C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - BOS GS4

CRL Document No. **C300-BFK-C4-RGN-CRT00_ST005-51215**

Contract MDL reference: C14.020

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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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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 4

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

All BFK excavation (tunnelling) works within the plan extent of the compensation grouting arrays from Bond Street Station Grout Shaft 4 were completed by mid-June 2015. An abridged version of this report was issued in July 2015 (C300-CCM-10799), 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 4 at Bond Street Station and includes manual monitoring up to October 2015 when the manual monitoring within the GS4 area was de-scoped under C300-PMI-01858. The purpose of this report is therefore to fully document the justification for the decommissioning of the shaft and also to provide a close-out report for 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 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 4 area comprises:

- Piezometers – Around WTH to monitor recovery following cessation of de-watering by C411
- Horizontal borehole inclinometers (SAA) installed from GS4

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

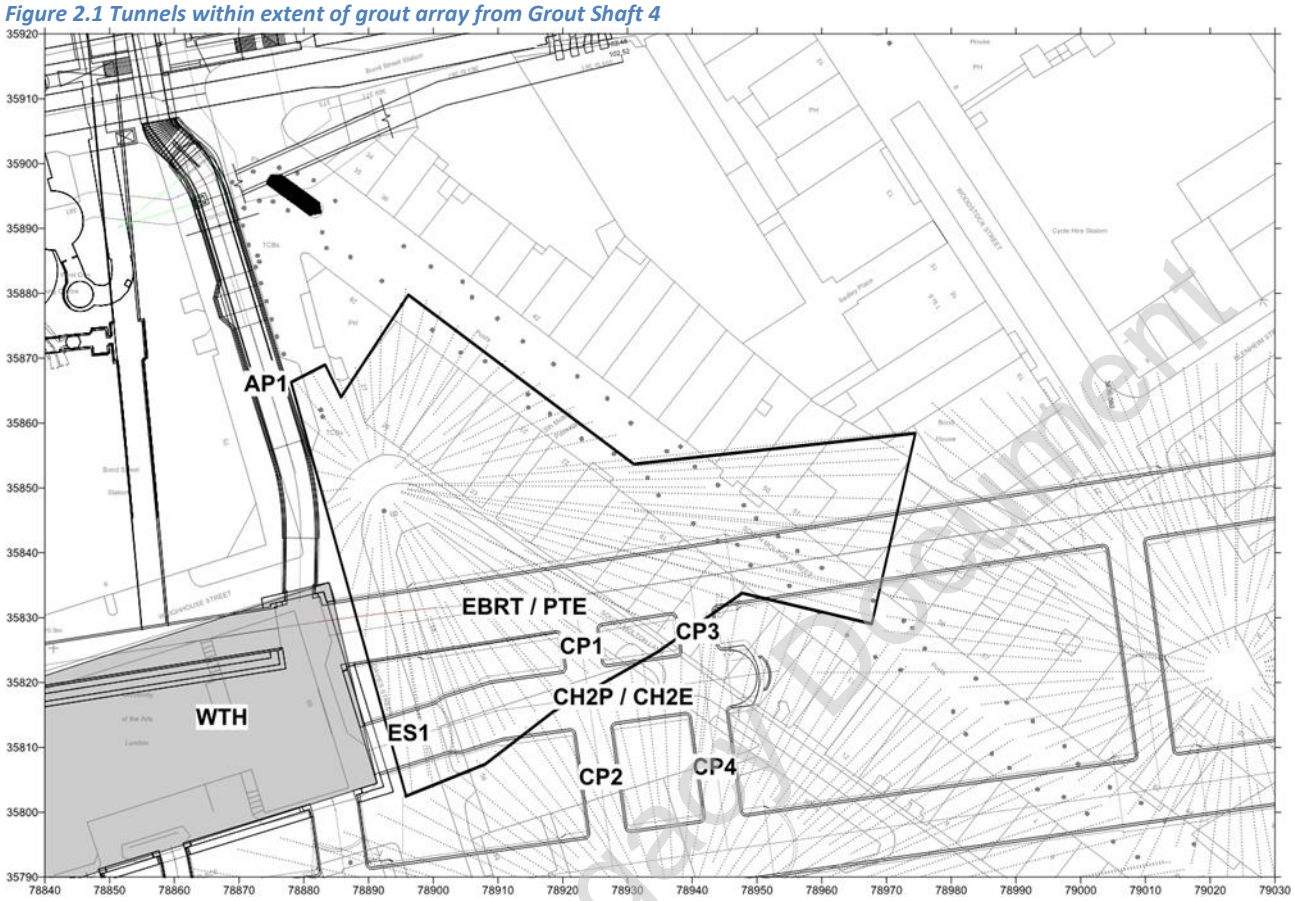
2.1. Tunnels

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 4 at Bond Street Station. Tunnel excavation commenced with the Eastbound TBM (EBRT) in May 2013 and was completed with the excavation of the cross passage junctions from CH2 in June 2015. To facilitate comparison of monitoring data with construction activities 7 periods (A to G) have been assigned. Tunnelling was completed in 3 of these periods (B, 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 GS4 area.

	TUNNEL	ABB.	START DATE	NOTES	END DATE
Period B	Eastbound Running Tunnel	EBRT	17/05/2013		08/06/2013
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	3m stub tunnel from PTE	10/09/2014
	Cross Passage 2	CP2	15/09/2014	3m stub tunnel from PTW	17/09/2014
	Cross Passage 3	CP3	10/09/2014	3m stub tunnel from PTE	12/09/2014
	Cross Passage 4	CP4	12/09/2014	3m stub tunnel from PTW	14/09/2014
	LU Link Tunnel (Access Passage 1)	AP1	06/12/2014	Excavated to 61m from WTH (up to LU vent tunnel)	01/02/2015
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	15/03/2015		14/05/2015
	Cross Passage 1 (Junction)	CP1 from CH2	26/05/2015		27/05/2015
	Cross Passage 2 (Junction)	CP2 from CH2	28/05/2015		03/06/2015
	Cross Passage 3 (Junction)	CP3 from CH2	11/06/2015		12/06/2015
	Cross Passage 4 (Junction)	CP4 from CH2	07/06/2015		11/06/2015

Figure 2.1 Tunnels within extent of grout array from Grout Shaft 4



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 (to October 2012)
- Excavation of WTH (from October 2012)

Works by BFK prior to the commencement of tunnelling in GS4 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

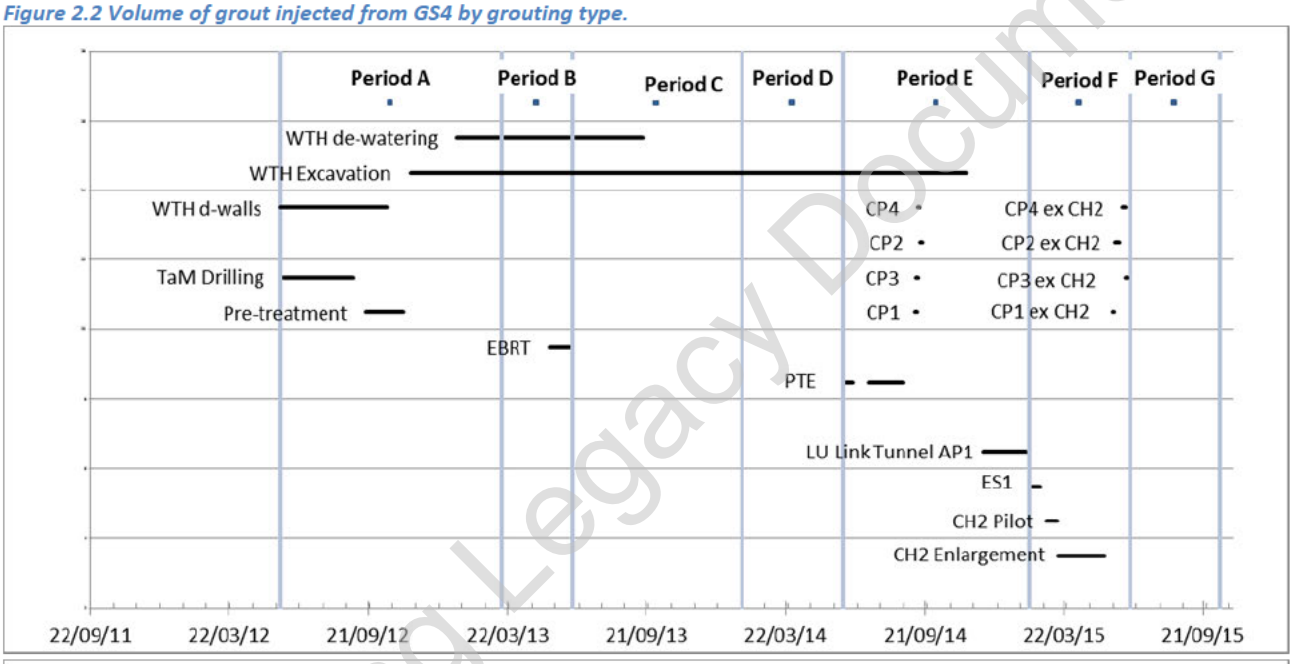
The volume of grout injected from GS4 is plotted against time on Figure 2.2 together with a plot of when each of the tunnels was constructed. Figure 2.3.1 shows that pre-treatment comprised approximately 35m^3 injected prior to tunnelling, concurrent grouting approximately 190m^3 and grout jacking almost 60m^3. Concurrent grouting was undertaken with all tunnels except the Cross Passages 1 to 4, EBRT, ES1 and AP1. 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 are short length tunnels and the extent of the exclusion zones over the tunnel face, as defined in the SCoGM, rendered concurrent grouting impractical. The crown elevation of the inclined ES1 tunnel was too high to allow concurrent grouting to be undertaken. In addition, over ES1, a pipe arch was installed which was at the same elevation as the compensation grouting TaMs. No TaMs were installed over the LU Link Tunnel (AP1) and hence concurrent grouting was not possible.

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 GS4 is shown in Figure 2.6. The grout intensity is the equivalent thickness of grout injected into the ground in millimetres which is equivalent to the number of litres per square meter. 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 works in BOS GS4 area.

Periods	Start Date	End Dates	Main Works
A	28/05/12	15/03/13	Tam drilling, Pre-treatment, WTH d-walls & de-watering (C411)
B	15/03/13	15/06/13	EBRT, Grout Jacking, WTH excavation & de-watering (C411)
C	15/06/13	20/01/14	No tunnelling, WTH excavation & de-watering (C411)
D	20/01/14	06/06/14	No tunnelling, WTH excavation (C411)
E	06/06/14	04/02/15	PTE, CP1, CP2, CP3, CP4, AP1 (to 61m from WTH), Concurrent Grouting, Grout Jacking, WTH excavation (C411)
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 GS4 by grouting type.



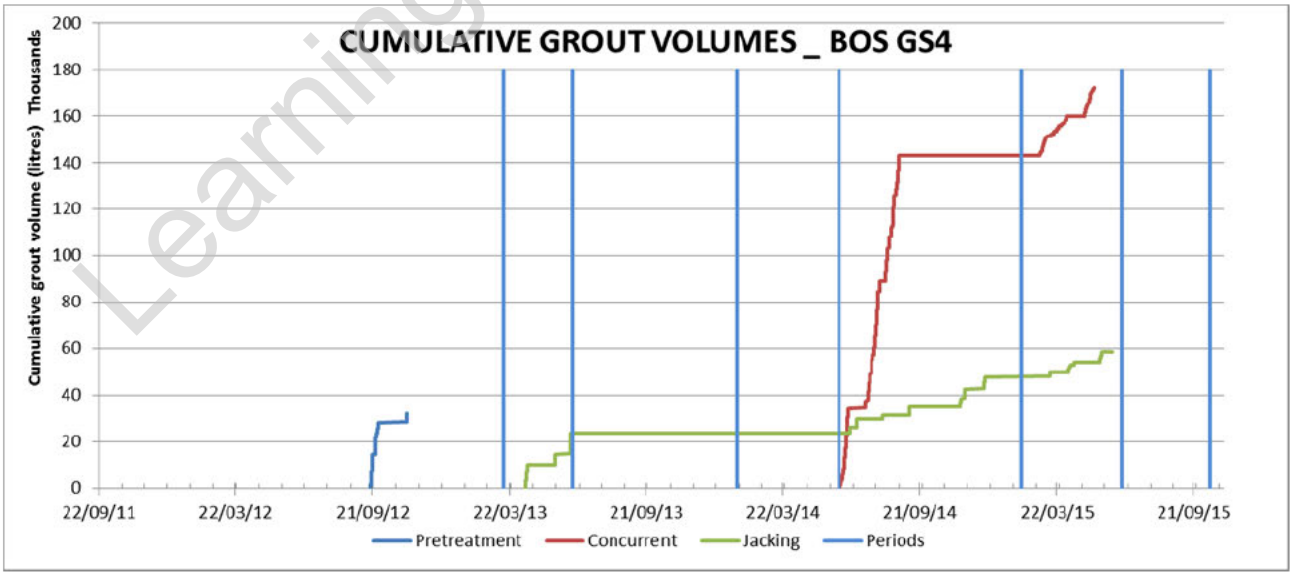


Figure 2.3 Distribution of grout injected from GS4: Pretreatment grouting. Grout Intensity (l/m^2).

