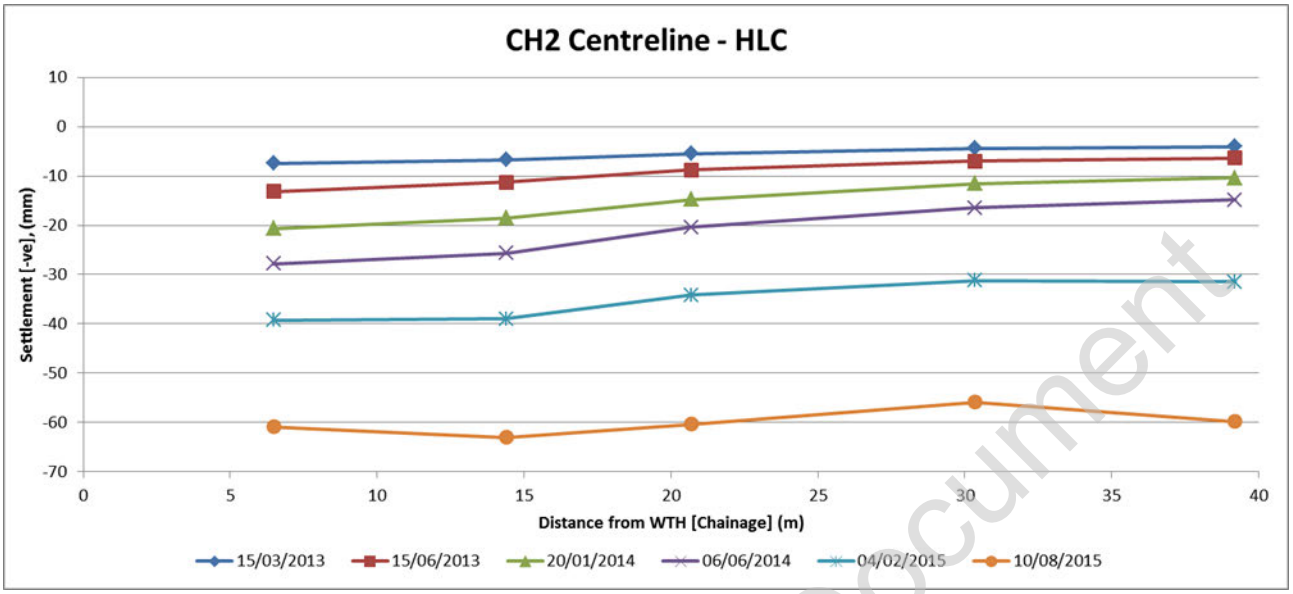
4.10. TA Centre, 56 Davies Street over CH2











The following points are noted:

- Although the HLC are primarily for construction control, damage was observed in the TA Centre, 56 Davies Street located directly above CH2. Four Crackmeters were installed (the data is presented in Appendix B) and the only settlement monitoring data applicable is from HLC. It is noted that the HLC from which data are presented are not located on a façade or a party wall.
- A comparison is presented between an HLC located close to the Davies Street east façade and a nearby BRE in the façade. This shows that the HLC closely matched the manual survey data up to Period C. Subsequently the HLC showed an increasing but gradual divergence with time: this is attributed to settlement of the reference cell and does not affect the *relative movements* i.e. the slopes, between the HLC.
- During Periods A to E there is little direct impact for any of the tunnels constructed or from concurrent grouting and no grout jacking was targeted at this area. Settlement increased gradually to about 40mm on Davies Street and 30mm on South Molton Lane. No slope trigger values were exceeded.
- In Period F, there was a further increase in the maximum total settlement to ~60mm associated with the construction of CH2 and an increased rate of consolidation settlement. The progression of settlement as the tunnel advanced can be seen on the timeplot as each sensor successively settled. This is directly reflected in the calculated slopes which show large, transitory changes as the settlement trough extends. A Red and an Amber slope occurred during construction but by the end of Period F all slopes were less than 0.5mm/m.
- The Crackmeters were installed during Period F as damage was reported during construction of CH2. The concurrent grouting strategy was modified and this was successful in both reducing slopes and generating closure of two of the cracks (see Appendix B).
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.

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. A larger version of Figure 5.1 is included in Appendix B. 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

Comparison of Figures 4.1 and 5.1 shows that slope triggers on buildings and on the ground have occurred in similar locations. This is as expected since no significant differential between building settlement and the adjacent pavements has been identified at reviews during construction. Consequently the commentary on the PLP monitoring data is essentially similar to that for the BRE data presented in Section 4.

Figure 5.1.1 Locations where ground slope triggers have been exceeded.

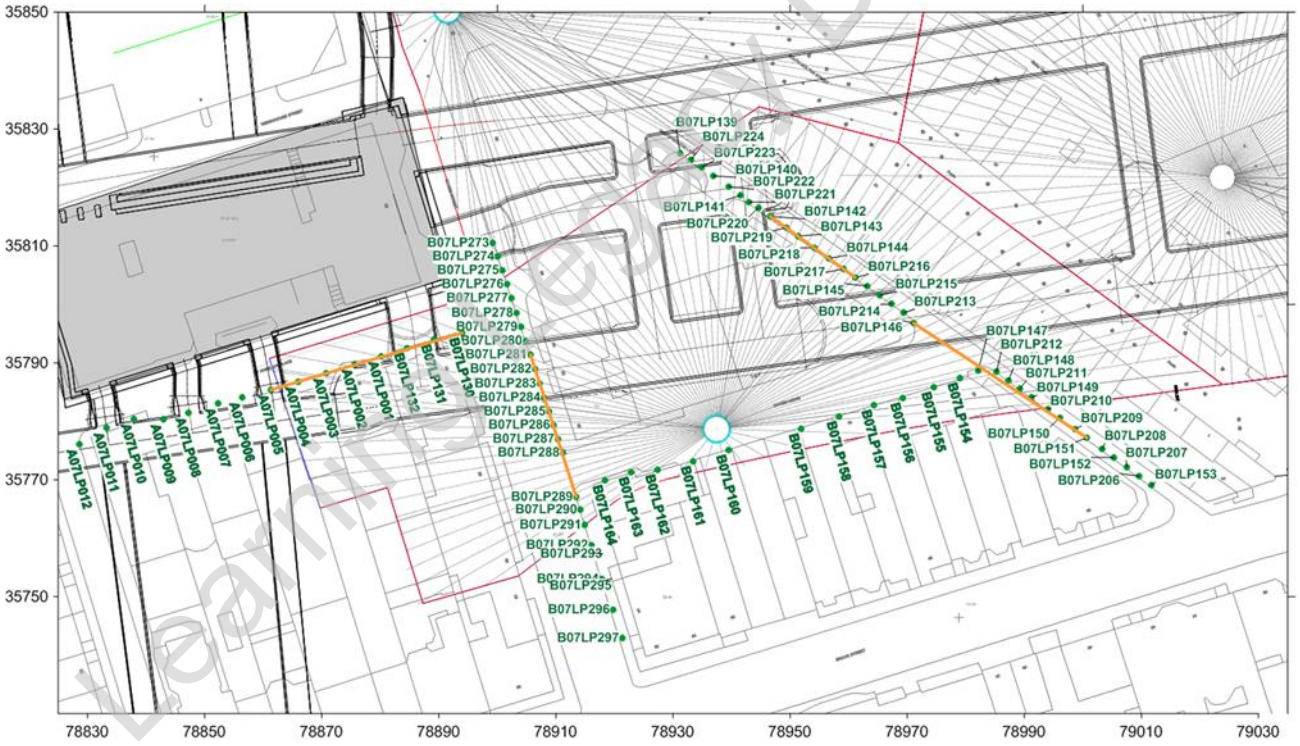


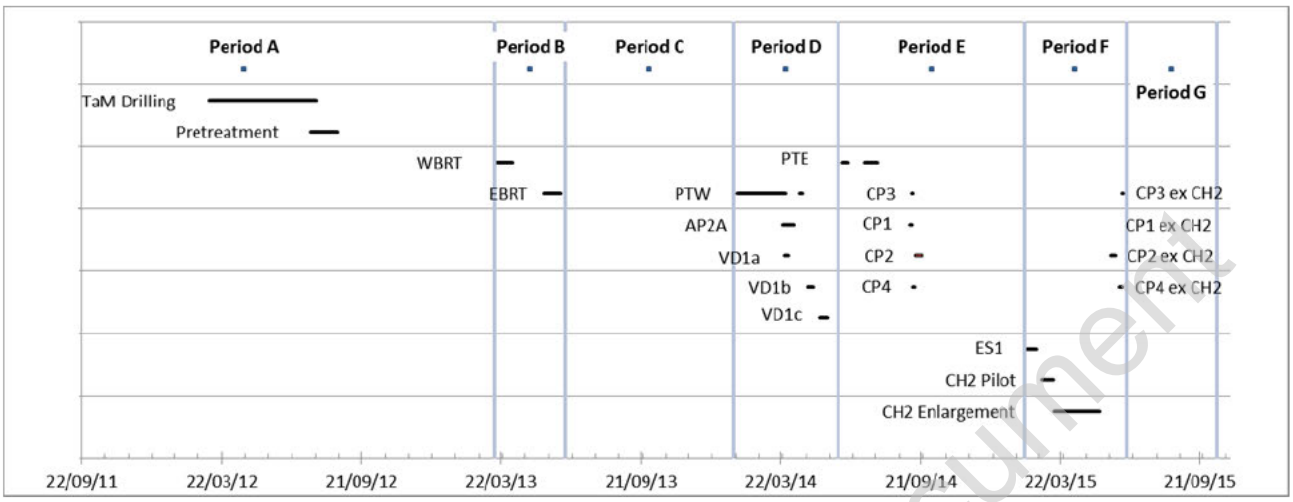
Table 5.1 Details of trigger breaches on PLP