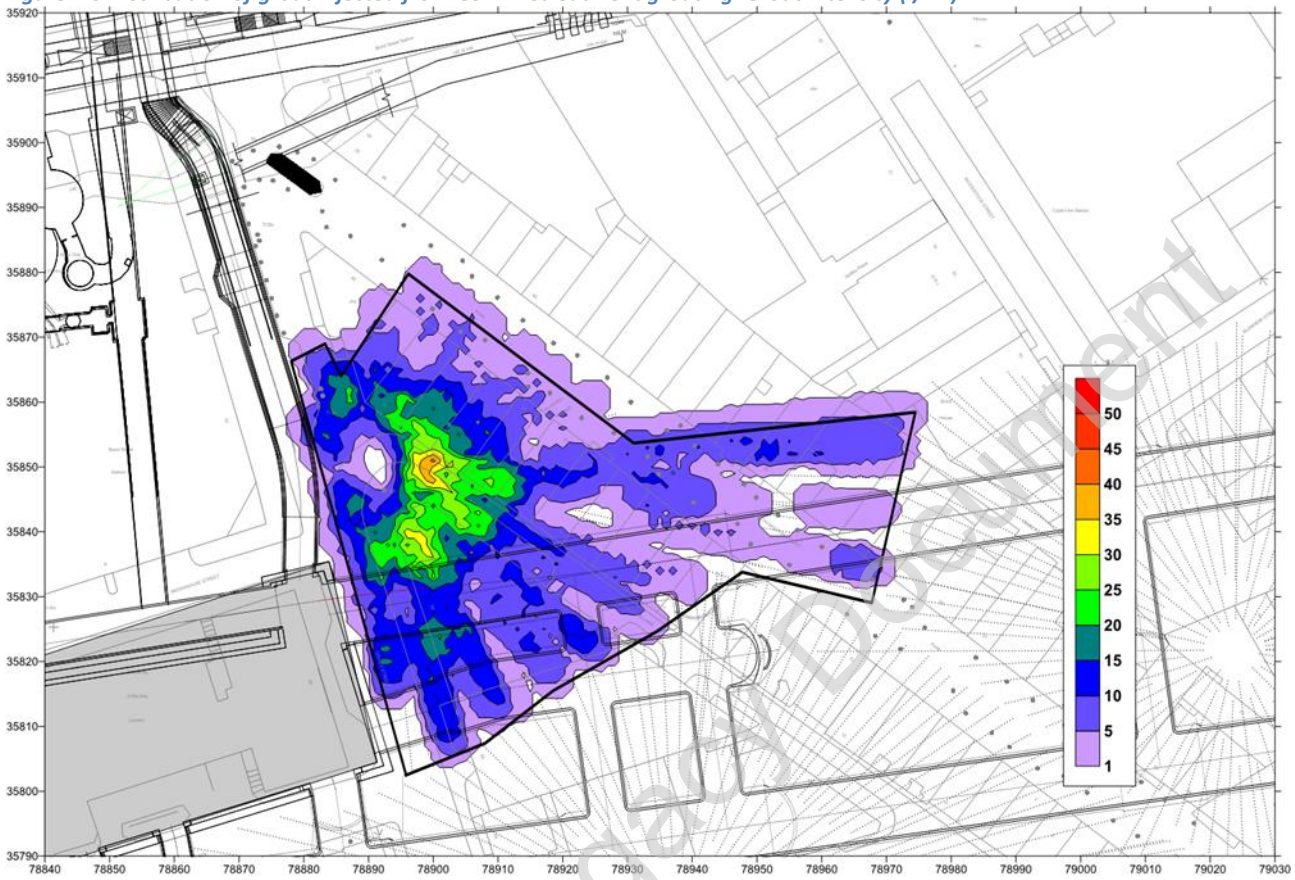


Figure 2.4 Distribution of grout injected from GS4: Concurrent grouting. Grout Intensity (l/m2).

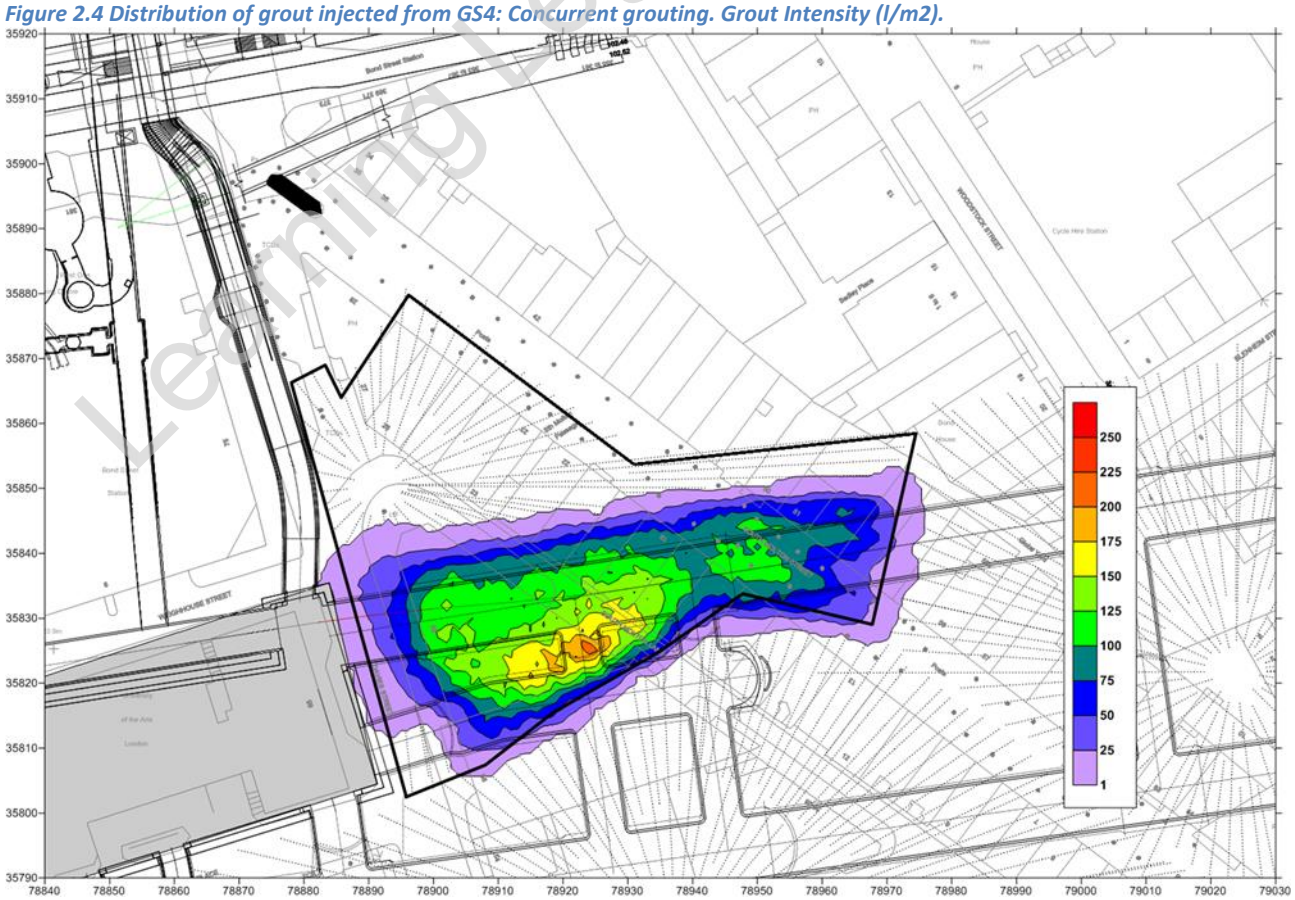


Figure 2.5 Distribution of grout injected from GS4: Jack grouting. Grout Intensity (l/m^2).

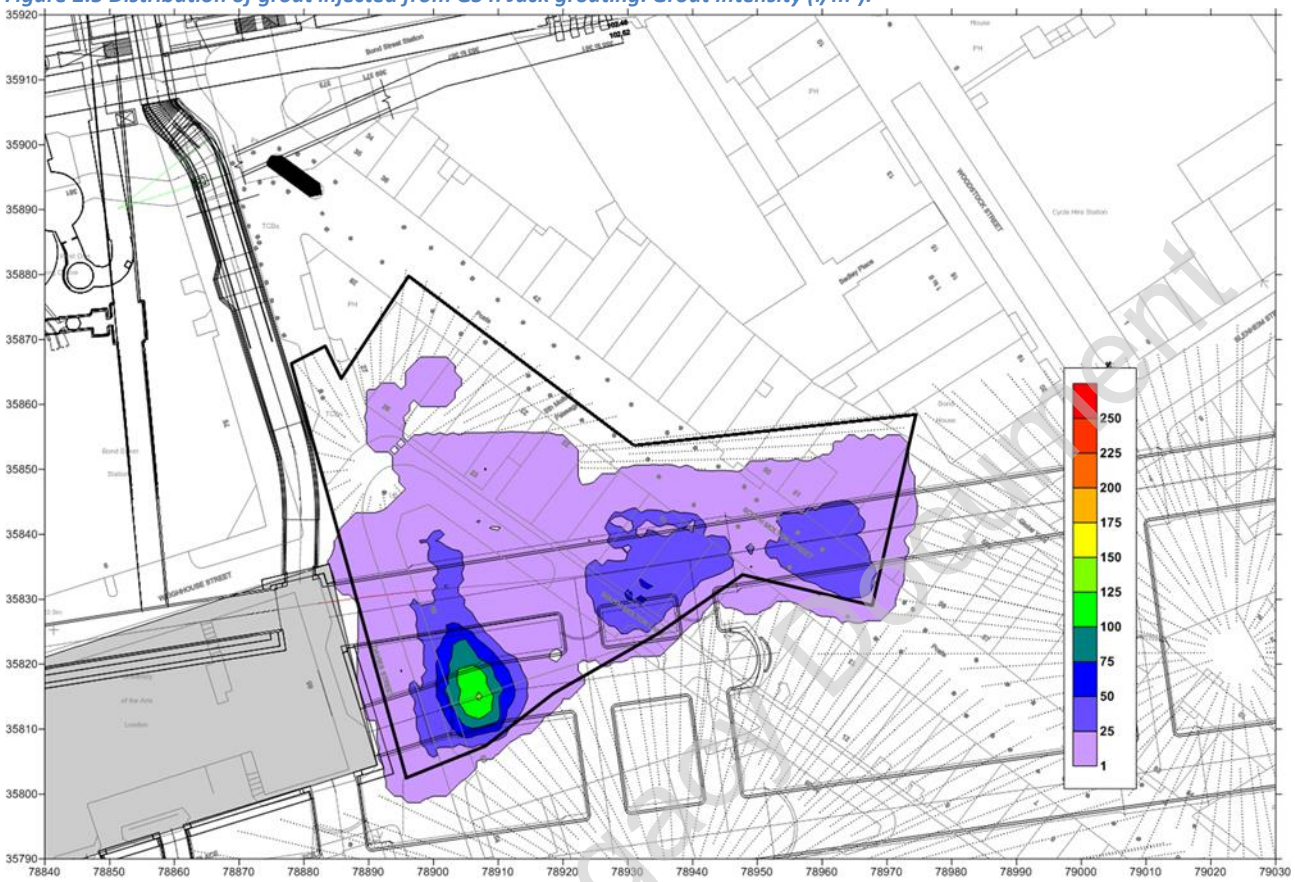
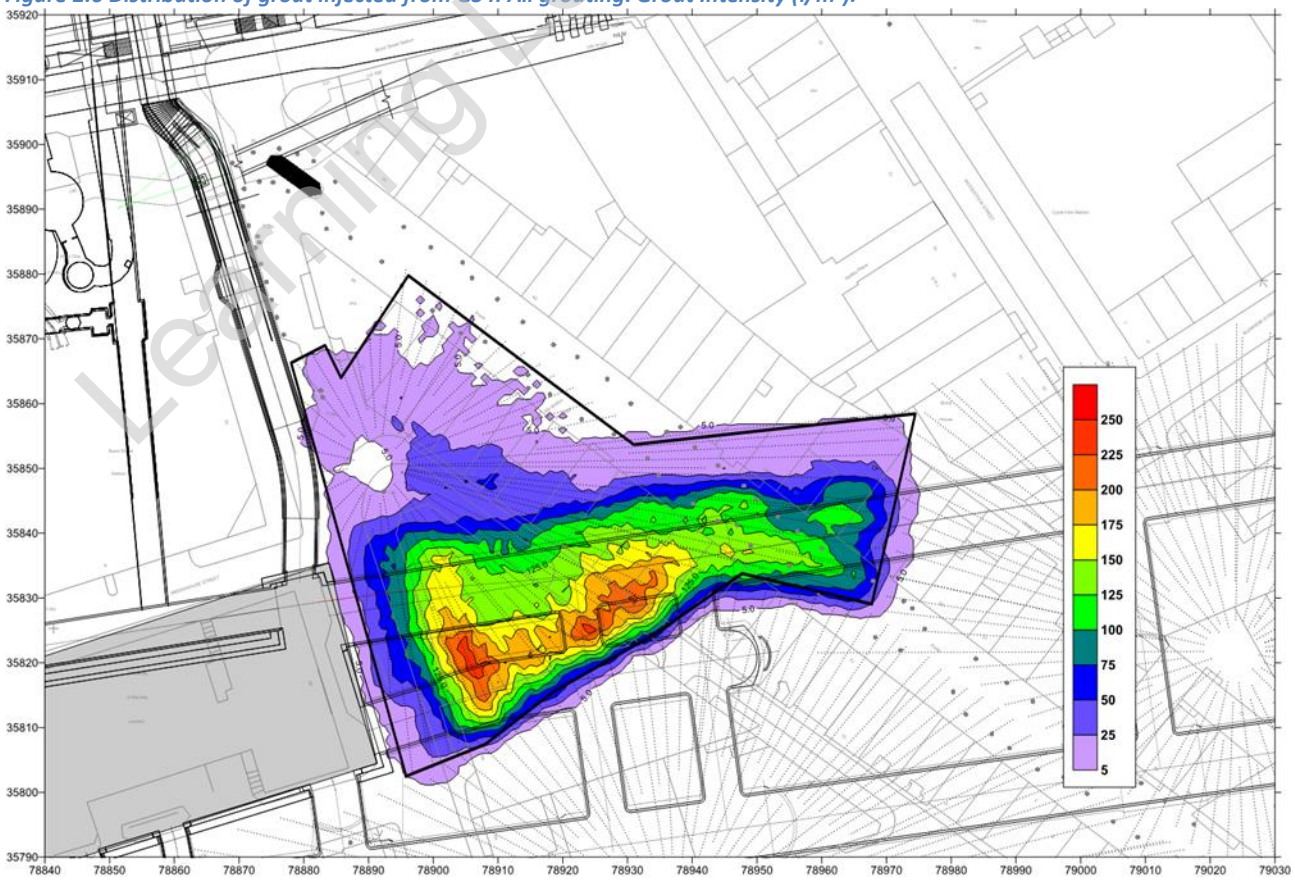


Figure 2.6 Distribution of grout injected from GS4: All grouting. Grout Intensity (l/m^2).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. SETTLEMENT OVERVIEW

Settlement contours have been generated showing the total measured settlement at the end of each Construction Period and the change in settlement during the Period. The latter is compared to the calculated 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 short term greenfield 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 GS4 area, is shown in Figure 3.1.2.