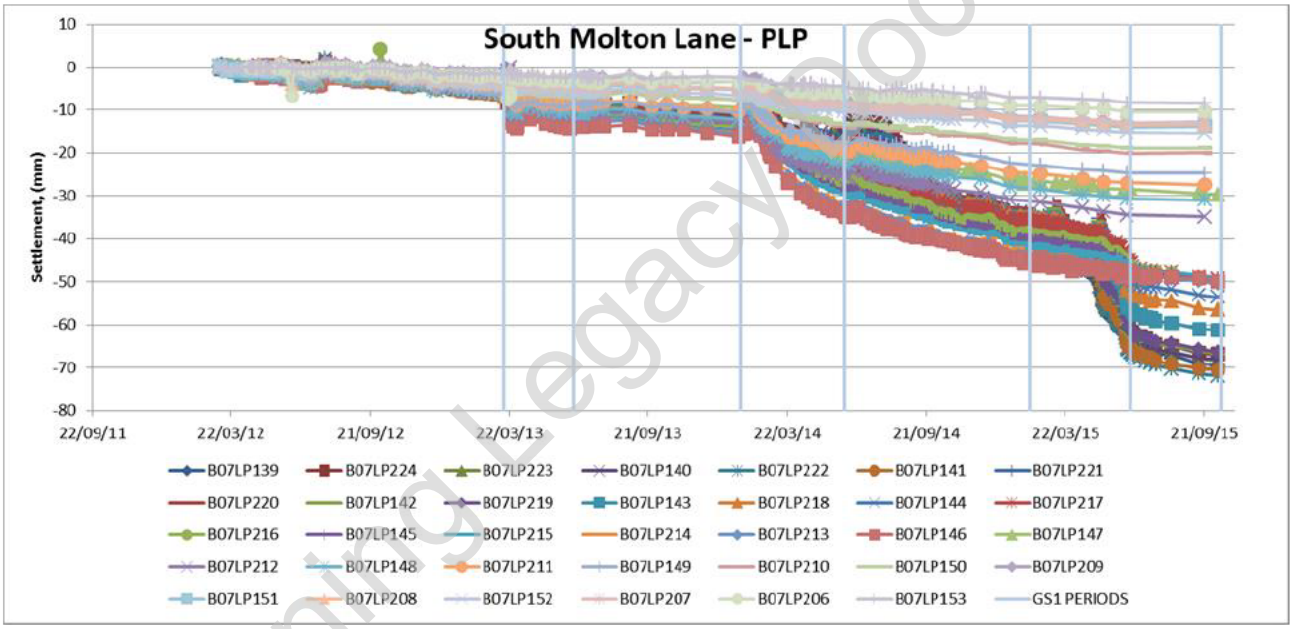
GROUND POINTS		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Davies Mews - South: NONE					
St Anselms					
A07LP003-A07LP005	Amber	Transitory during PTW / AP2A to 19/04/14	24/03/2014	1.92	0.50
A07LP002-A07LP004	Amber	Transitory during PTW / AP2A to 16/04/14	23/03/2014	1.63	0.42
B07LP132-A07LP002	Amber	Transitory during PTW / AP2A to 03/05/14 - Single reading at 2.01 not confirmed	24/03/2014	2.01	0.85
B07LP131-A07LP001	Amber	Transitory during PTW / AP2A to 16/04/14	28/03/2014	1.74	0.25
A07LP005-A07LP007	Amber	Transitory during PTW / AP2A to 10/03/14	03/03/2014	1.21	0.10
Davies Street (E)					
B07LP277-B07LP281	Amber	Transitory during PTW to 20/03/14	05/03/2014	1.14	0.14
B07LP278-B07LP282	Amber	Transitory during PTW to 20/03/14	04/03/2014	1.30	0.15
B07LP279-B07LP283	Amber	Transitory during PTW to 20/03/14	07/03/2014	1.15	0.26
B07LP281-B07LP285	Amber	CH2	14/02/2015	1.41	1.41
B07LP282-B07LP286	Amber	PTW	07/03/2014	1.73	1.73
B07LP283-B07LP287	Amber	PTW	05/03/2014	1.83	1.83
B07LP284-B07LP288	Amber	PTW	07/03/2014	1.64	1.62
B07LP288-B07LP289	Amber	Post PTW	17/03/2015	1.41	1.41
South Molton Lane					
B07LP142-B07LP144	Amber	Post CH2	09/06/2015	1.31	1.30
B07LP219-B07LP217	Amber	Post CH2	31/05/2015	1.69	1.69
B07LP143-B07LP216	Amber	Post CH2	22/06/2015	1.15	1.11
B07LP146-B07LP147	Amber	PTW. Final reading RED but not confirmed	25/03/2014	2.00	2.00
B07LP212-B07LP210	Amber	Post PTW	20/04/2014	1.47	1.47
B07LP148-B07LP150	Amber	Post PTW	28/10/2014	1.20	1.20
B07LP211-B07LP209	Amber	Post PTW	15/04/2014	1.45	1.45
B07LP149-B07LP151	Amber	Post PTW	19/02/2015	1.09	1.09

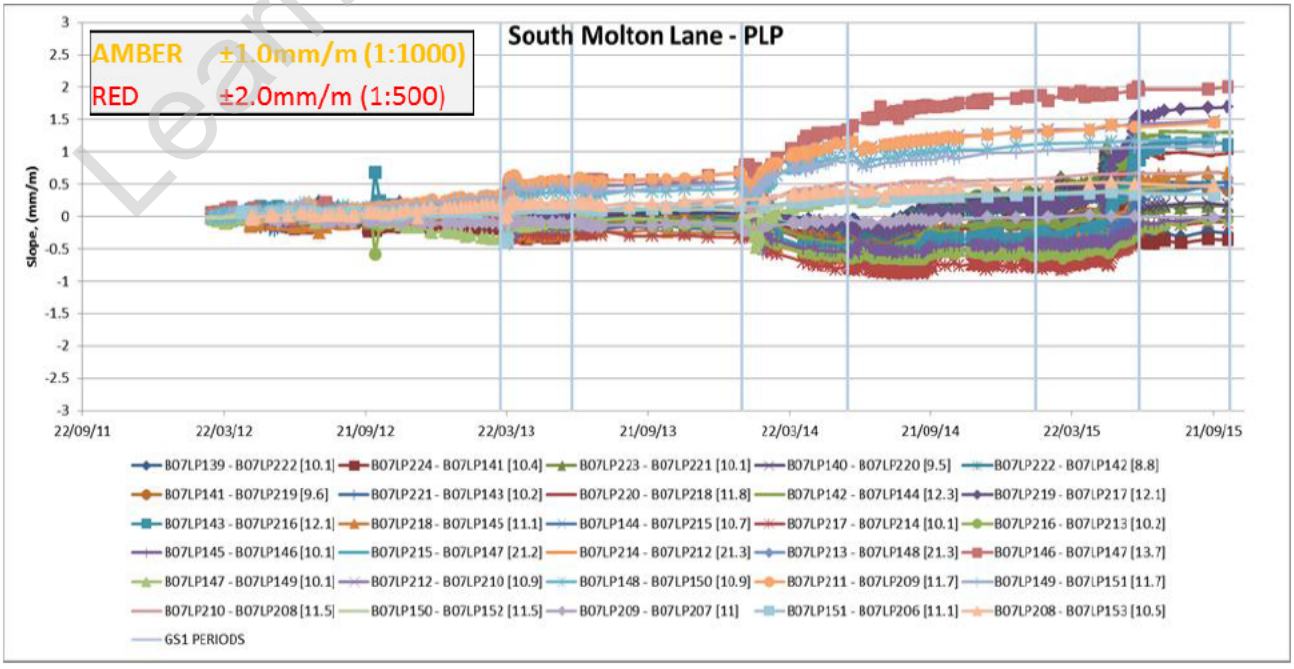
PLP monitoring data from the kerb lines within the footprint of GS2 are presented in the following sections. The plots presented for each comprise:

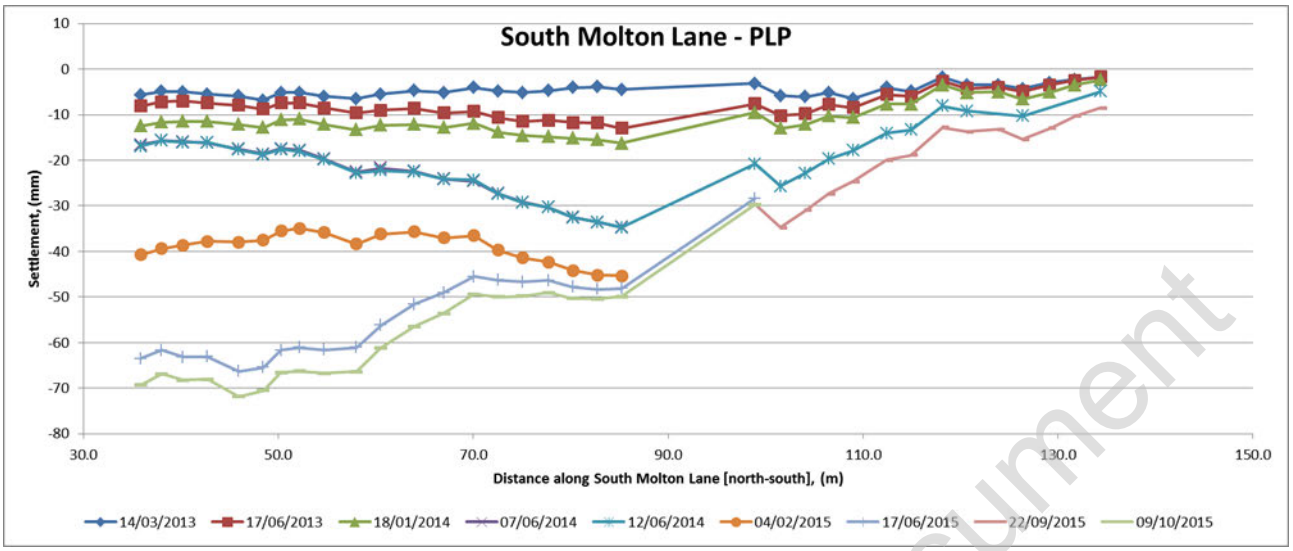
1. Summary of tunnel construction and associated construction periods.
2. Time settlement history.
3. Settlement profile plots with series as close to the end of each construction period as is available.
4. Time slope history over the full construction period with the distances between the points in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

5.2. South Molton Lane





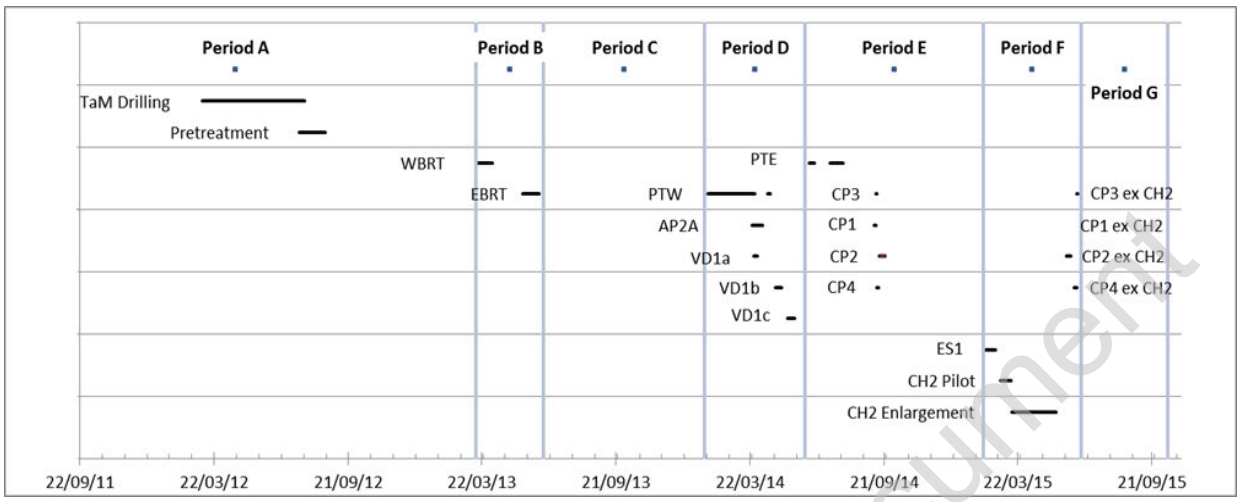


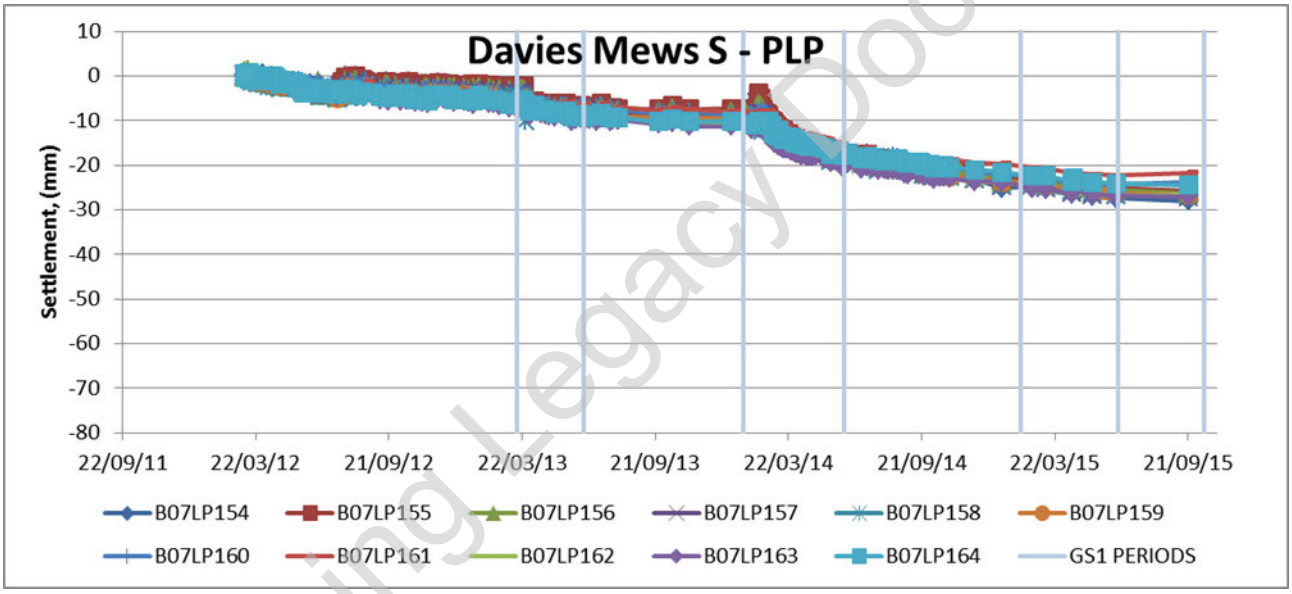


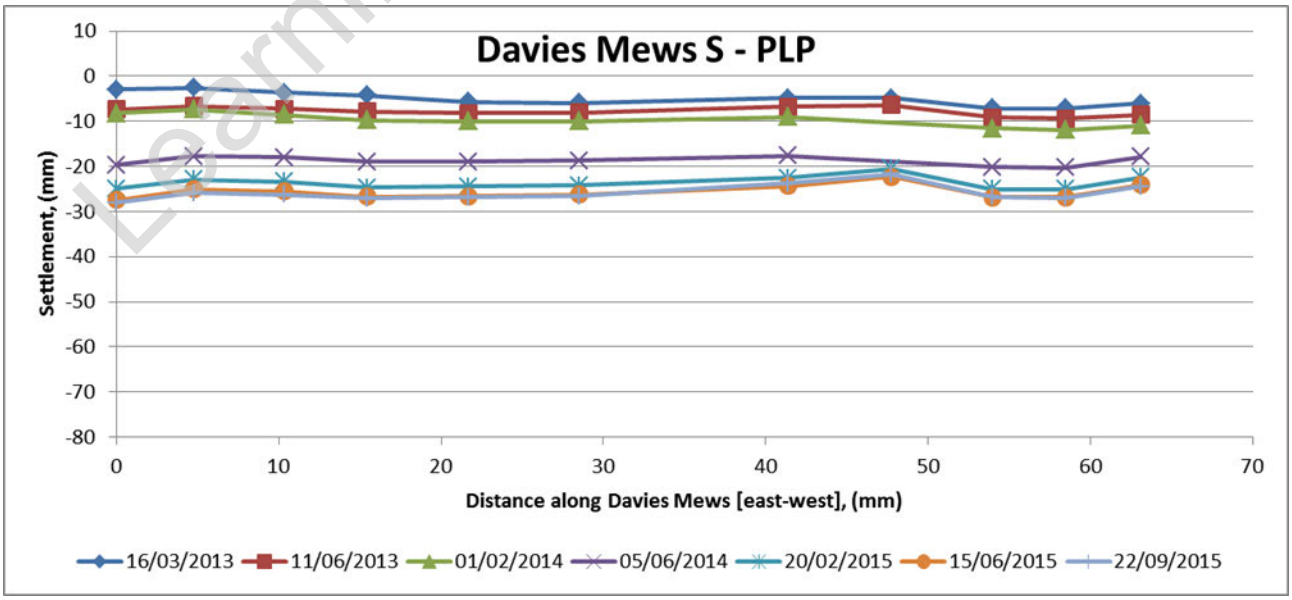
The following points are noted:

- The southern part of the South Molton Lane is within the GS1 array (from distance 35m): data from all points shown on Figure 5.1.1 are presented.
- South Molton Lane traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTW in Period D and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~8mm but there was only minor variation over the full length of the façade.
- In Period B, the WBRT generated a maximum of 8mm settlement with a trough extending from distance 60m to 110m even though grout jacking was undertaken. No significant effect is evident from the EBRT.
- There was little change In Period C indicating small time related movements following the TBM drives.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement was controlled to ~10mm by concurrent compensation grouting, but also by large and rapid consolidation settlement which increased the total settlement within the Period to almost 20mm, producing a total settlement of 35mm. Despite a number of grout jacking episodes, 3 Amber triggers were generated due to post construction movements some time after the tunnelling. Details are given in Table 5.1.
- In Period E the construction of PTE had an immediate effect between distances 35m and 70m but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to almost 50mm despite further grout jacking. The CP excavations had little apparent immediate effect. A further Amber trigger occurred due to post construction movements from PTW.
- In Period F, there was a further increase in total settlement to ~70mm associated with the construction of CH2 and an increased rate of consolidation settlement. A further 3 Amber triggers were recorded (see Table 5.1).
- Post construction, in Period G, settlement has continued to increase. As expected the movements become relatively uniform and hence the impact on slopes becomes minor. However one further Amber trigger was recorded and one slope approached the Red trigger due to movement following CH2 construction.
- By inspection, no Deflection Ratio trigger levels were exceeded.

5.3. Davies Mews - South



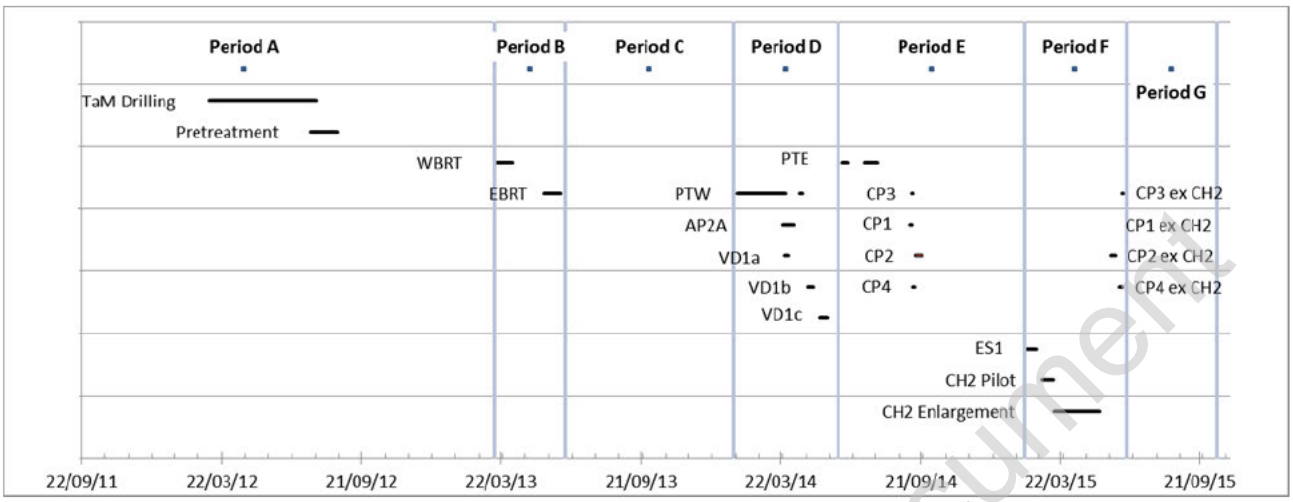


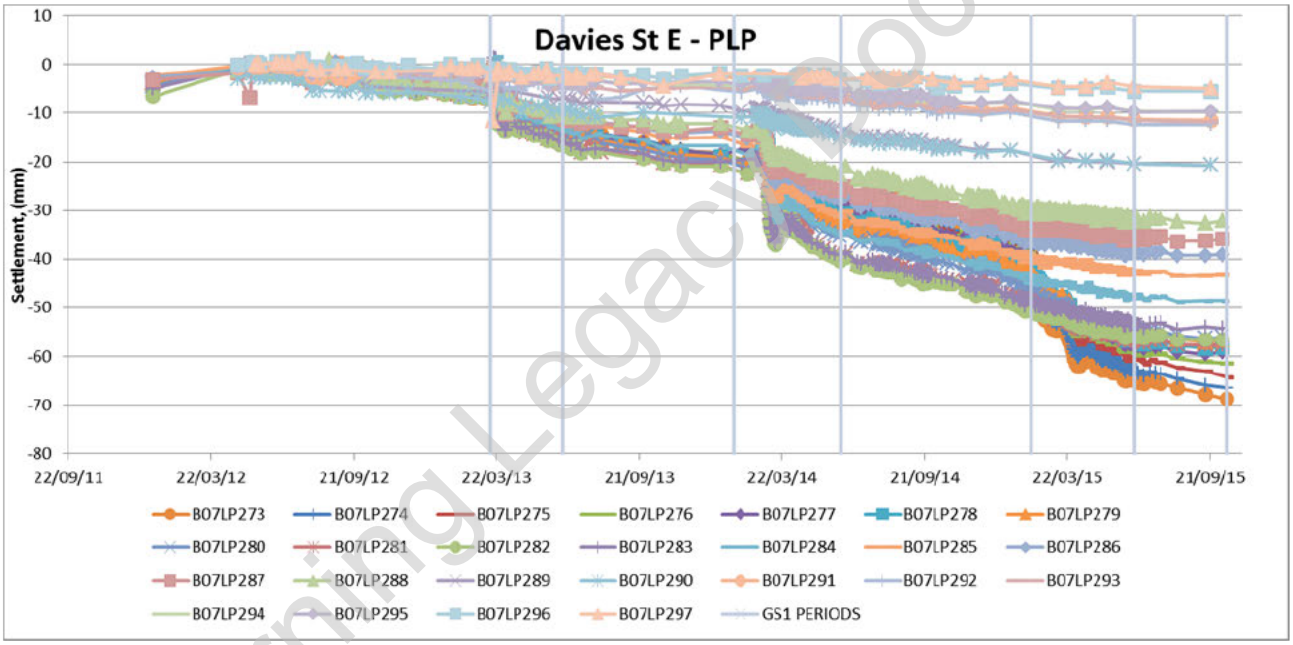


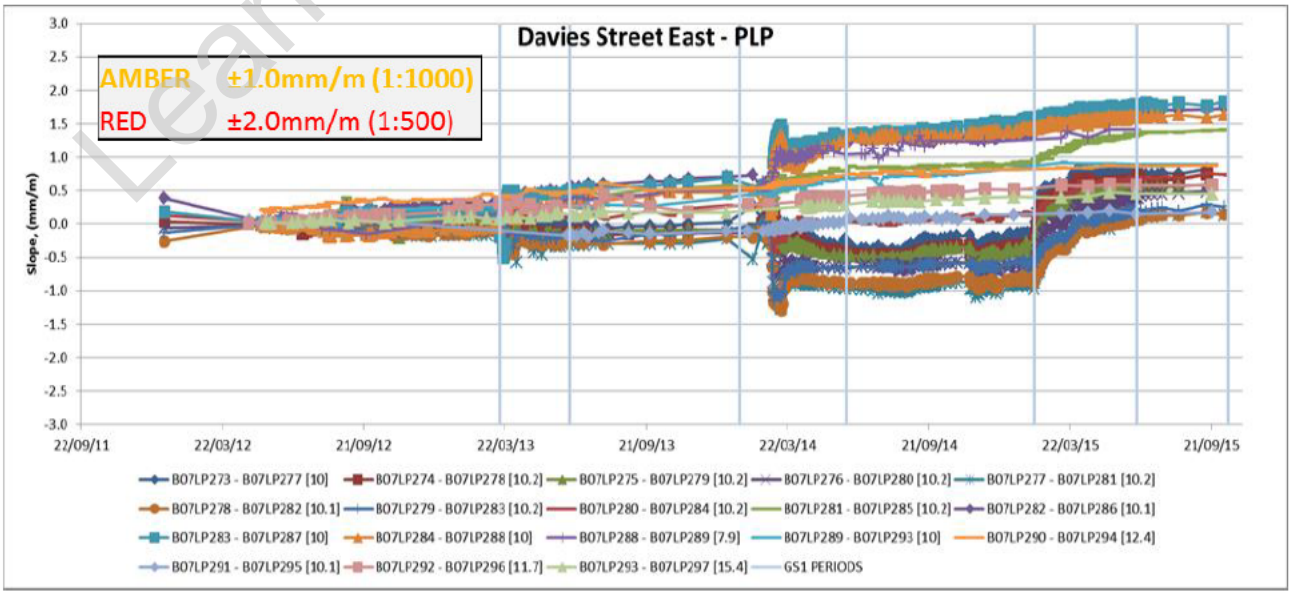
The following points are noted:

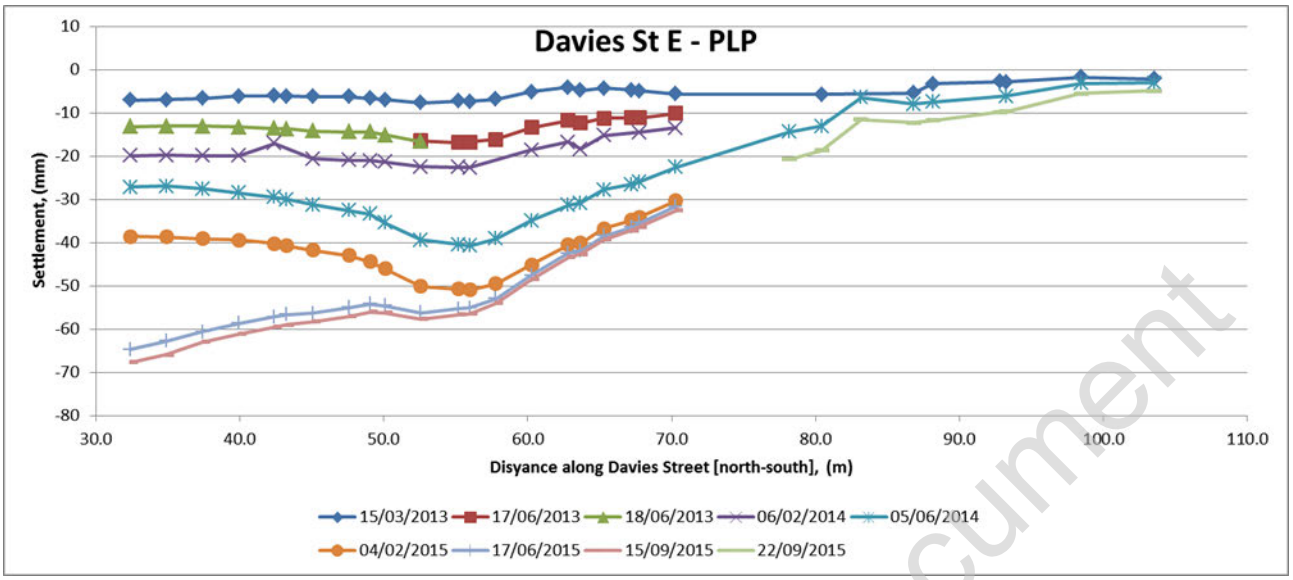
- The south kerbline of Davies Mews is immediately adjacent to the south façade (see Section 5.6). The full extent of the façade is within the GS1 array.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~5mm and there was only minor variation over the full length of the façade.
- In Periods B and C, the WBRT generated a further 5mm settlement. Maximum settlement was about 10mm at the end of Period C.
- The construction of the PTW in Period D had a more significant effect, not just during construction where settlement was controlled to ~5mm by concurrent compensation grouting, but also by consolidation settlement which increased the total settlement within the Period to about 10mm, producing a total settlement of up to 20mm.
- In Period E, F and G there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 8mm to ~28mm.
- By inspection of the time and profile plots, there are no slope triggers.
- By inspection, no Deflection Ratio trigger levels were exceeded.

5.4. Davies Street – East





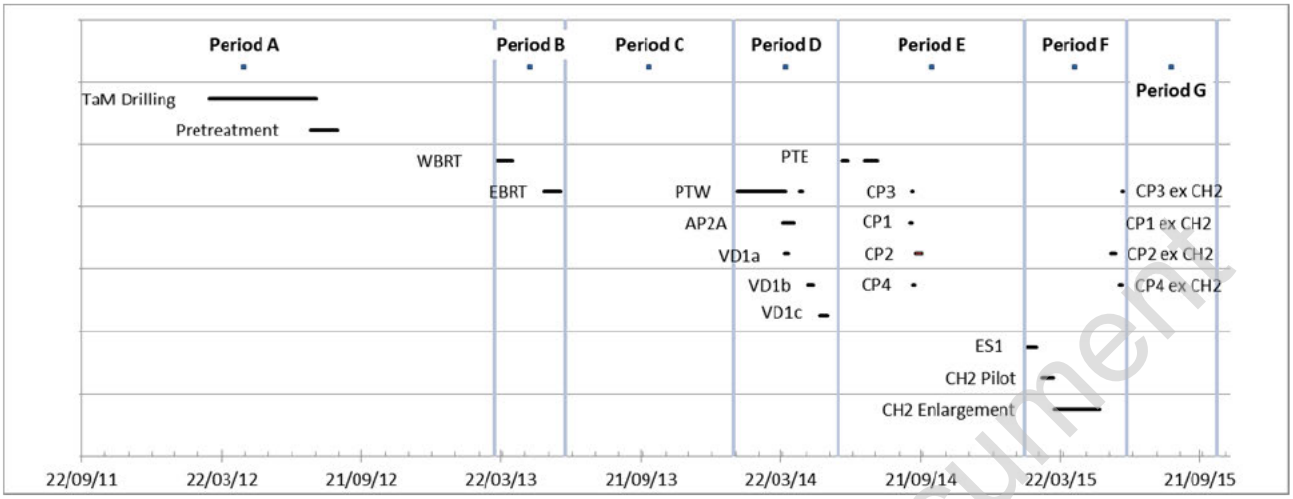


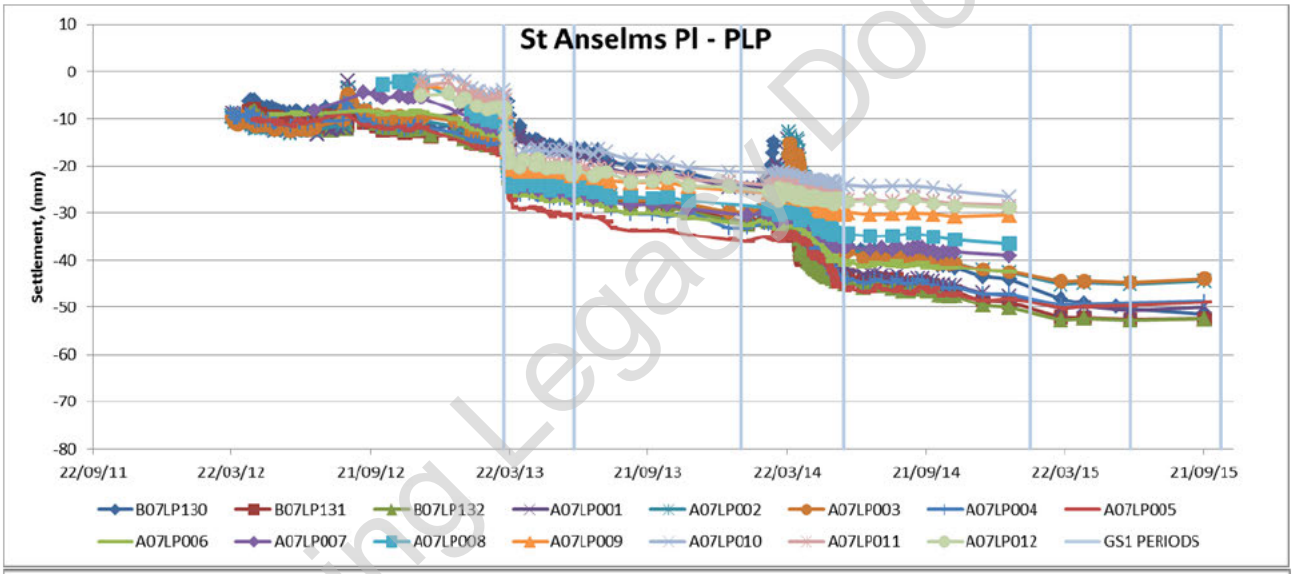


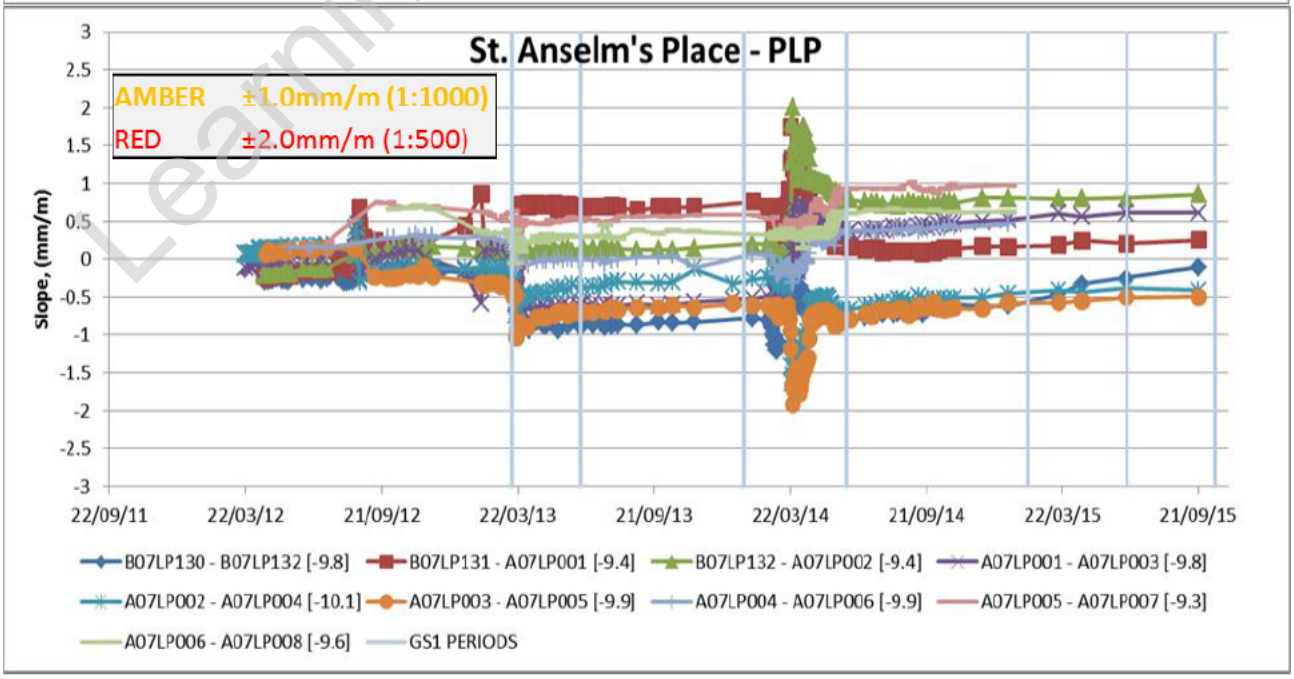
The following points are noted:

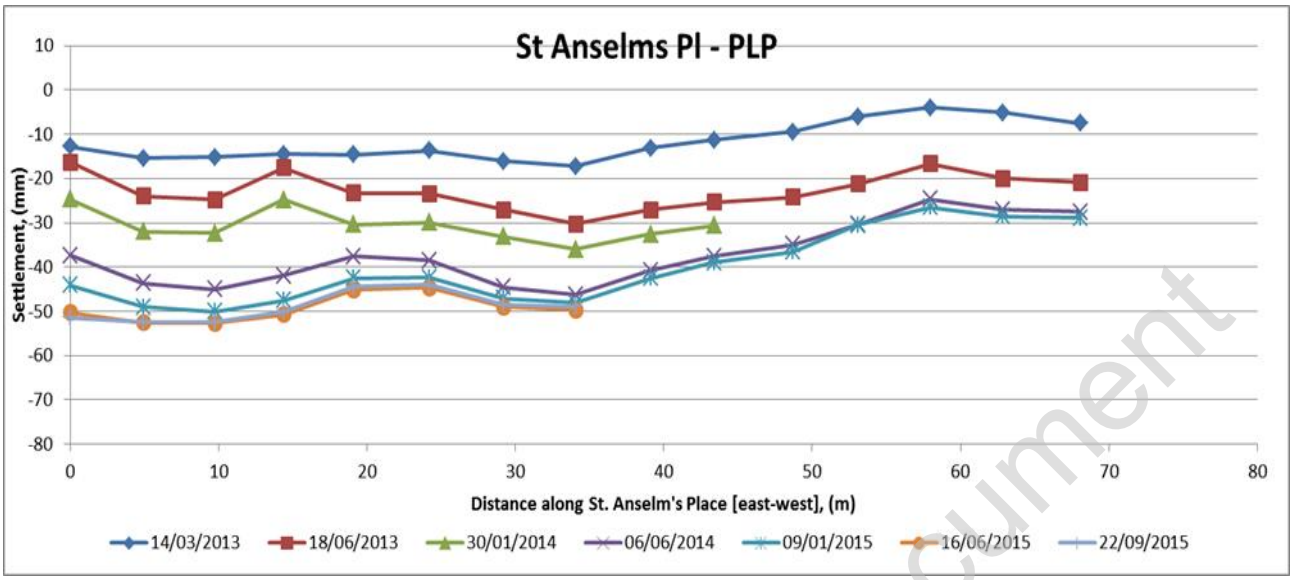
- The southern part of Davies Street is within the GS1 array (from distance 35m): data from all points shown on Figure 5.1.1 are presented.
- Davies Street traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTW in Period D and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~8mm but there was only minor variation over the full length of the façade.
- In Periods B and C, the WBRT and subsequent consolidation generated a further 12mm settlement even though grout jacking was undertaken.
- The construction of the PTW in Period D had a major effect, not just during construction where settlement increased by ~15mm, but also by significant consolidation settlement which increased the total settlement within the Period to almost 20mm, producing a total settlement of 40mm. Despite concurrent grouting and a number of grout jacking epidodes, 7 Amber slope triggers were generated, albeit 3 of these were transitory during the advance of the tunnel below Davies Street. Details are given in Table 5.1.
- In Period E the construction of PTE had a minor immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 10mm to over 50mm despite further grout jacking. The CP excavations also had a minor immediate effect.
- In Period F, there was a further increase in the maximum total settlement to ~65mm associated with the construction of CH2 and an increased rate of consolidation settlement. The location of the greatest settlement moved from over PTW to the northern end of the transect adjacent to CH2. One further Amber slope trigger developed due to post construction movements over PTW.
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, no Deflection Ratio trigger levels were exceeded.

5.5. St Anselm's Place - South









The following points are noted:

- The St Anselm's Place façade extends from the northern end of the Davies Street west façade (see Section 4.8) to the west approximately parallel to the WTH south wall and over the PTE and WBRT. The façade is within the GS1 array up to distance 30m: data from all points shown on Figure 4.1 are presented.
- The most notable events were the construction of WBRT in Period B and PTW and AP2A in Period D.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~20mm with the maximum value located at the west end of the façade, adjacent to the Davies Street.
- In Period B, the WBRT and subsequent consolidation generated a further 10mm settlement, despite uplift of 5mm generated by grout jacking.
- In Period C time-related movement resulted in an increase in settlement of 8mm to a maximum of 38mm by the end of the Period.
- The construction of the PTW in Period D had a major effect: during construction the effect of concurrent grouting produced a small uplift, but this was followed by significant consolidation settlement which increased the total settlement within the Period to over 30mm. The total settlement increased to ~70mm, despite further grout jacking. 5 Amber triggers were generated, albeit all of these were transitory, leaving no remaining Amber triggers at the end of the Period. Details are given in Table 5.1.
- In Periods E and F the tunnelling had no immediate effect but there was ongoing consolidation throughout the transect which increased the maximum settlement by a further 12mm to over 80mm.
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements become relatively uniform and hence the impact on slopes becomes minor.
- By inspection, no Deflection Ratio trigger levels were exceeded.

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 1. 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: in general, this objective has been achieved, however, a number of particular issues have become apparent as the works have progressed:

- Noteworthy movements occurred prior to the commencement of tunnelling due to installation of the compensation grouting TaMs as well as from works by others, given the nature and extent of the works completed at this point.
- Pre-treatment and pre-TBM grout jacking reversed these movements to some extent within the constraints of the Works Information which limits uplift to 5mm.
- The exclusion zone specified in the SCoGM over the tunnel face placed significant constraints on concurrent grouting for the Cross Passages between the platform and concourse tunnels and adits to the WTH because of their short length. No grouting could be undertaken for the escalator tunnel (ES1) since it is at a higher elevation the TaMs were within the exclusion zone.
- 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 final settlements are negligible;
- 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). For PLPs "rolling average" values calculated in accordance with the C122 I&M Plan have not exceeded the Amber trigger value.
- Grout jacking has been undertaken on numerous occasions to reduce settlements and slopes in various locations; up to 250mm equivalent thickness of grout has been injected below the corner of Davies Street and St. Anselm's Place.

7. CONCLUSION

Tunnelling was completed in June 2015: subsequently the increase in movements was reviewed on a daily, weekly or monthly basis at SRG and / or CTC meetings and it was concluded that further grouting to reduce movements could not be justified given the risk of increased damage from any significant episodes of grout jacking. Consequently, no further grouting was undertaken.

An abridged version of this report was submitted in July 2015 to justify de-commissioning of Bond Street Grout Shaft 1. This was accepted by CRL and the grout shaft was subsequently de-commissioned.

The post-construction monitoring was terminated under C300-PMI-01858 from CRL. This report comprises a Final And Close Out Report and contains all of the data collected by BFK, with the final readings being from September / October 2015.

Appendix A

Assumptions used to produce contour plots of grout intensity

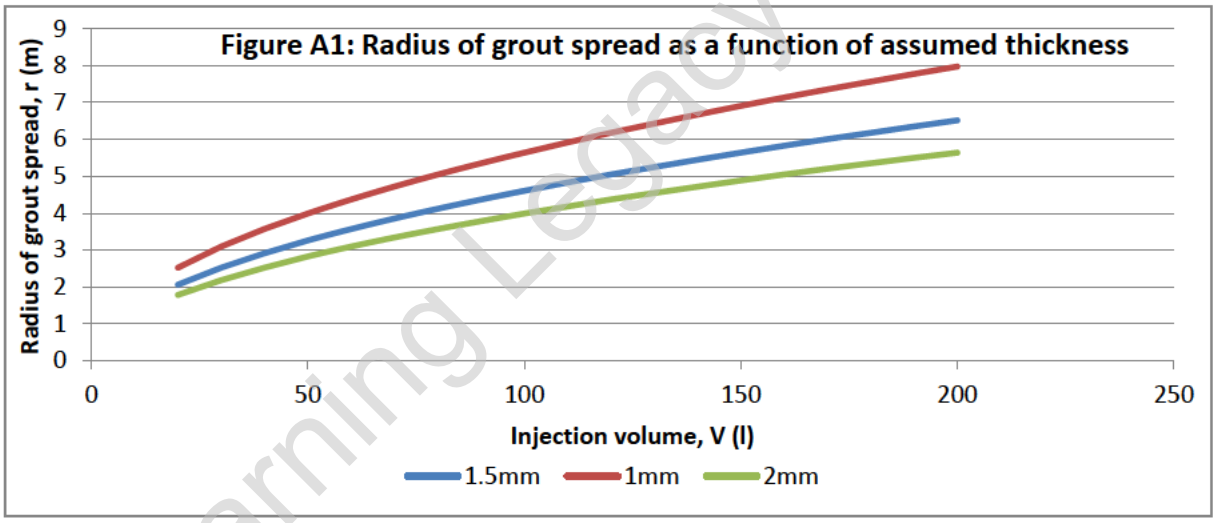
A method of producing a visualisation of the quantity and distribution of grout injected during compensation grouting is useful in interpreting performance. For each injection the volume and the location of the port used are known. The model used is intended to approximate the distribution of grout within 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:

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

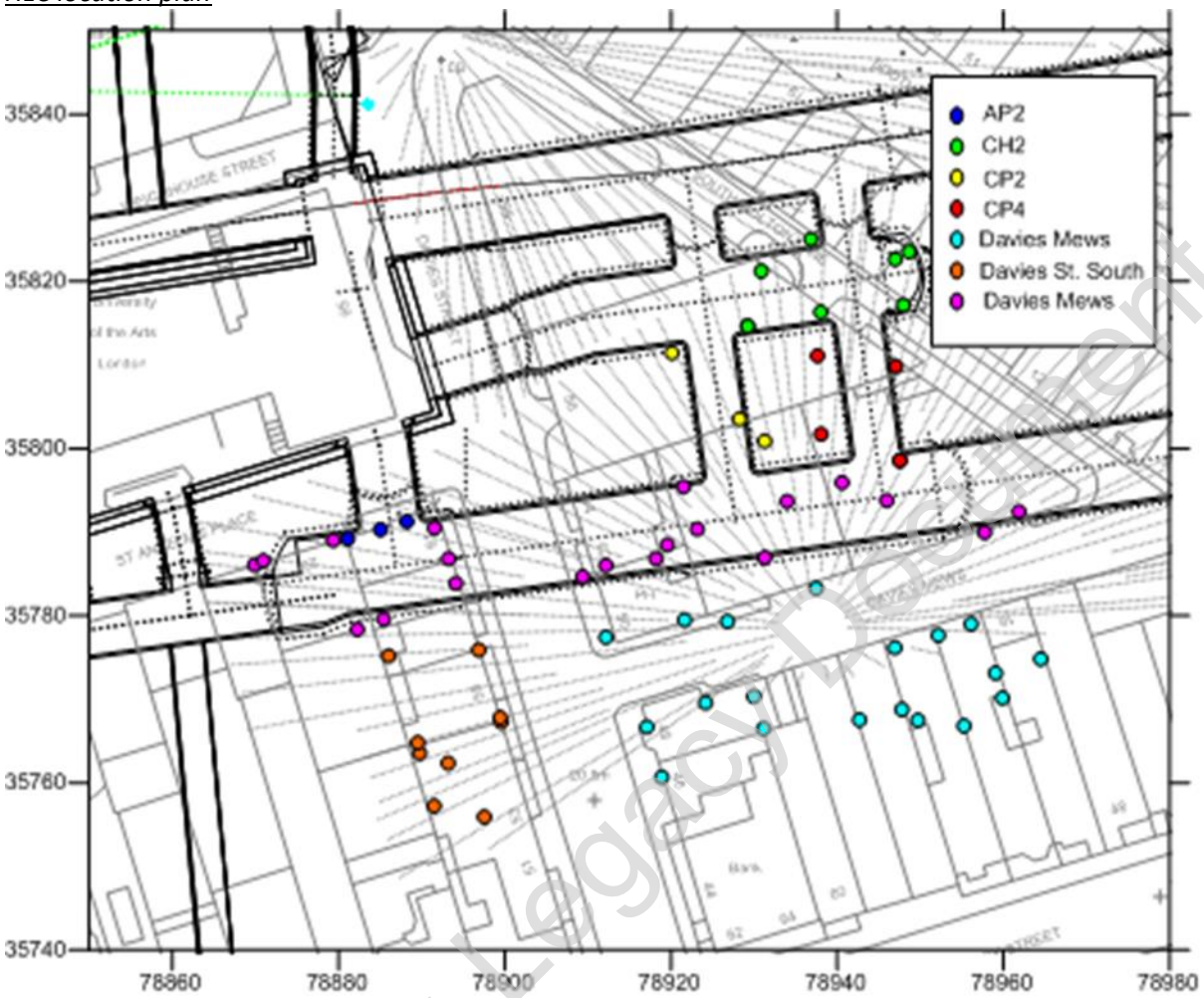


Observation of grout in the ground suggests that a thickness of 1 – 2mm is predominantly achieved. All of the plots included in this report are based on an assumed thickness of 1.5mm. Figure A1 shows the variation in radius for thicknesses of 1.0, 1.5 and 2.0mm. The contribution of each injection within a specified data set are summed at each node within a grid. This grid file is then contoured within Surfer.