The following points are noted:

- Settlements were 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 predictions and the observations are:
    - The settlements in the GS4 area are generally less than predicted (60mm maximum contour cf. 90mm).
    - Over the platform tunnel (PTE) the recorded magnitude of settlement was similar to that predicted (40 to 50mm).
    - The settlement on the northern boundary of GS4 is greater than predicted with ~20mm settlement recorded at the 10mm predicted contour.
    - The comparisons described above are in a large part affected by a large contribution from consolidation during the construction period.
    - Above AP1, adjacent to the GS4 area, settlement is less than predicted.

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

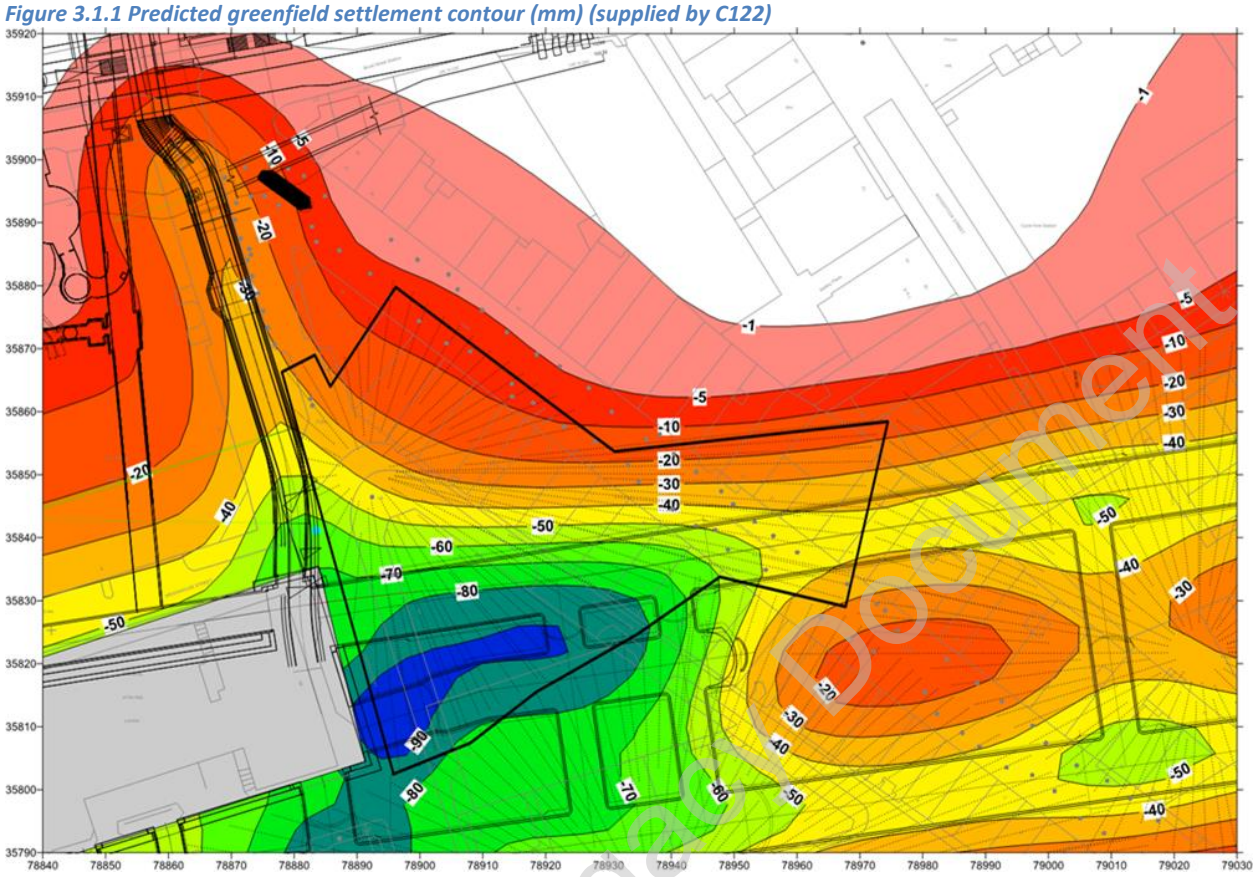
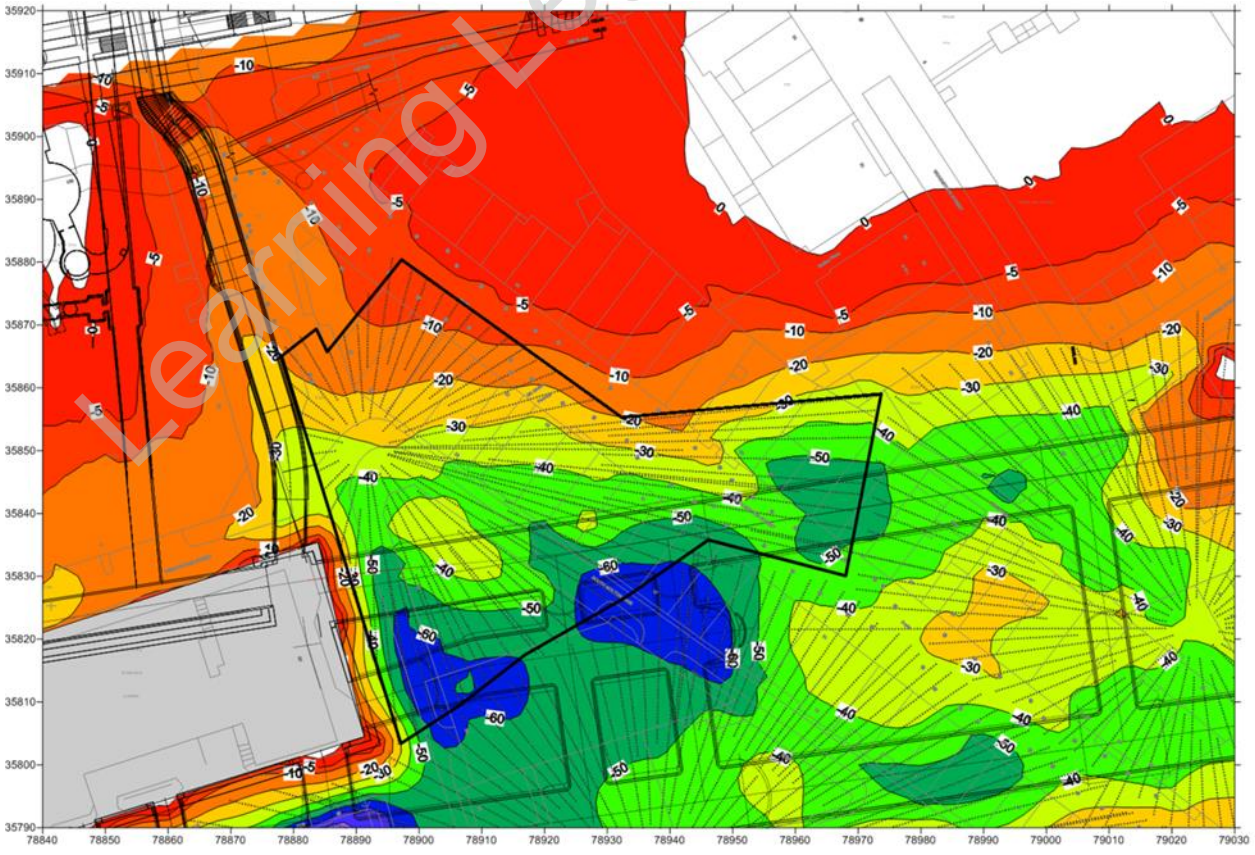


Figure 3.1.2 Observed settlement contour in June 2015 (mm)



In order to compare the predicted and actual movements at various stages of construction, a number of periods have been identified based on the BFK works progress commencing in May 2012 up to the termination of monitoring in October 2015. 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 – Prior to tunnelling: 28/05/12 – 15/03/13

BFK works in Period A comprised the drilling and pre-treatment of TaMs from GS4. 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 is evident over a significant part of the GS4 area. The contours of grout intensity show that, during pretreatment, effort was concentrated in the area of maximum settlement around the shaft where up to 35l/m^2 was injected to complete pre-treatment. Over the remainder of the area less than 15l/m^2 was required.

Figure 3.2.1 Period A: Total measured settlement (mm)

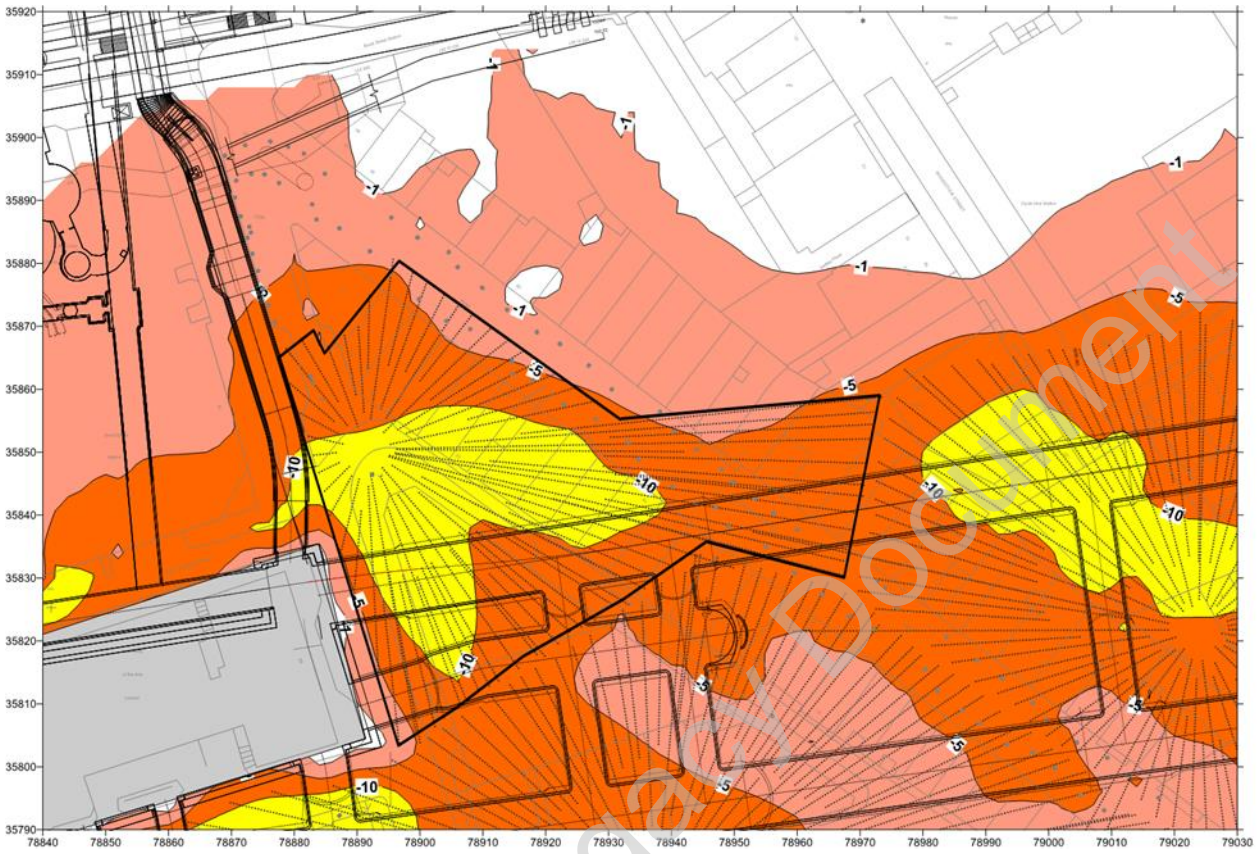
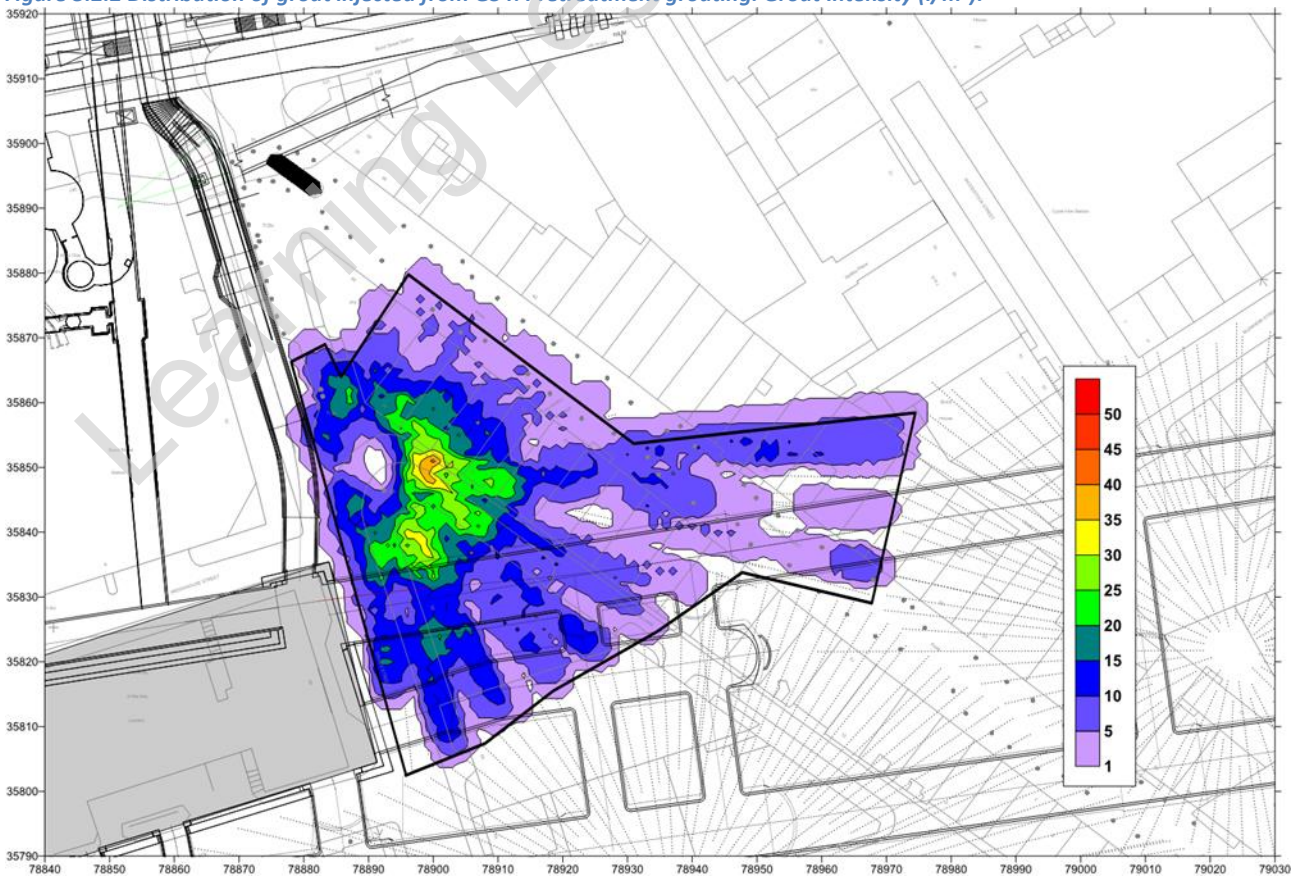