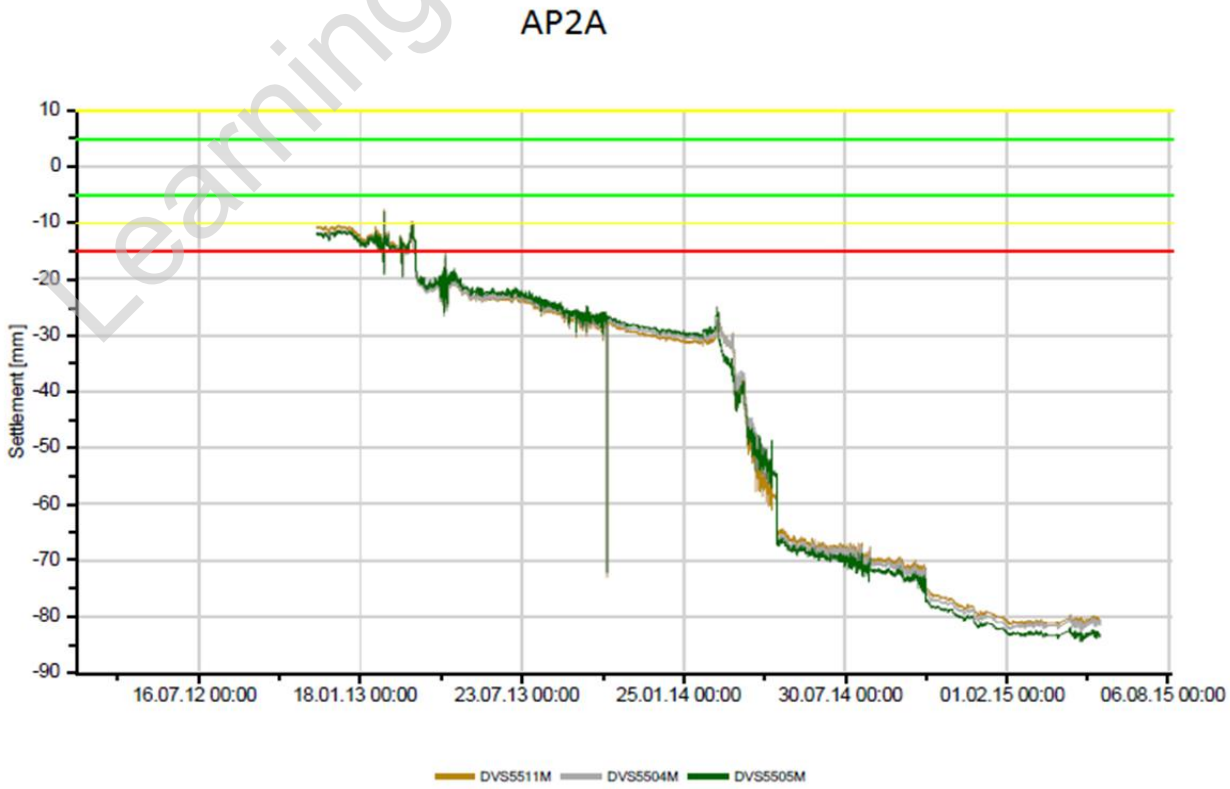
Appendix B

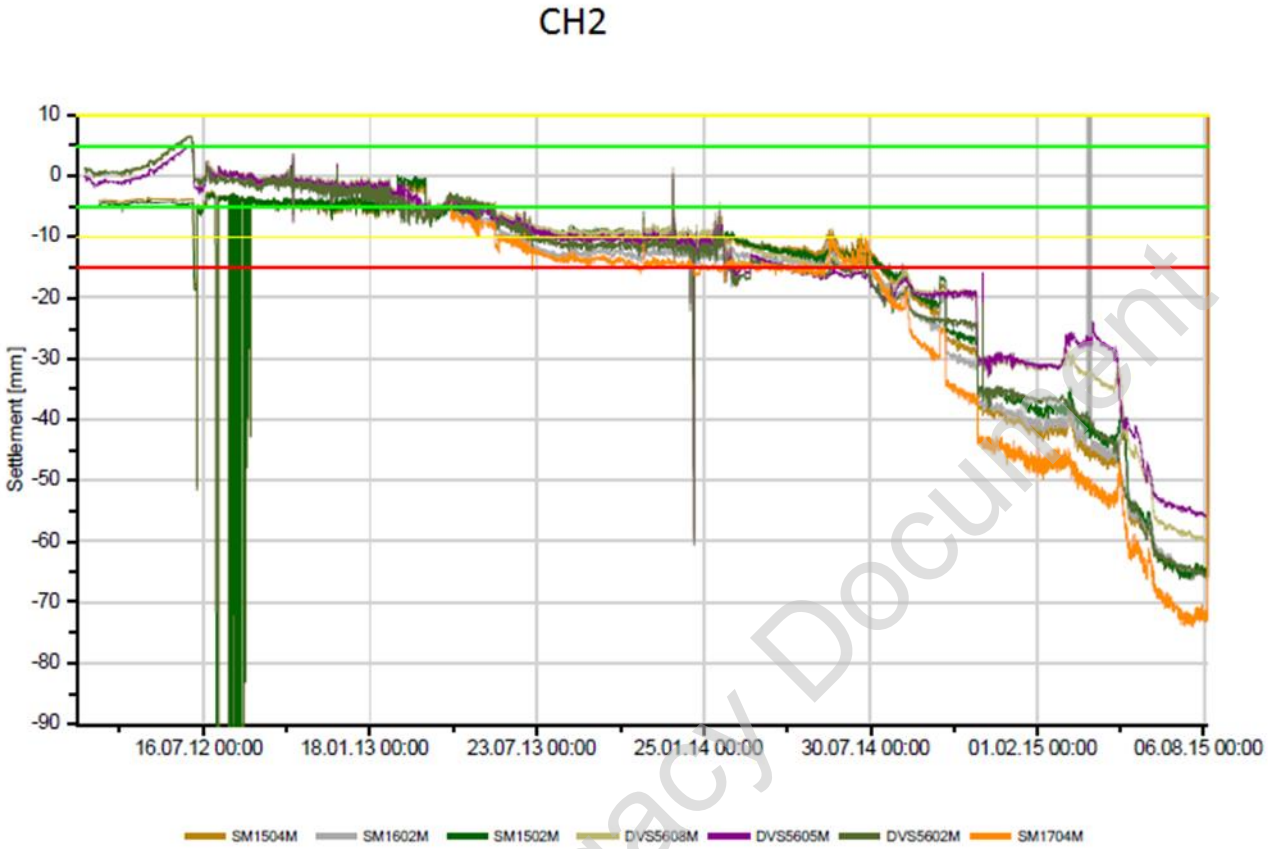
HLC, Crackmeter and Groundwater Monitoring data

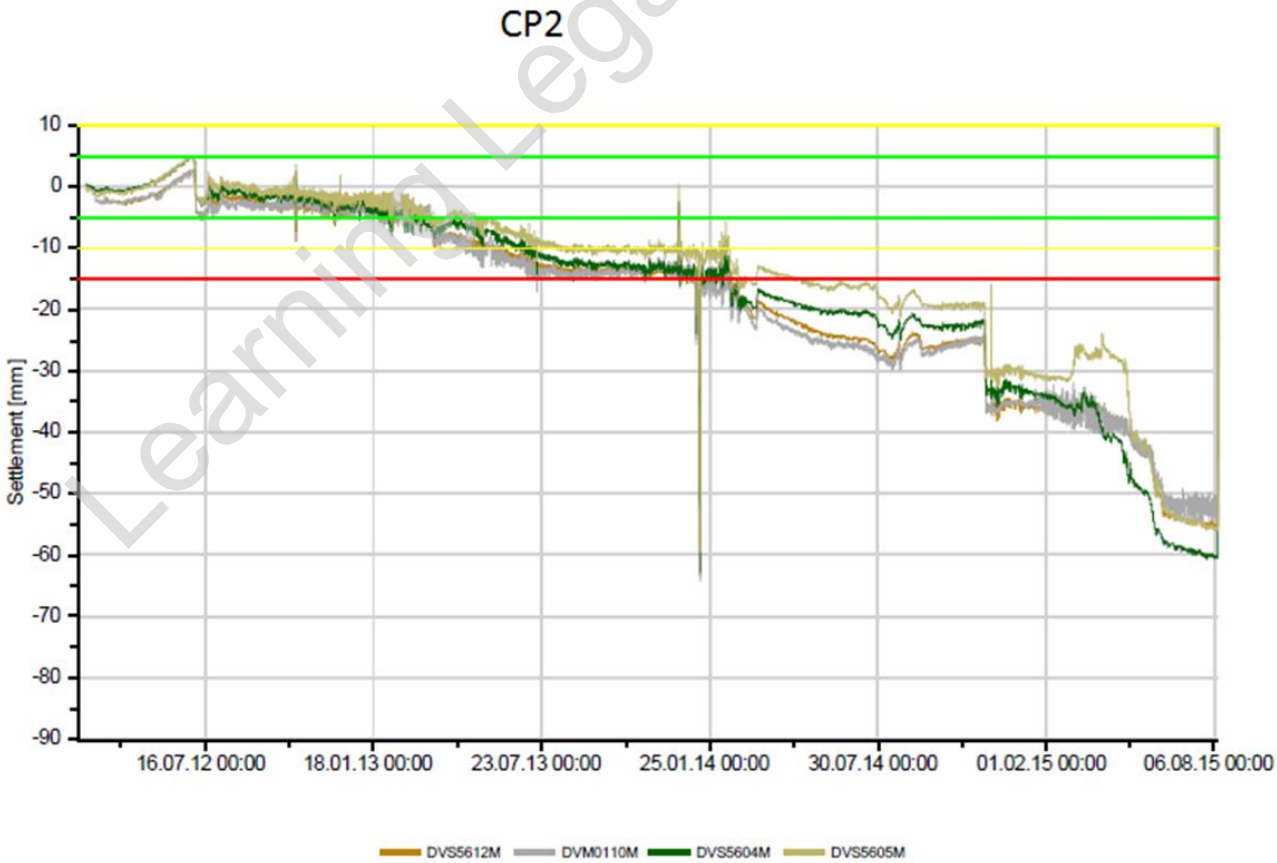
HLC location plan



HLC Data

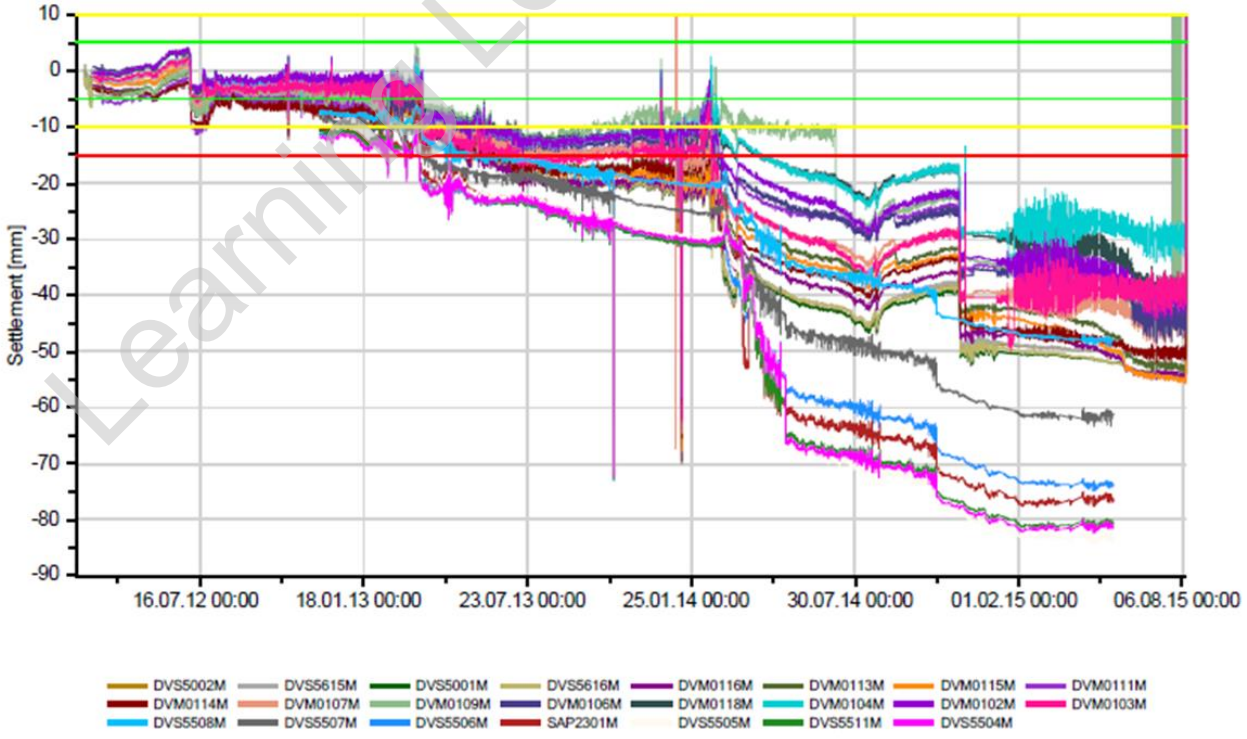


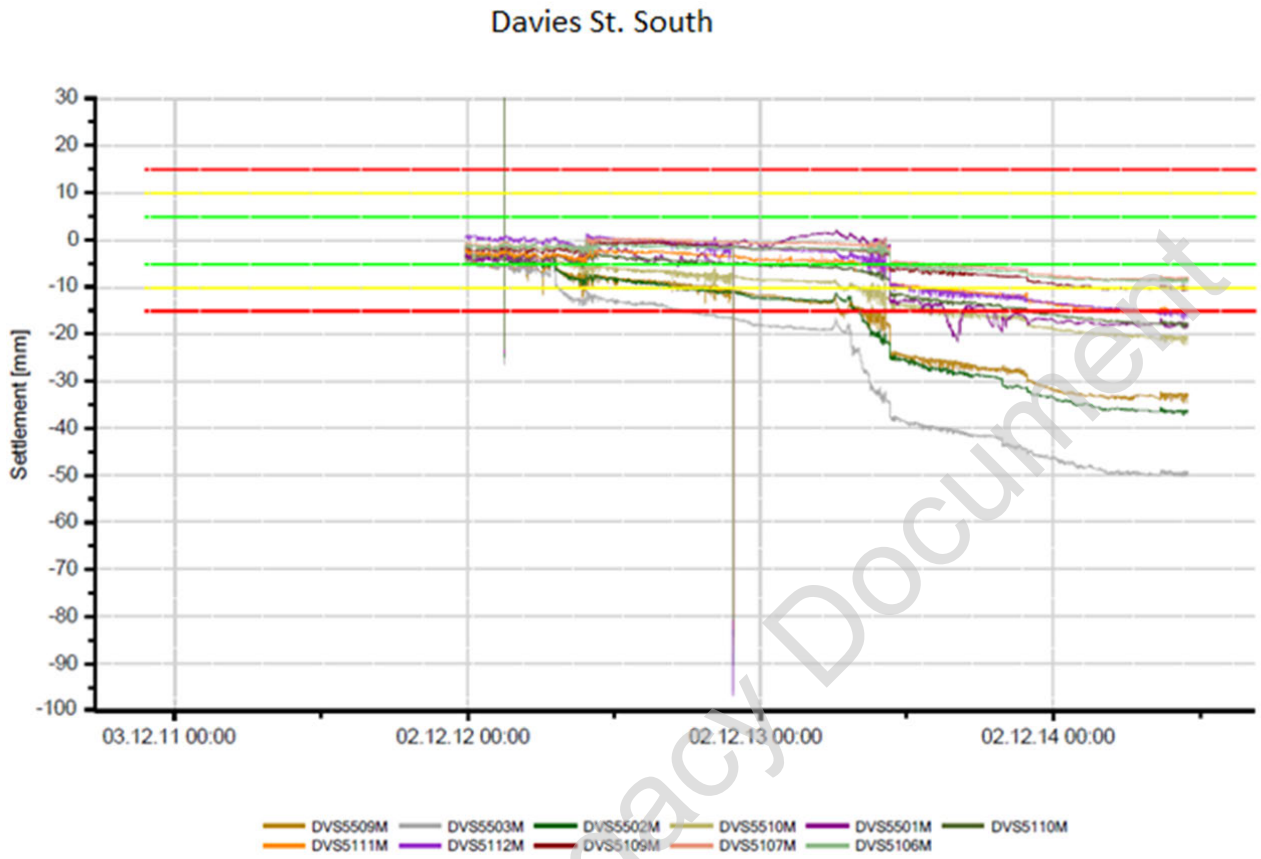


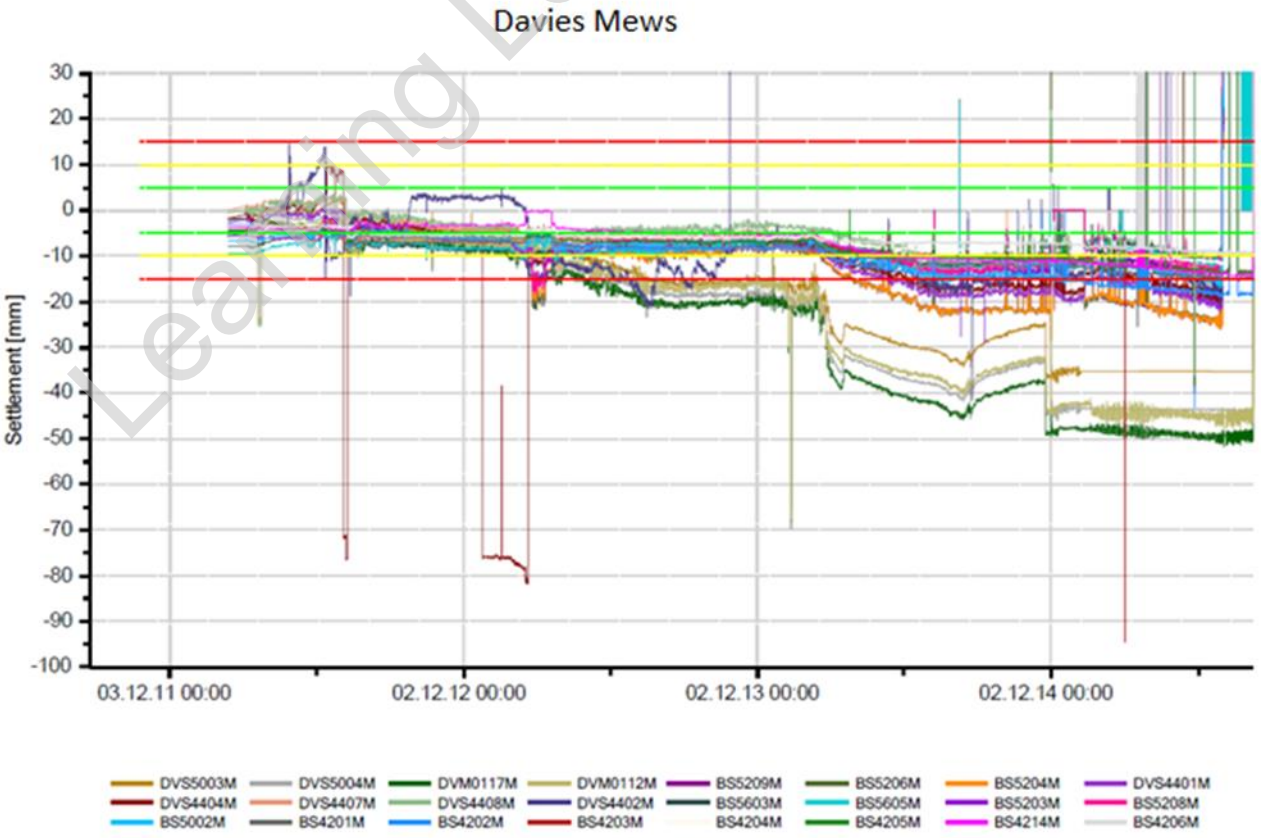


CP4

PTW







TA Centre, 56 Davies Street – Crack monitoring

Location plan

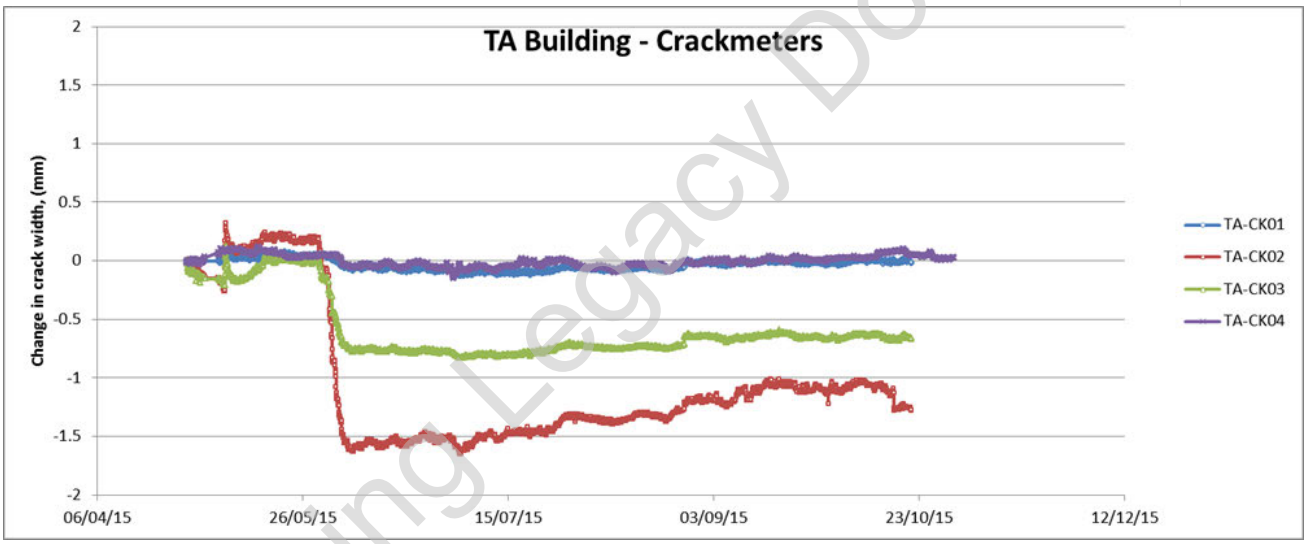
TA Centre Crack meter Pictures

Logger 1: Crack TA-CK01

Logger 1: Crack TA-CK02