Figure 3.2.2 Distribution of grout injected from GS4: Pretreatment grouting. Grout Intensity (l/m^2).



3.3. Period B – EBRT: 15/03/13 – 15/06/13

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

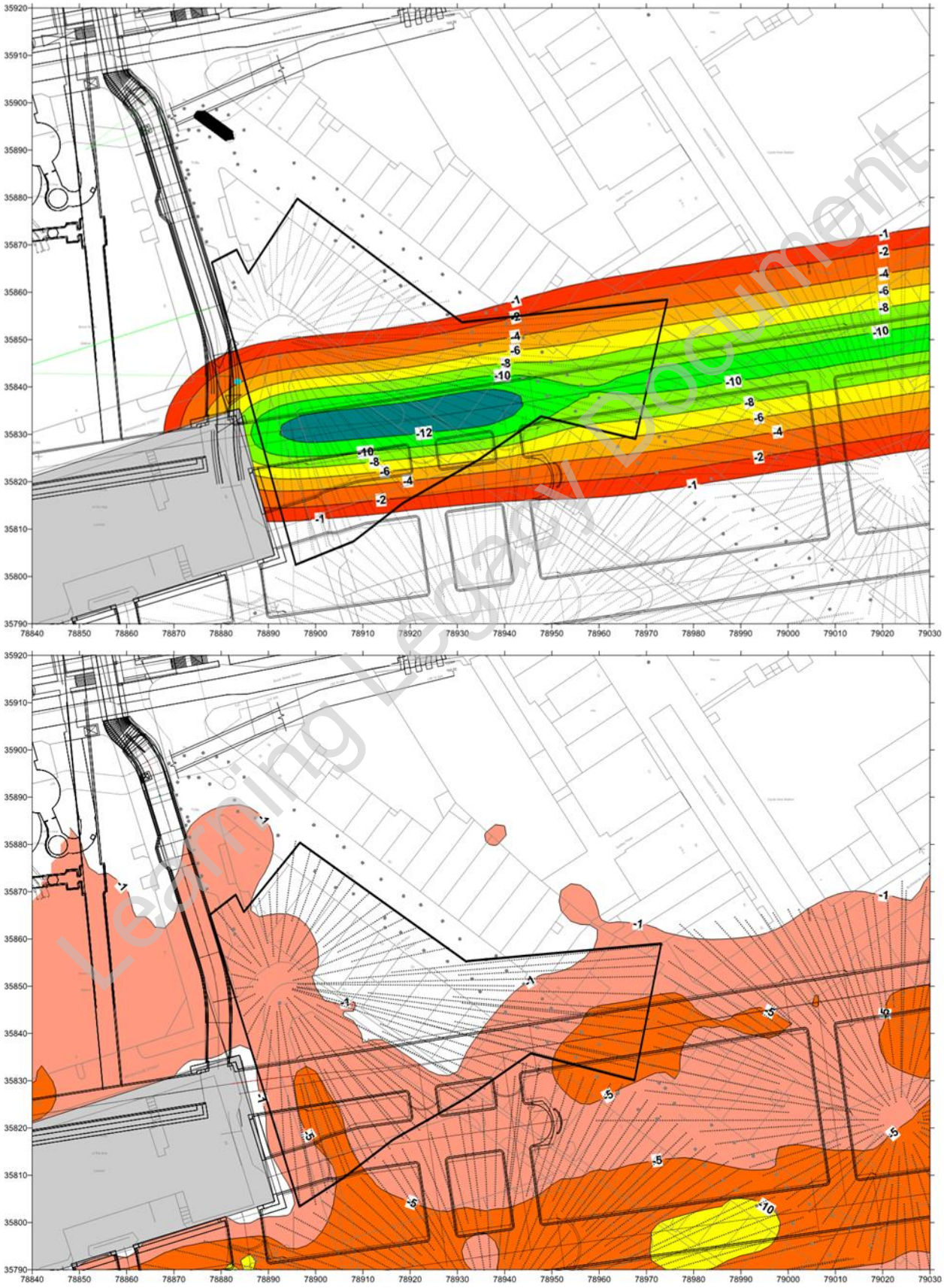


Figure 3.3.2 Period B: Total measured settlement (mm).

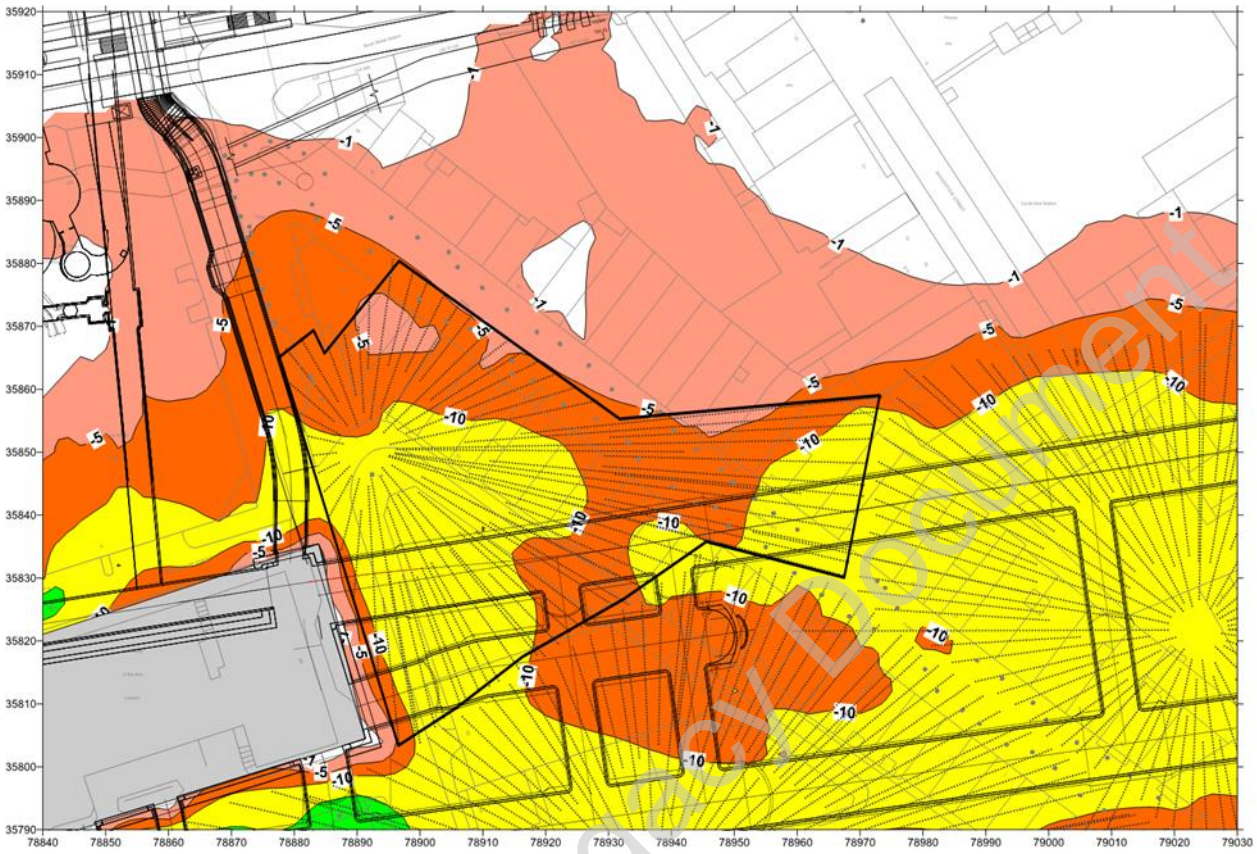


Figure 3.3.3 Period B: Distribution of grout injected from GS4: Jack grouting. Grout Intensity (l/m^2).

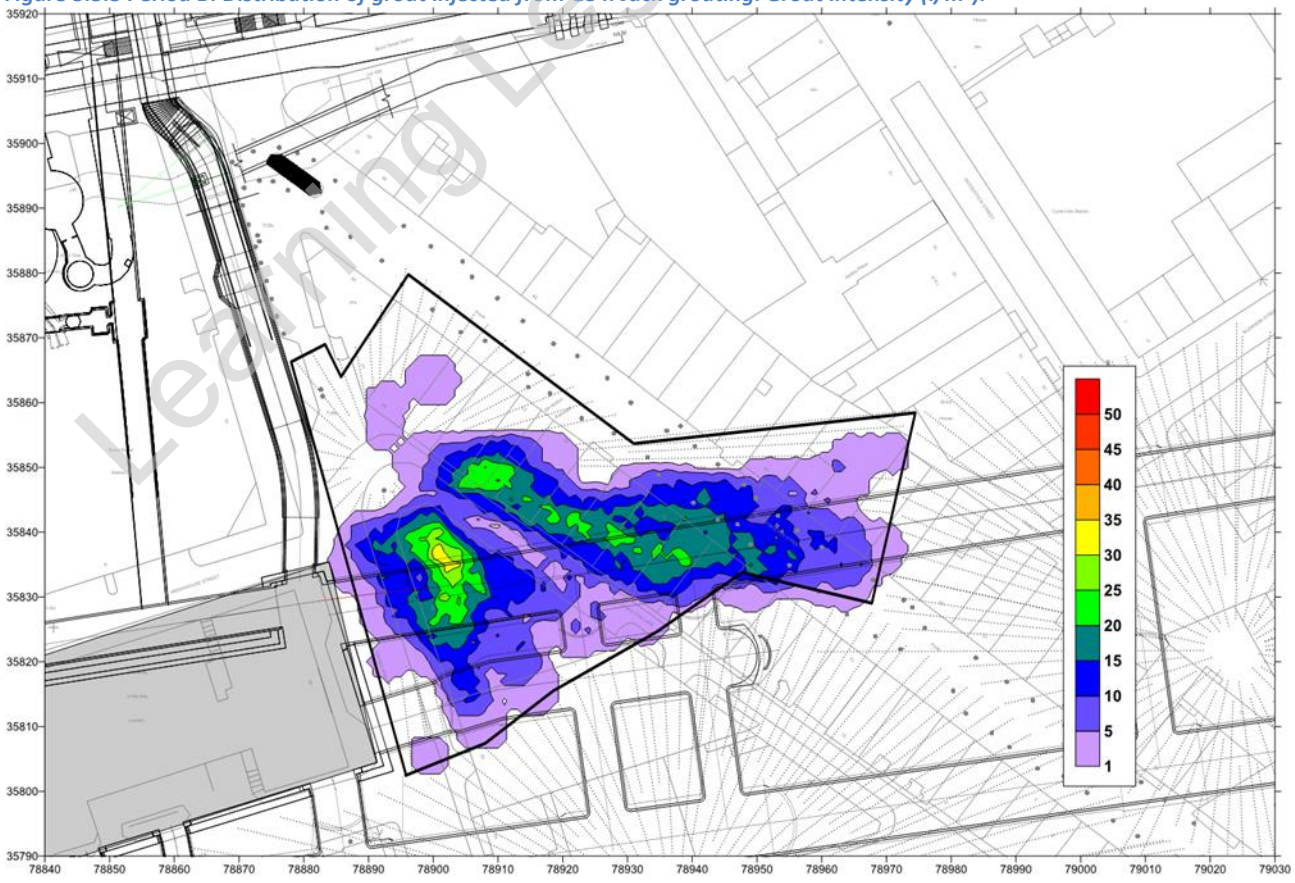


Figure 3.3.1(a) shows that just over 12mm volume loss settlement was anticipated for the EBRT drive. Figure 3.3.1(b) shows that maximum recorded change in settlement was ~5mm.

At the end of Period B the cumulative movements (Figure 3.3.2) show a maximum of between ~10mm and ~15mm over the EBRT in the GS4 area.

No concurrent grouting was undertaken with the EBRT. 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, with a maximum intensity of 30l/m^2.

3.4. Period C – No Tunnelling: 15/06/13 – 20/01/14

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

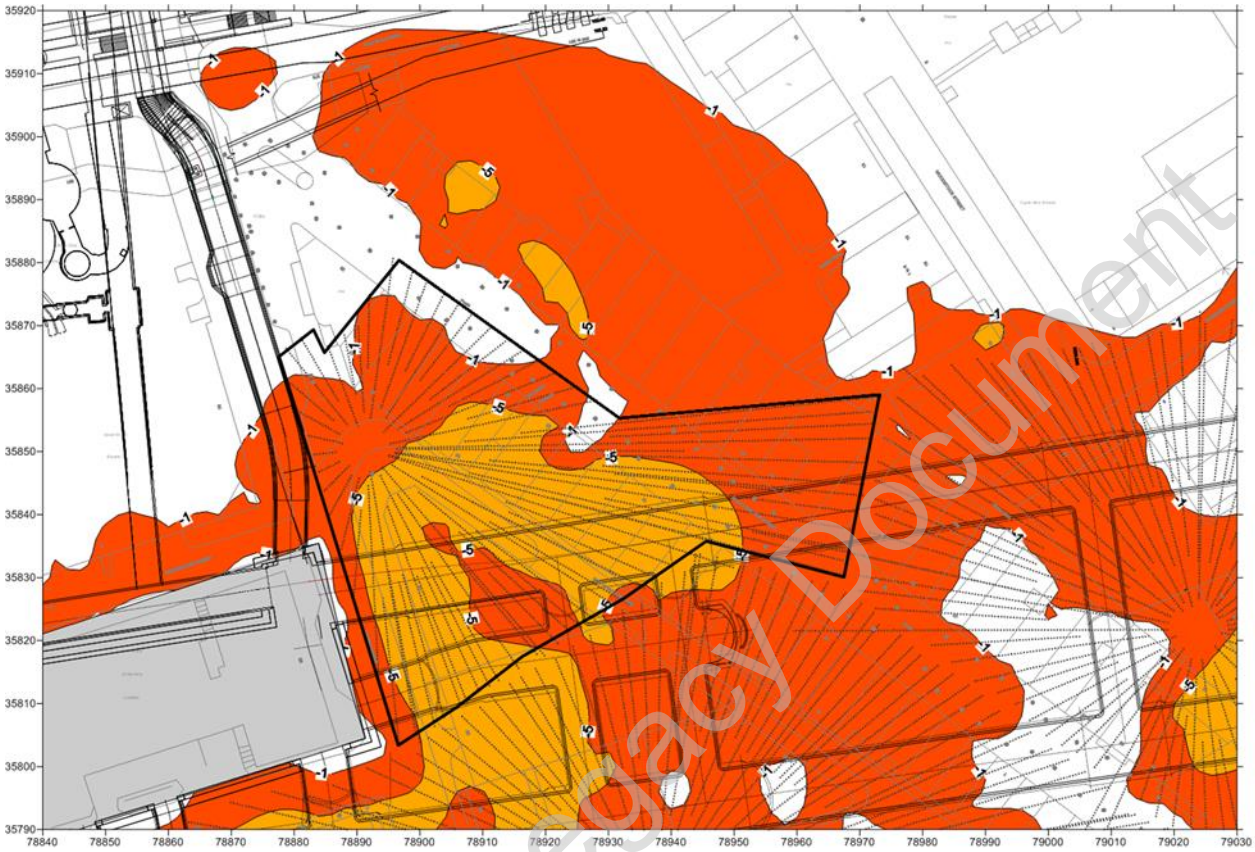
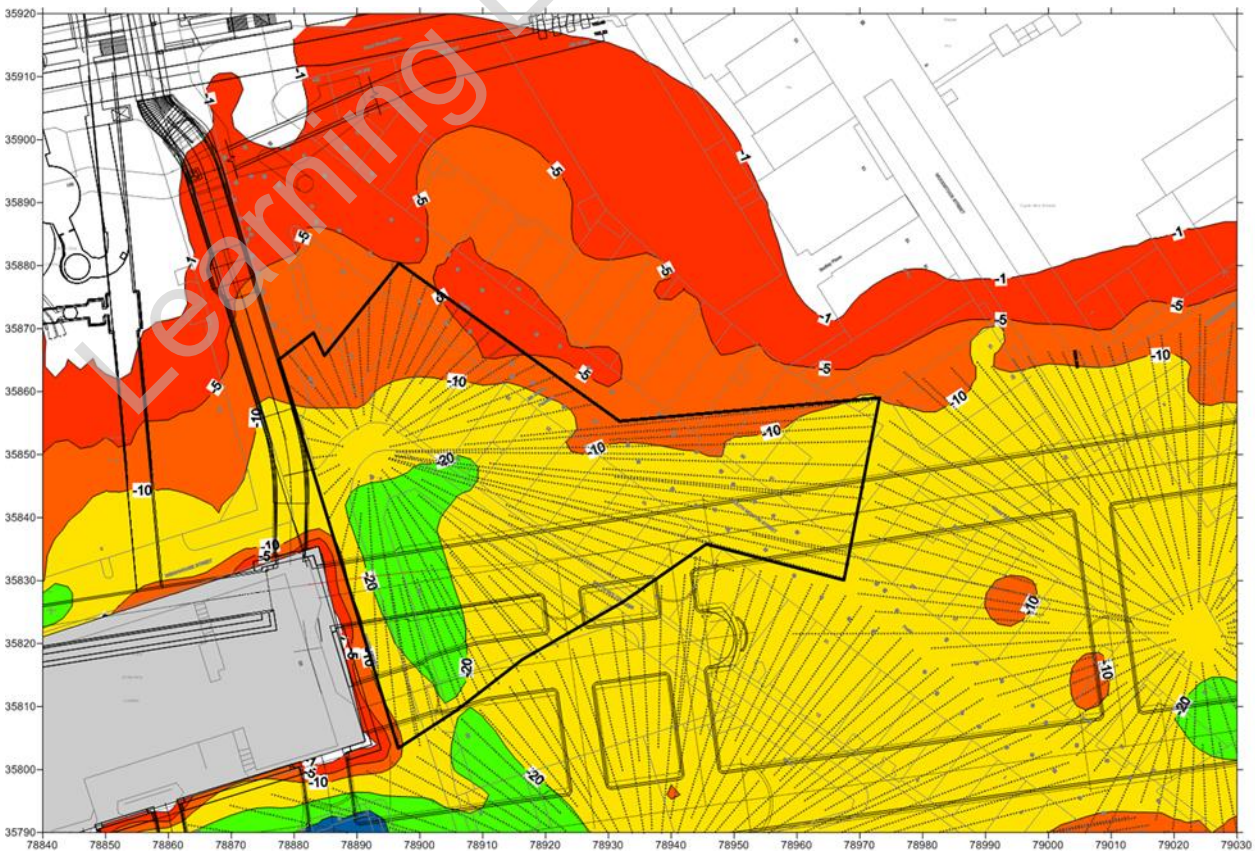


Figure 3.4.2 Period C: Total measured settlement (mm).



There was no tunnel excavation in Period C.

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 in the GS4 area exceeded 20mm locally adjacent to the WTH eastern wall.

No grout jacking was undertaken from GS4 in Period C.

3.5. Period D – No Tunnelling: 20/01/14 – 06/06/14

Figure 3.5.1 Period D: Change in measured settlement (mm).

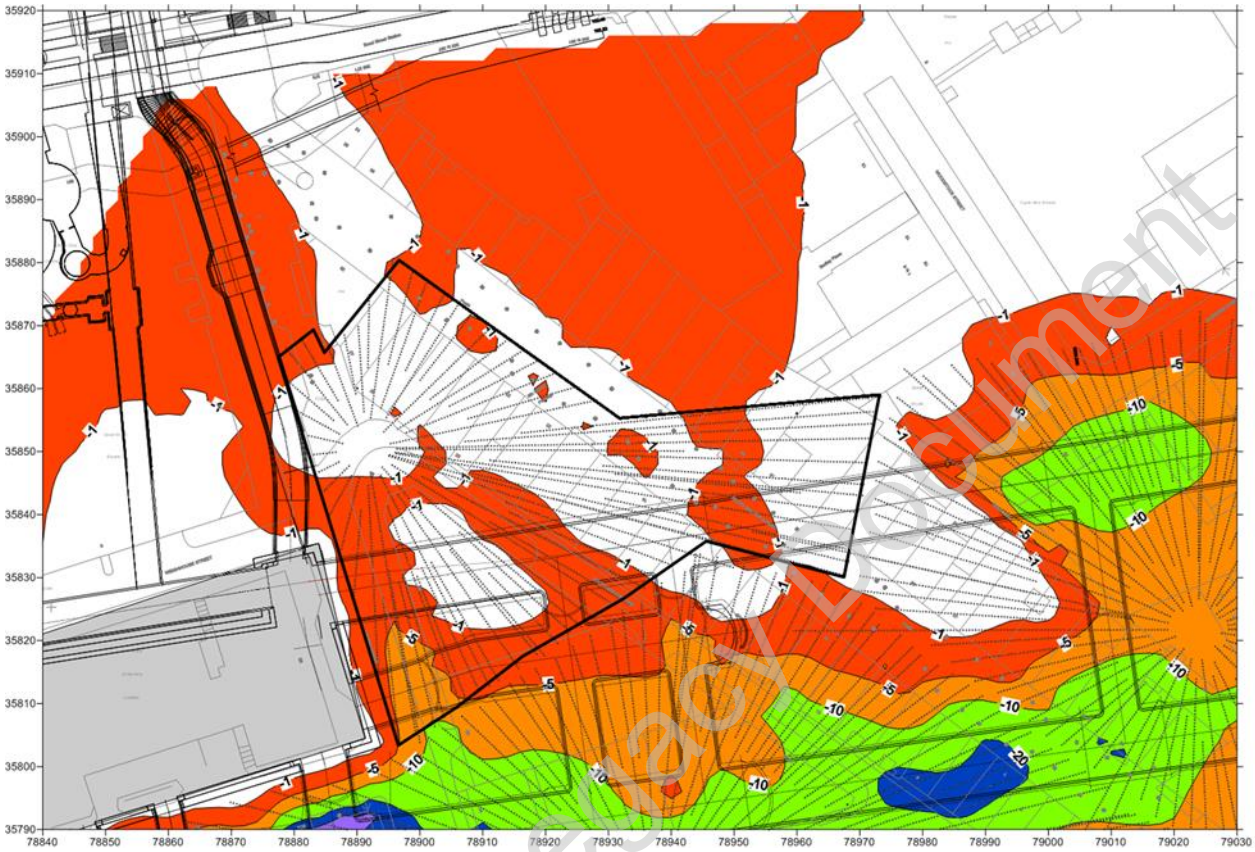
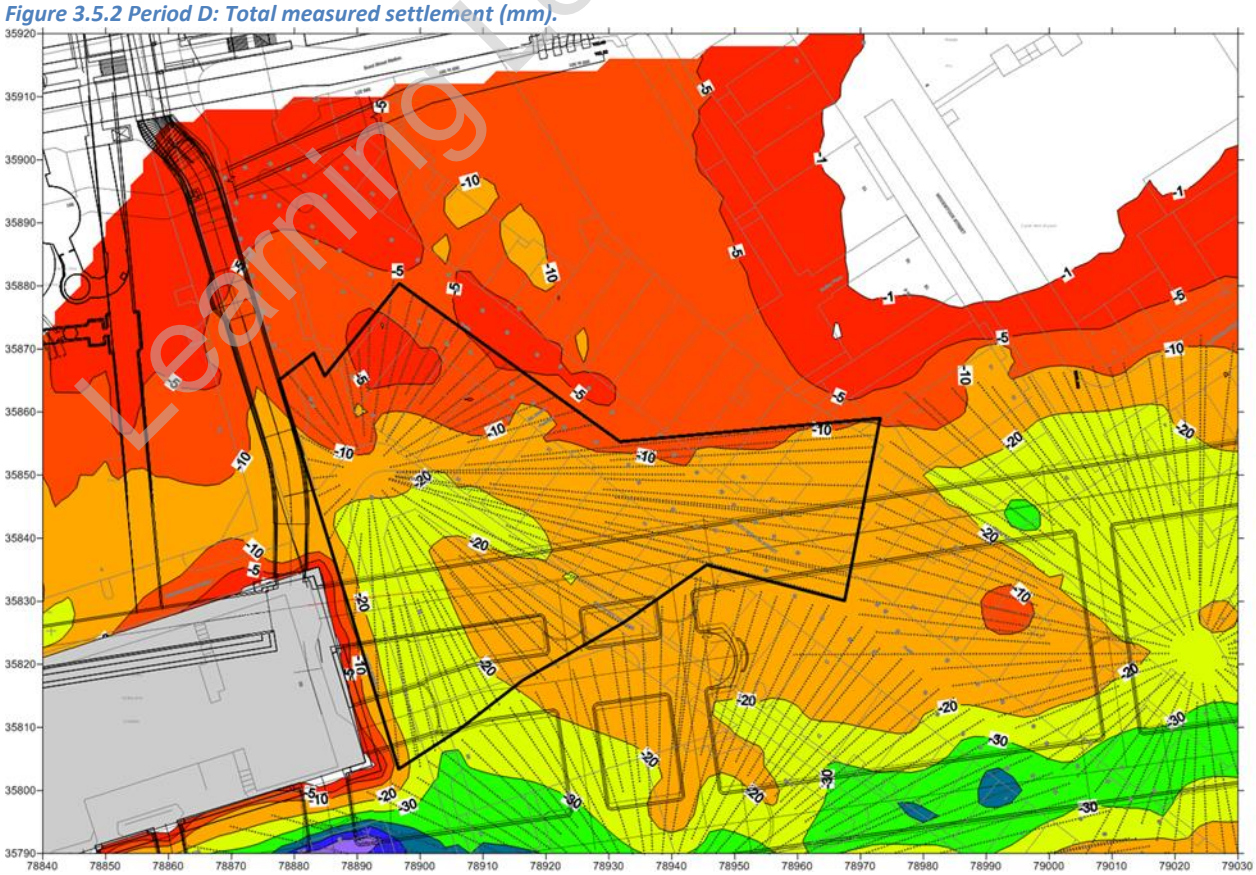


Figure 3.5.2 Period D: Total measured settlement (mm).