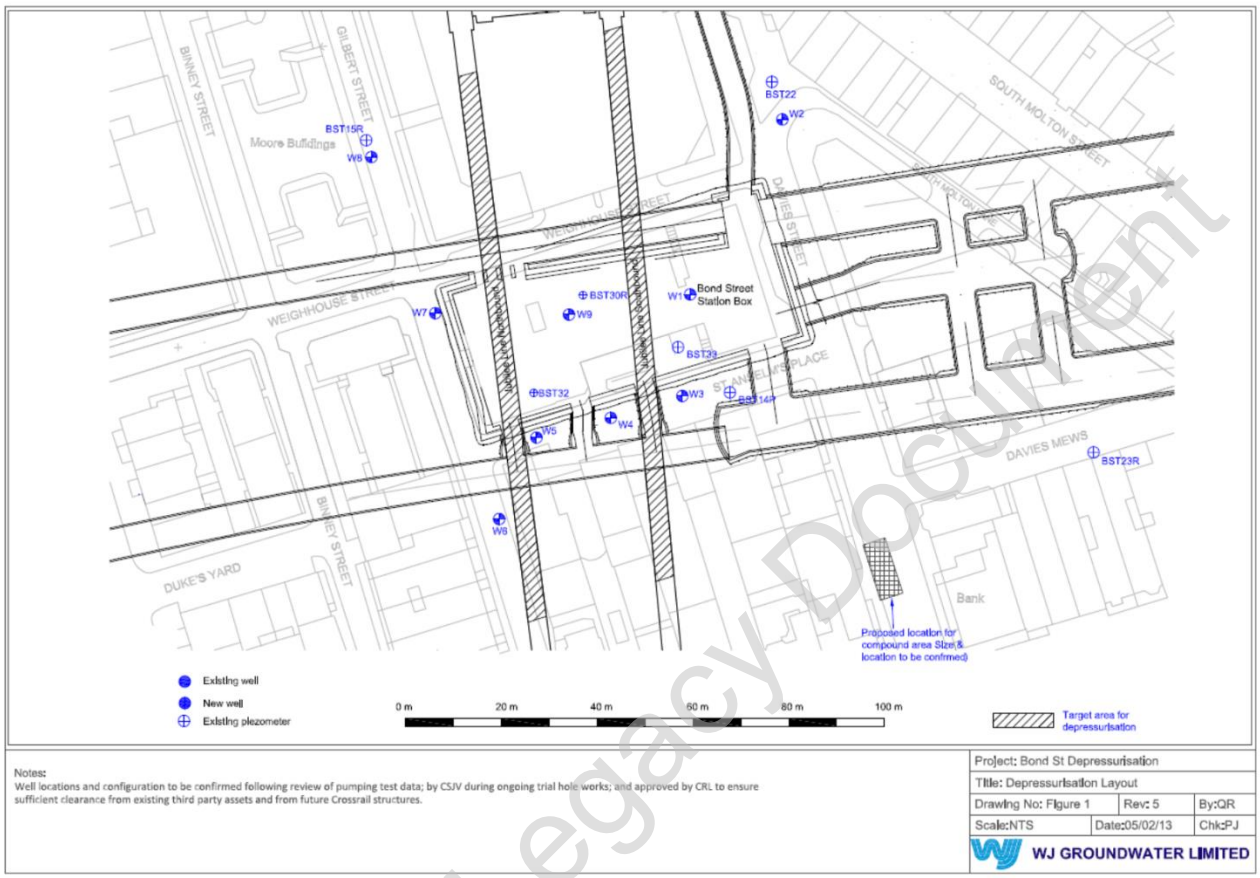
Logger 1: Crack TA-CK03

Logger 2: Crack TA-CK04

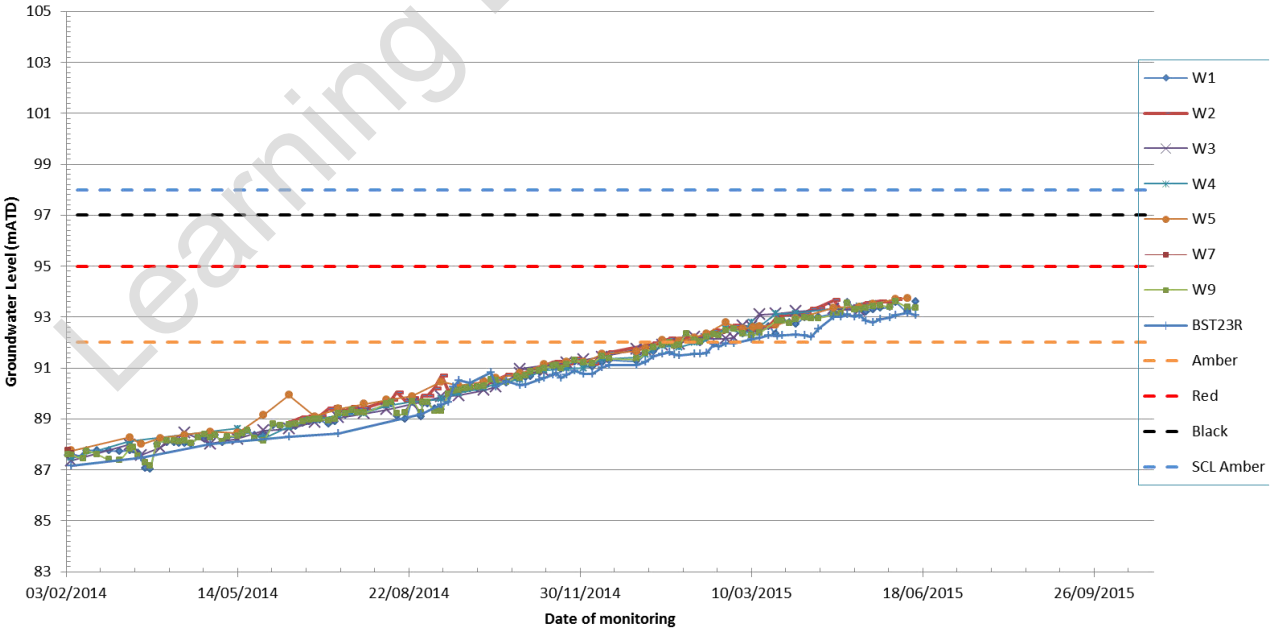


Groundwater Monitoring at West Ticket Hall

Location Plan

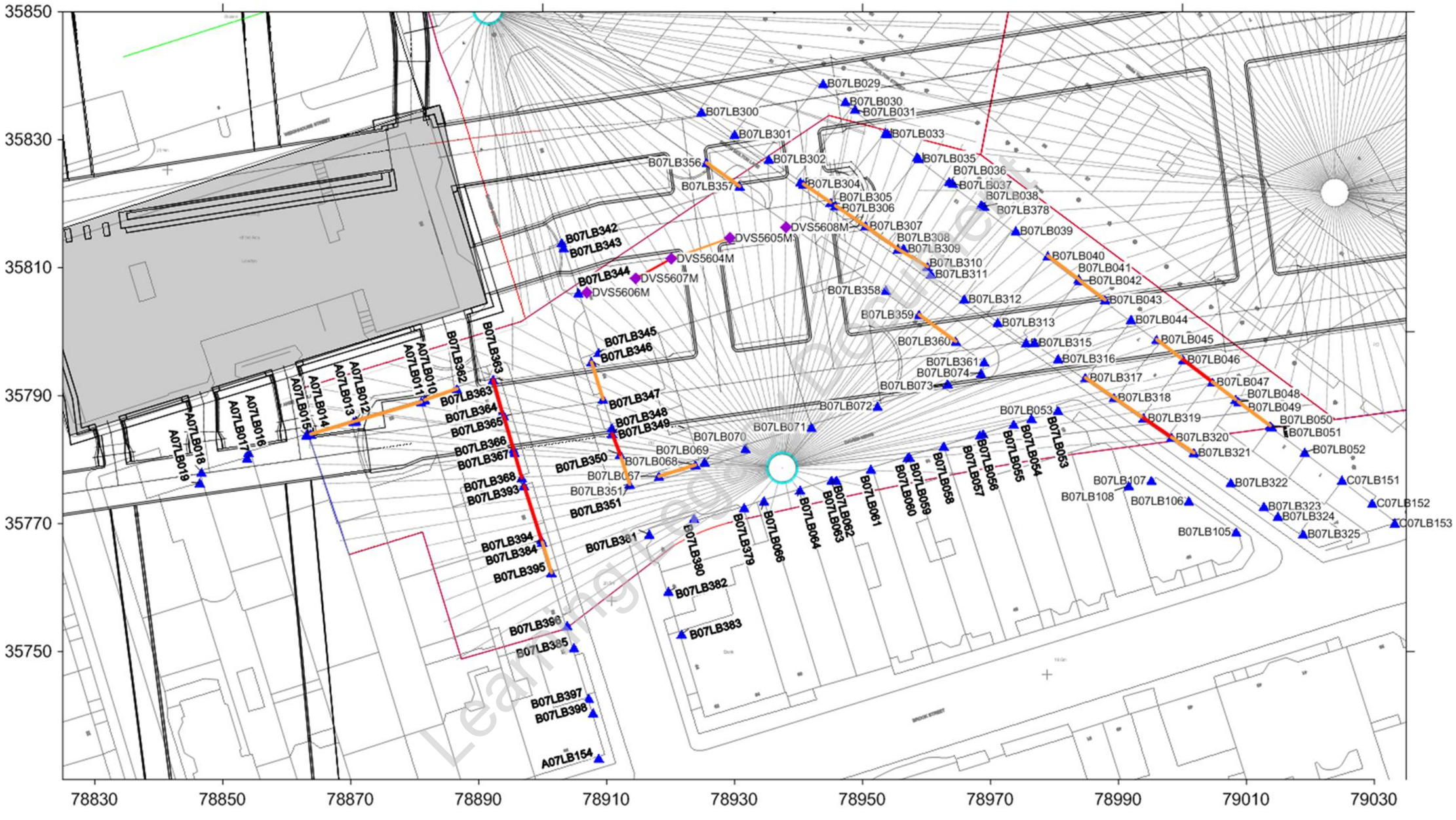


BFK Monitoring Data



Appendix C

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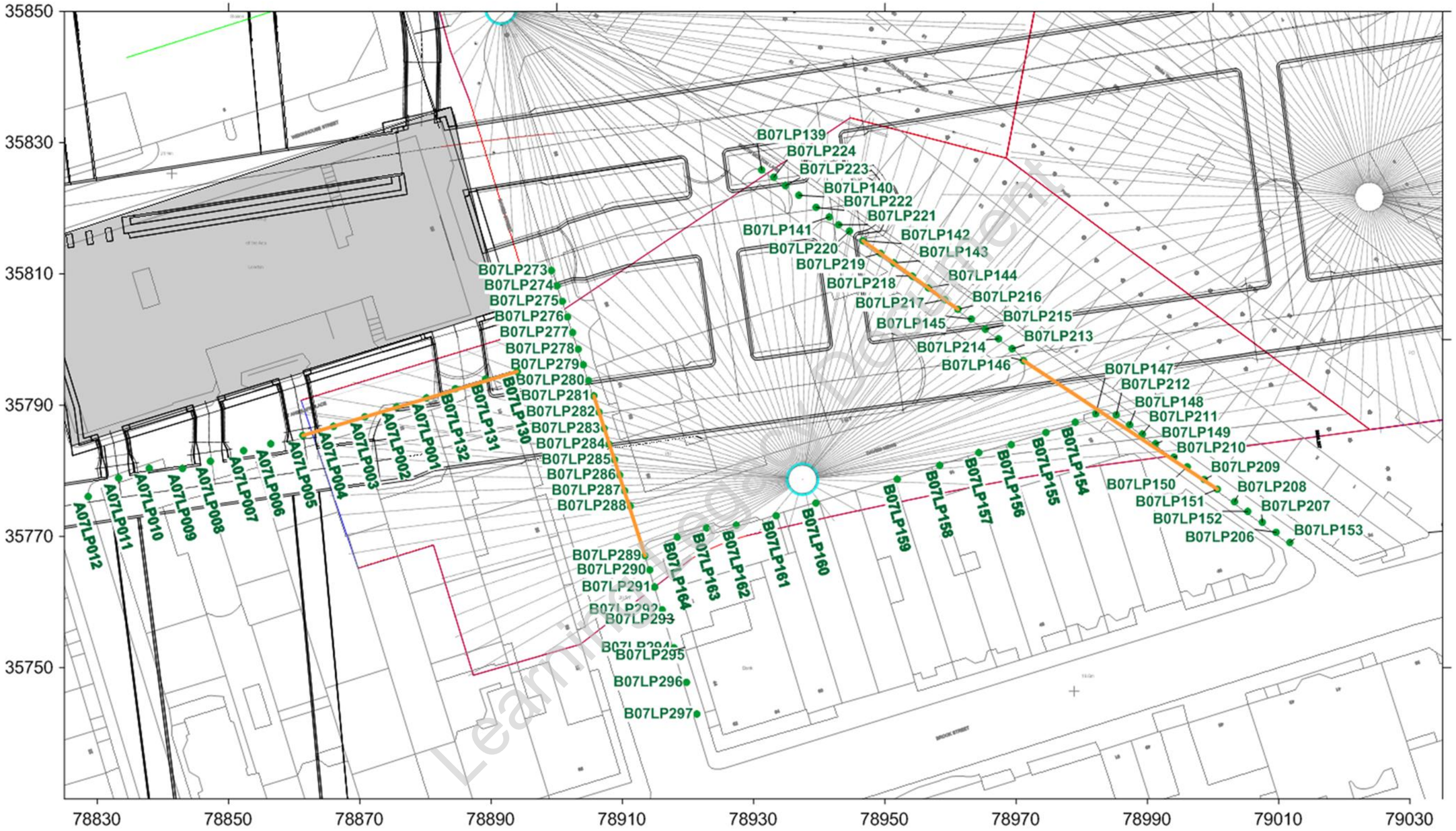
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