There was no tunnel excavation in Period D.

Figure 3.5.1 shows that there was a small (<5mm) uniform increase in settlement in Period D over the majority of the GS4 area. The exception is in the south-west corner where the impact of PTW and AP2A is evident (see GS1 report for more detail), where a 10mm increase in settlement was recorded.

Figure 3.5.2 shows that the maximum total settlement reached almost 30mm locally close to the PTW / AP2A junction, with more generally 10 to 20mm over the remainder of the GS4 area.

No grout jacking was undertaken from GS4 in Period D.

3.6. Period E – PTE, CP1 , CP3, AP1: 06/06/14 – 04/02/15

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

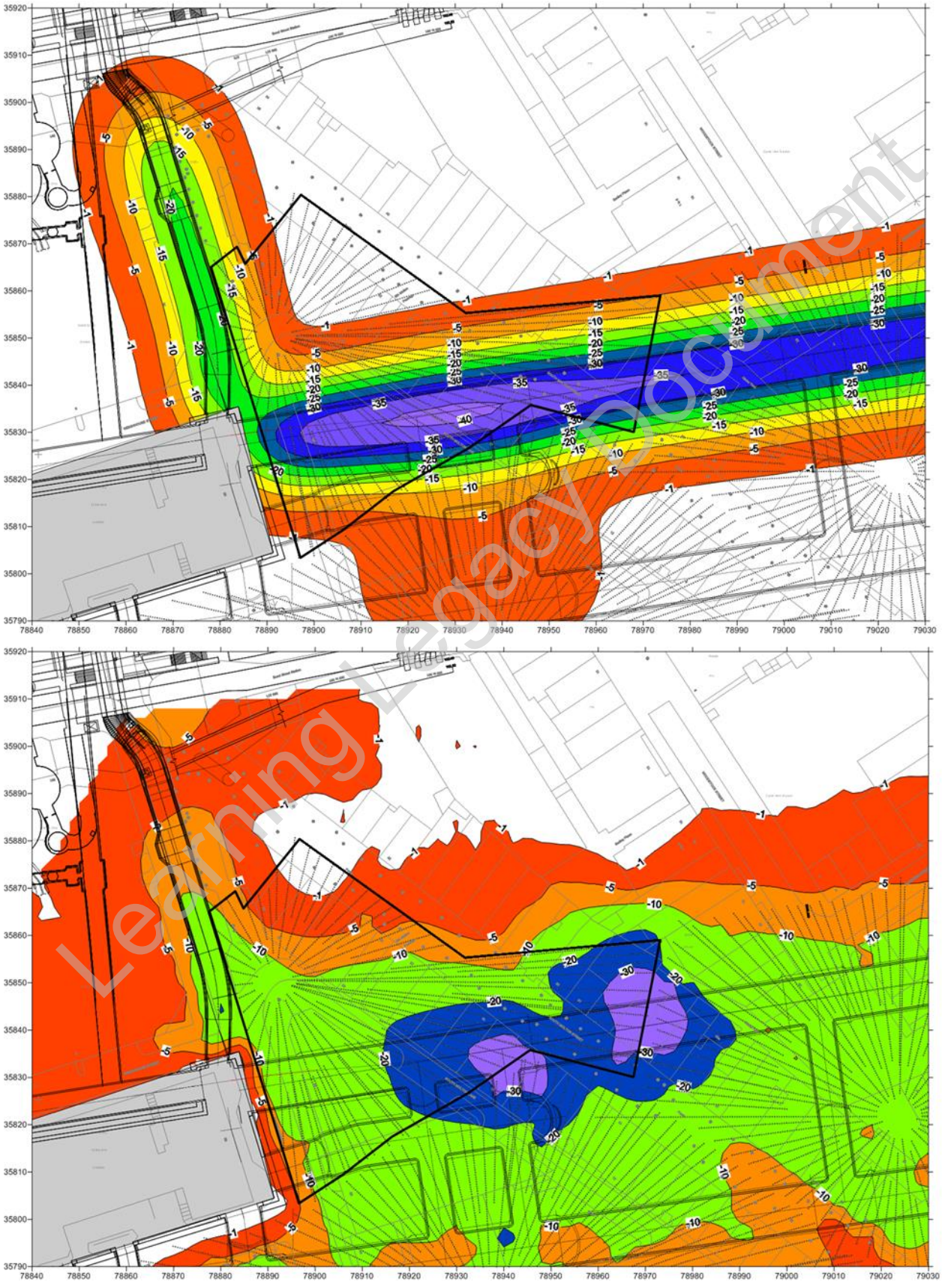


Figure 3.6.2 Period E: Total Measured Settlement (mm)

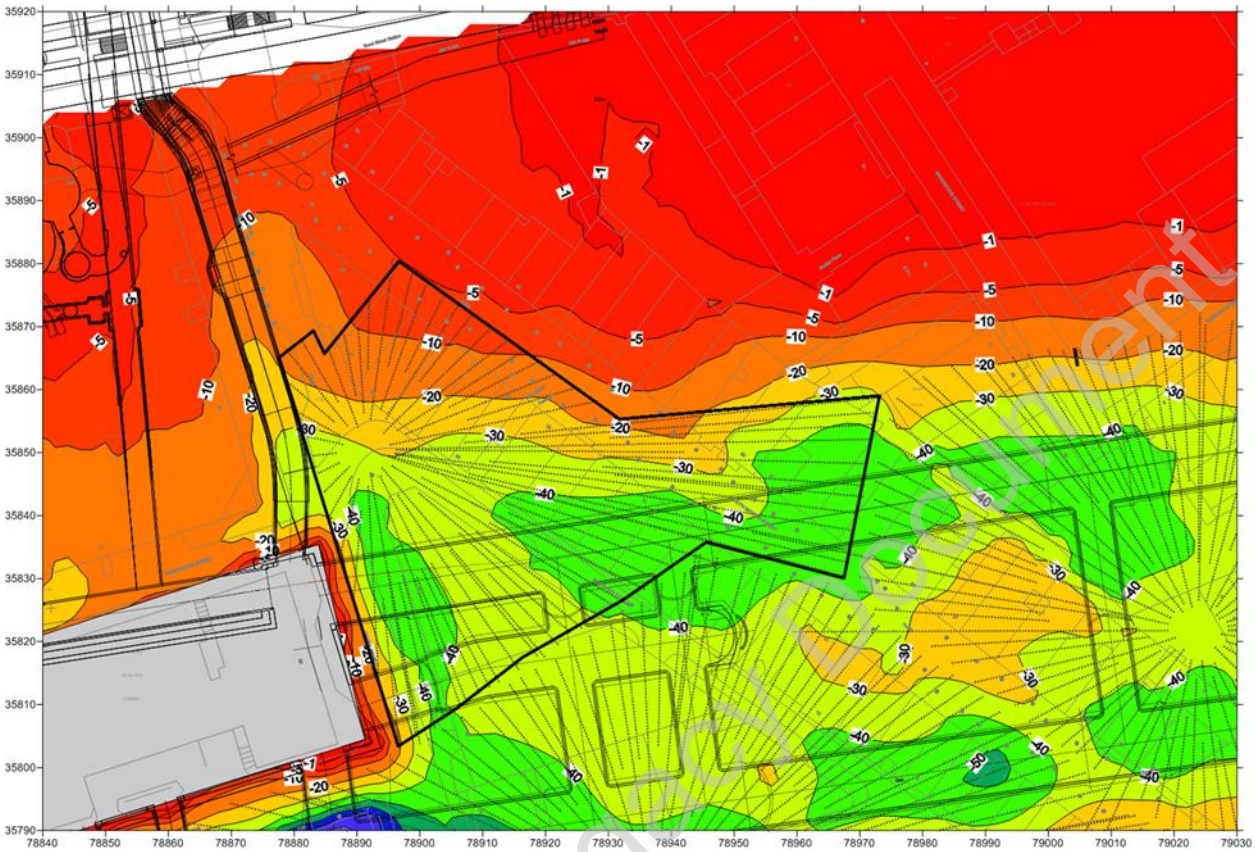


Figure 3.6.3 Period E: Distribution of grout injected from GS4: Concurrent grouting. Grout Intensity (l/m^2).

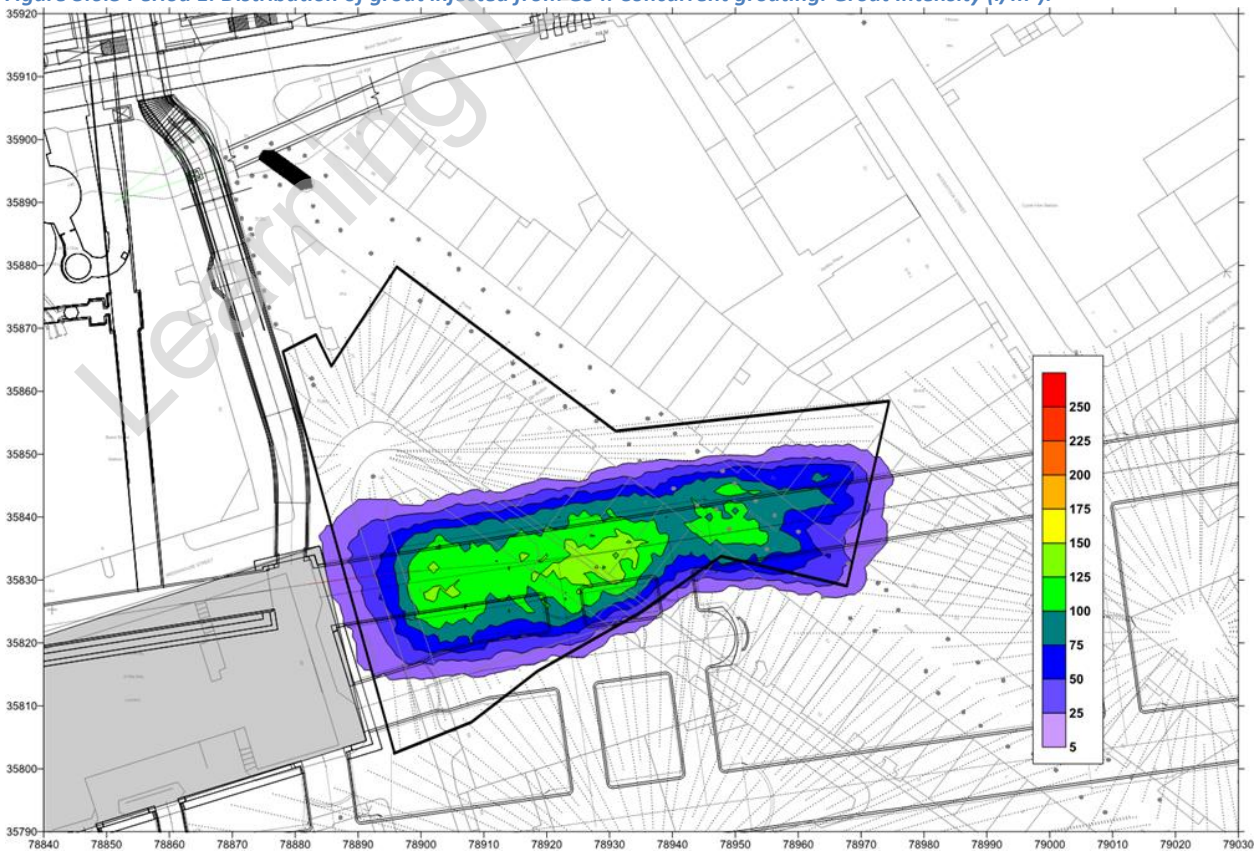
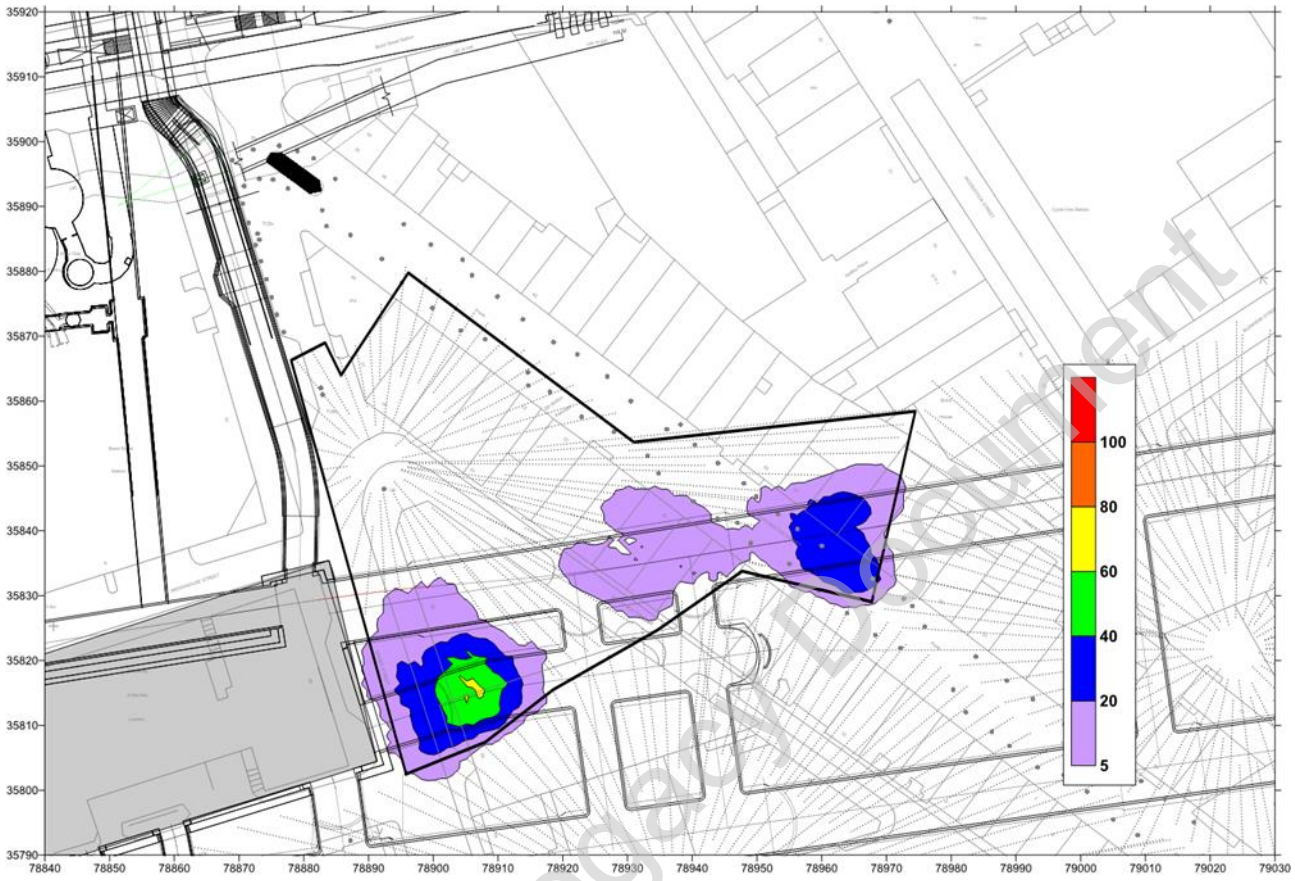


Figure 3.6.4 Period E: Distribution of grout injected from GS4: Grout jacking (l/m2).



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 tunnelling activities in Period E were the PTE and AP1. Stub tunnels commencing the cross passages from PTE and PTW were also excavated in Period E. The maximum calculated volume loss settlement over PTE is ~40mm and over AP1 ~20mm as shown in Figure 3.6.1(a).

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.

Total settlement shows a local maximum of over 50mm above PTE with more than 40mm over most of its length (Figure 3.6.2). Settlement above AP1 decreases to the north as the influence of other activities diminishes: adjacent to the GS4 area the settlement decreases from 40mm to 20mm.

Concurrent grouting and grout jacking were undertaken in Period E, as illustrated in Figures 3.6.3 and 3.6.4. Over 100l/m^2 was injected over the PTE during concurrent grouting. Grout jacking episodes were undertaken over PTE in the eastern part of the GS4 area. A pre-jacking was undertaken over ES1 since concurrent grouting was not possible because of the elevation of the crown of this tunnel: up to 60l/m^2 was injected. No grouting was possible for AP1 due to its elevation.

3.7. Period F – ES1, CH2P, CH2E, CP1 & CP3 junctions: 04/02/15 – 17/06/15

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

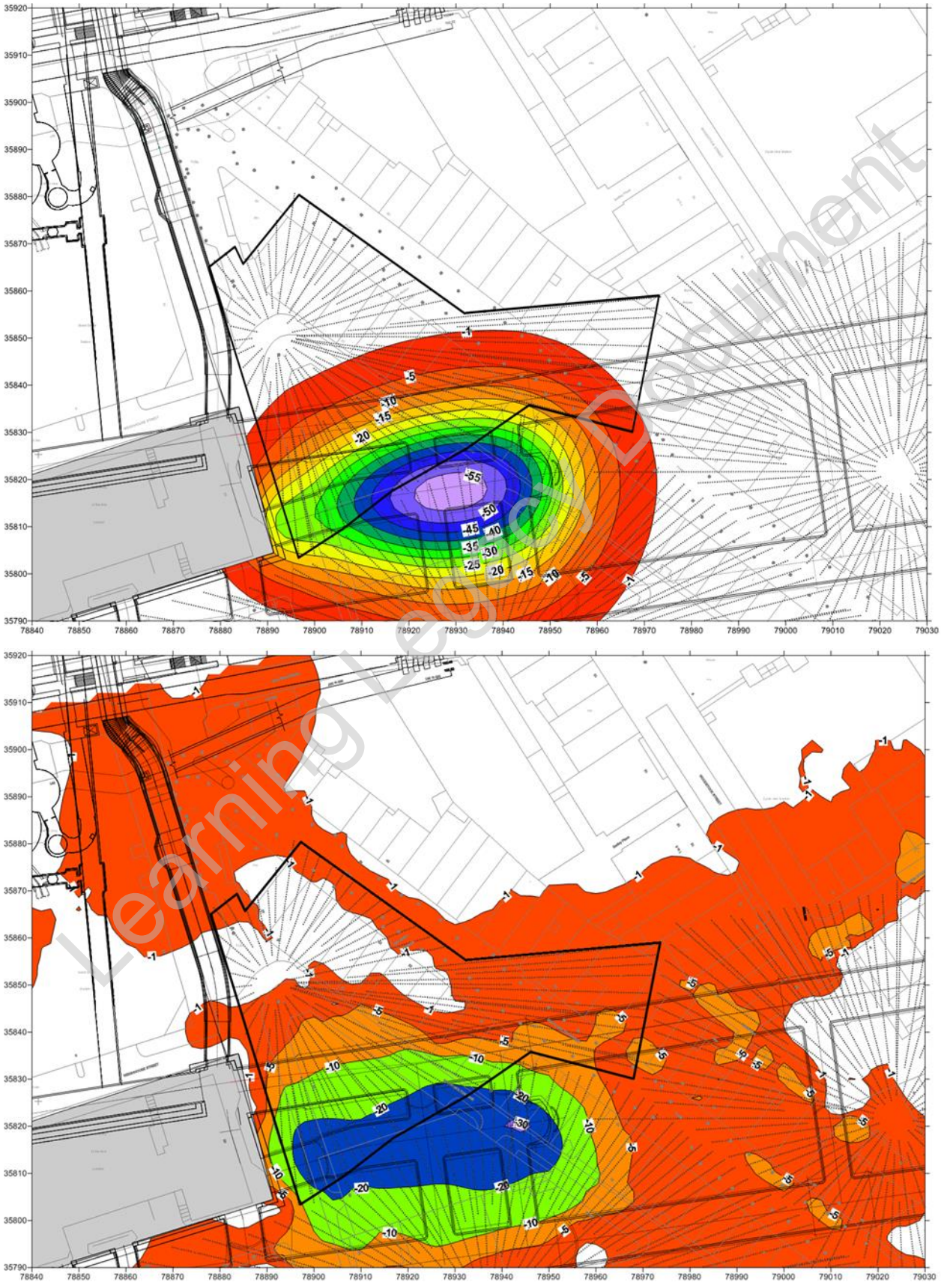


Figure 3.7.2 Period F: Total measured settlement (mm)

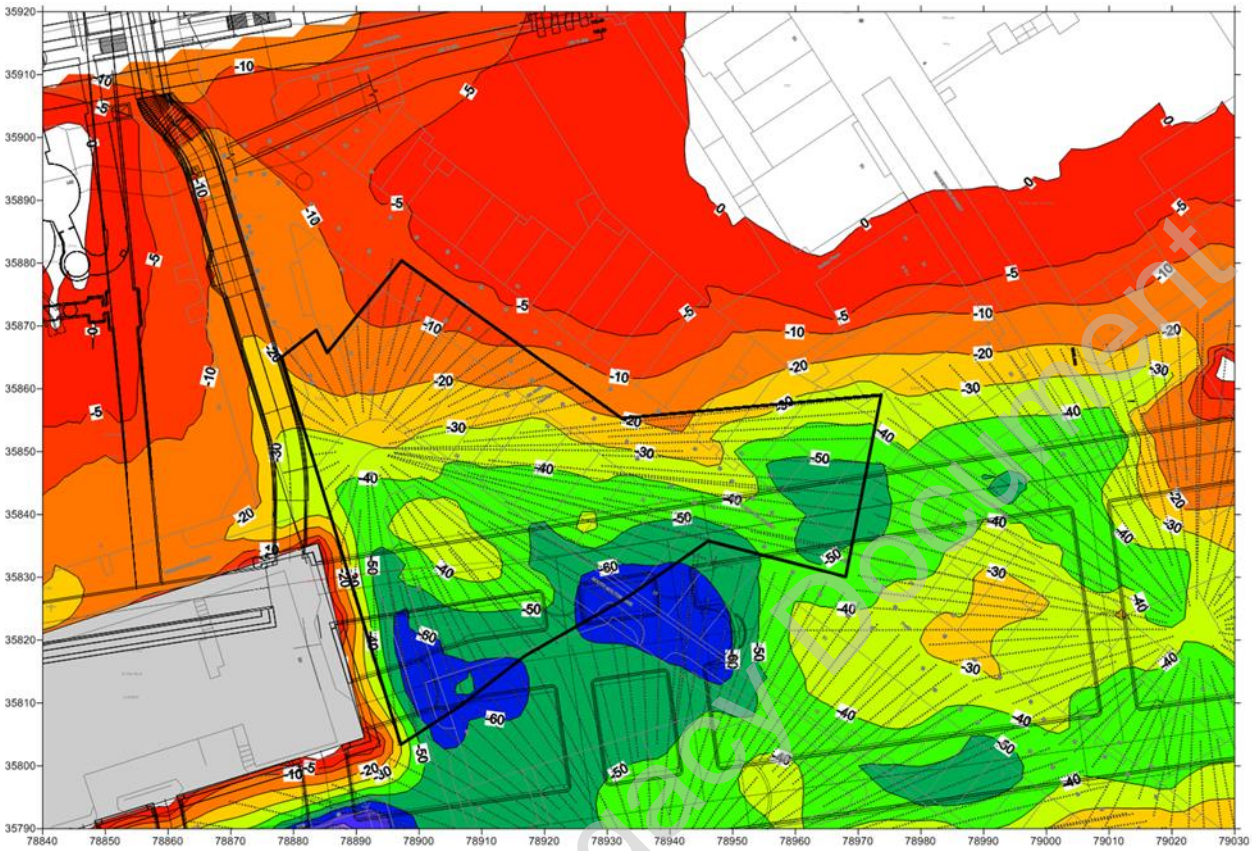


Figure 3.7.3 Period F: Distribution of grout injected from GS4: Concurrent grouting. Grout Intensity (l/m^2).

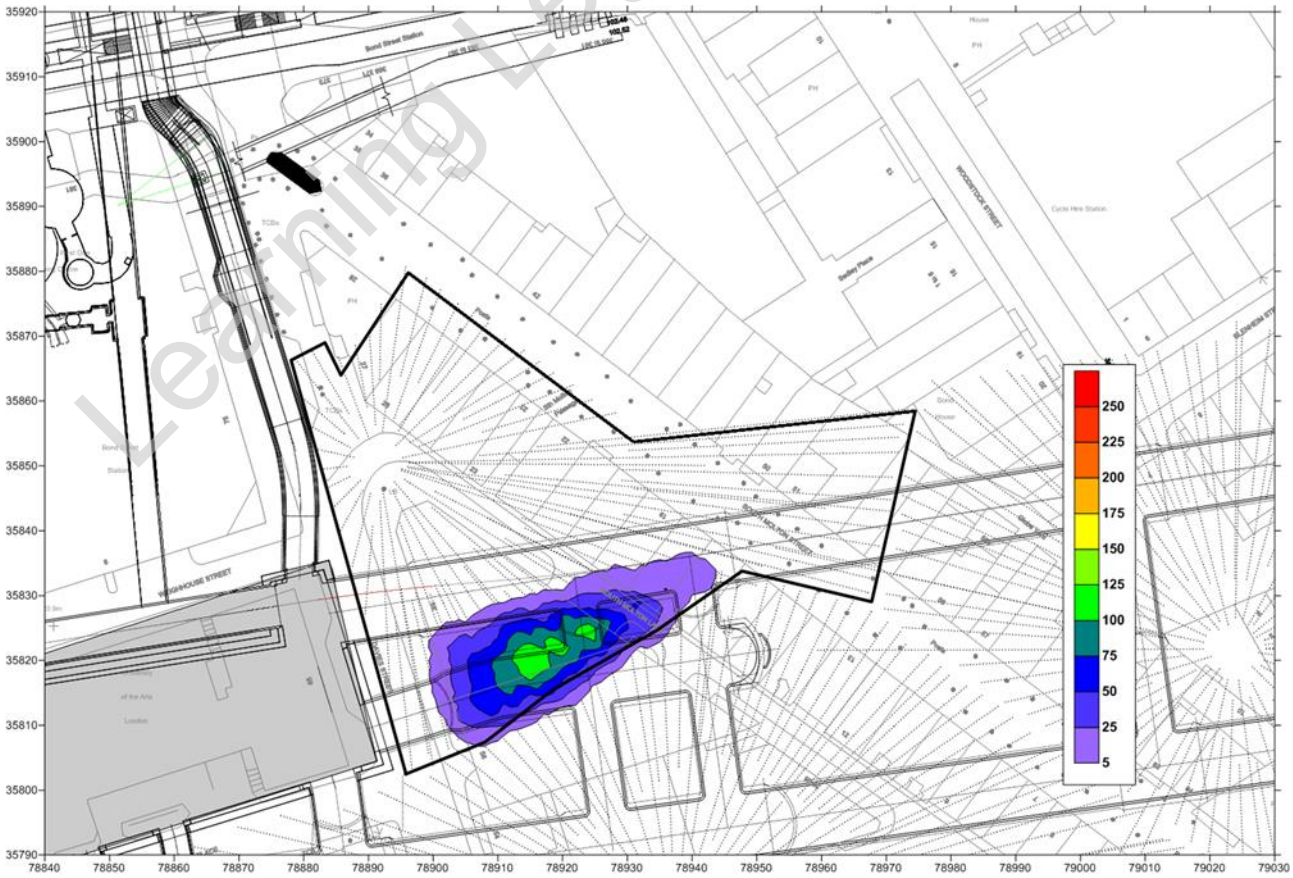
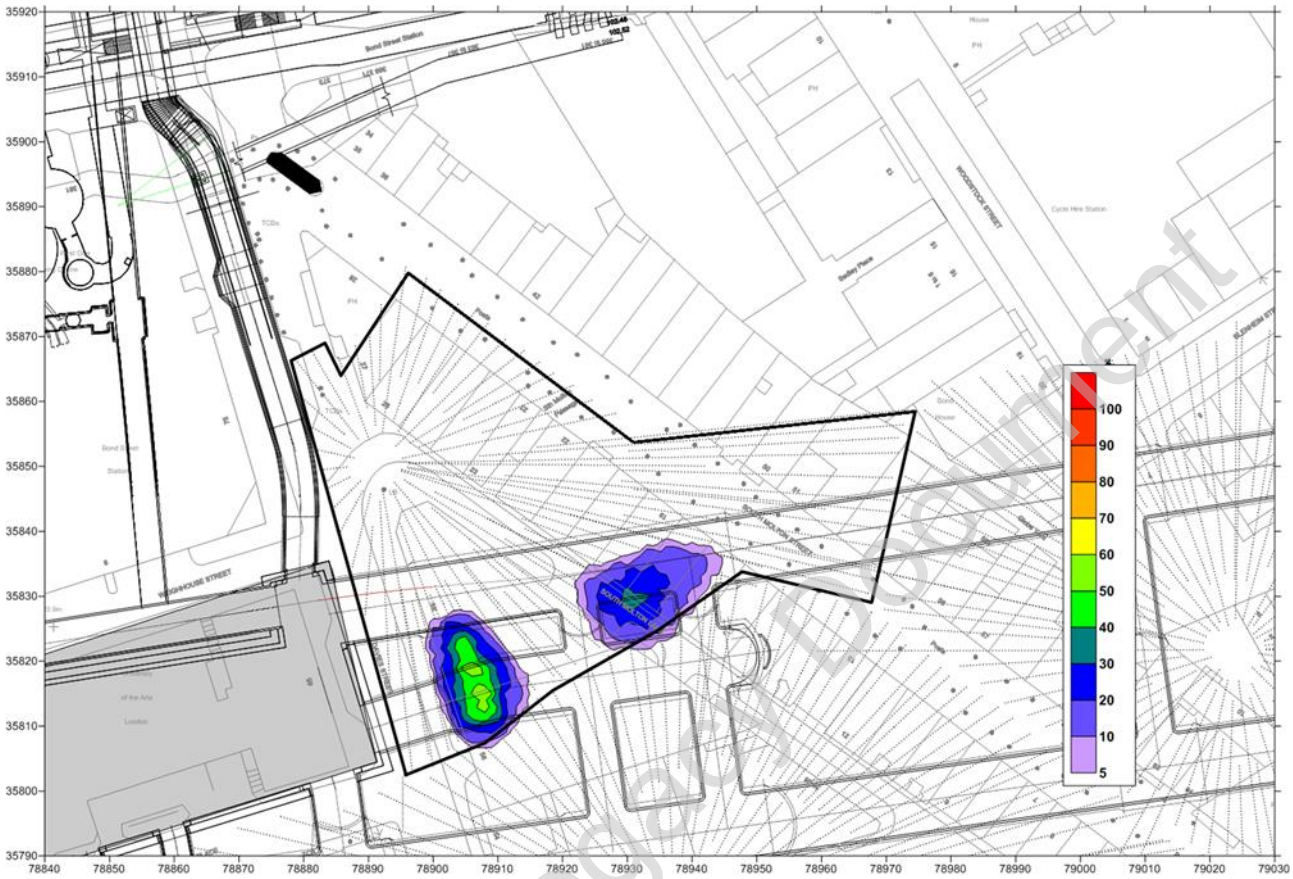


Figure 3.7.4 Period F: Distribution of grout injected from GS4: Grout jacking. Grout Intensity (l/m^2).



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 a maximum of 30mm. It is noted that the 5mm contour is at a similar location to that given in the prediction.

The maximum total settlement within the GS4 area over CH2 increased to over 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 St which were perceived to be related primarily to horizontal movements (see Close Out Report for GS1 C300-BFK-C4-RGN-CRT00_ST005-51211 for crack width data). A maximum intensity of ~40 l/m^2 was injected.

3.8. Period G – Post Construction: 17/06/15 – 13/10/15

Figure 3.8.1 Period G: Observed settlement in Period G (mm)

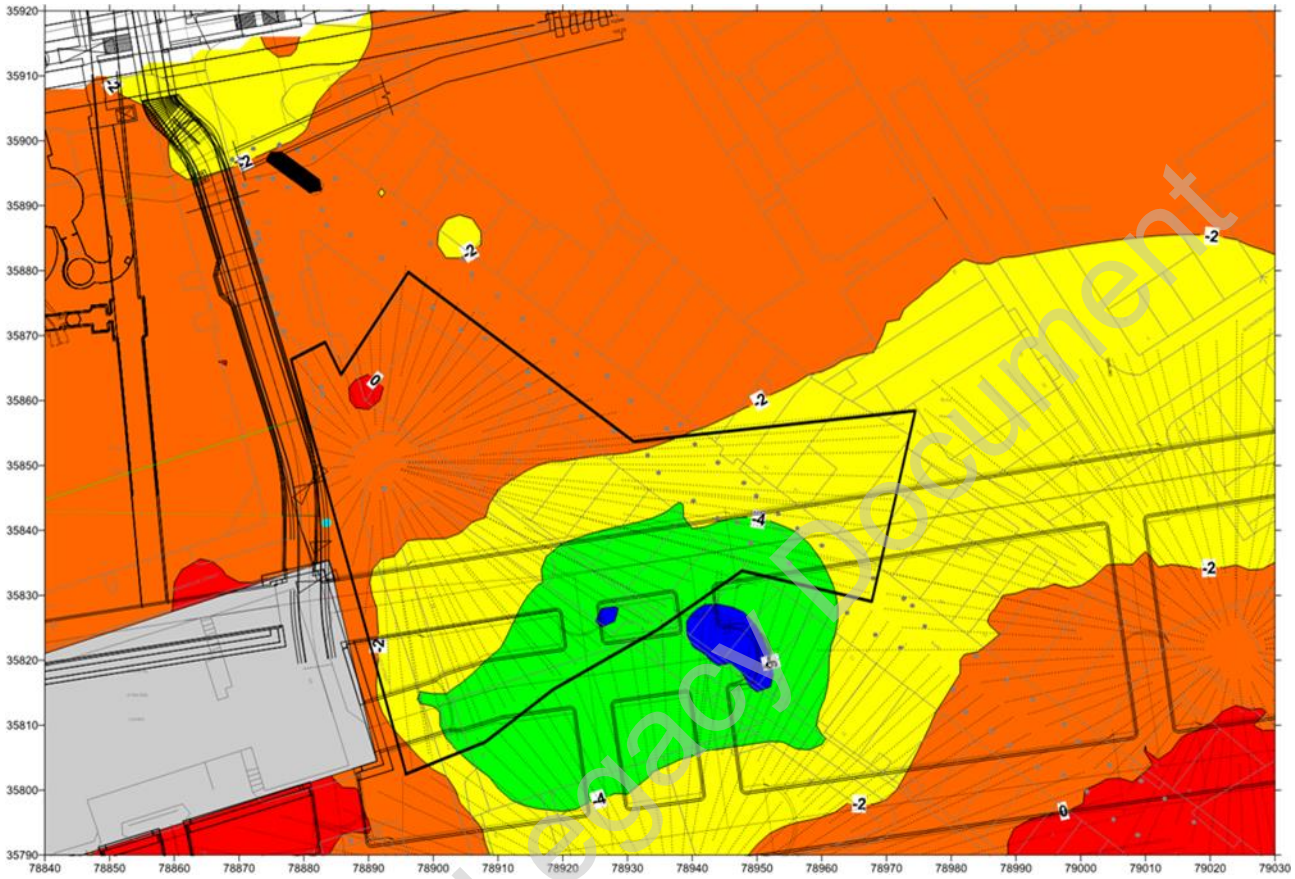


Figure 3.8.2 Period G: Total settlement at cessation of monitoring (mm)

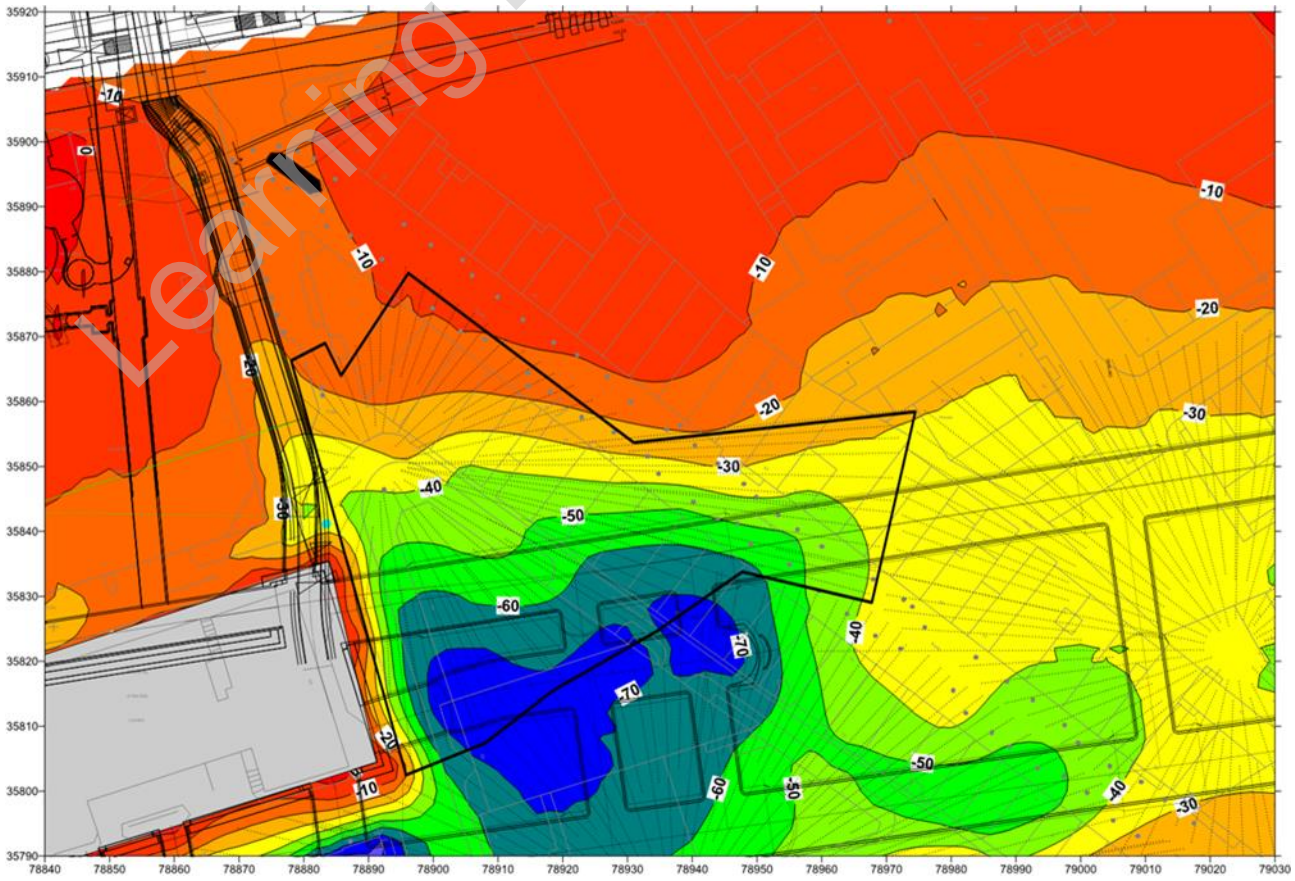


Figure 3.8.1 shows an increase of settlement of up to 6mm during the 4 months following the completion of tunnelling. The maximum total settlement is over 70mm and is located above CH2. The contours are centred over CH2 and the cross passages which were the final excavations in this area.

The total settlement at the end of Period G is shown on Figure 3.8.2 and indicates a maximum movemeny of over 70mm over most of the plan extent of CH2.

4. BUILDING SETTLEMENT AND SLOPES

4.1. Slope triggers

The locations where slope triggers have been exceeded are shown for BRE monitoring of building facades on Figure 4.1.1. 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

Figure 4.1.1 Locations where building slope triggers have been exceeded.

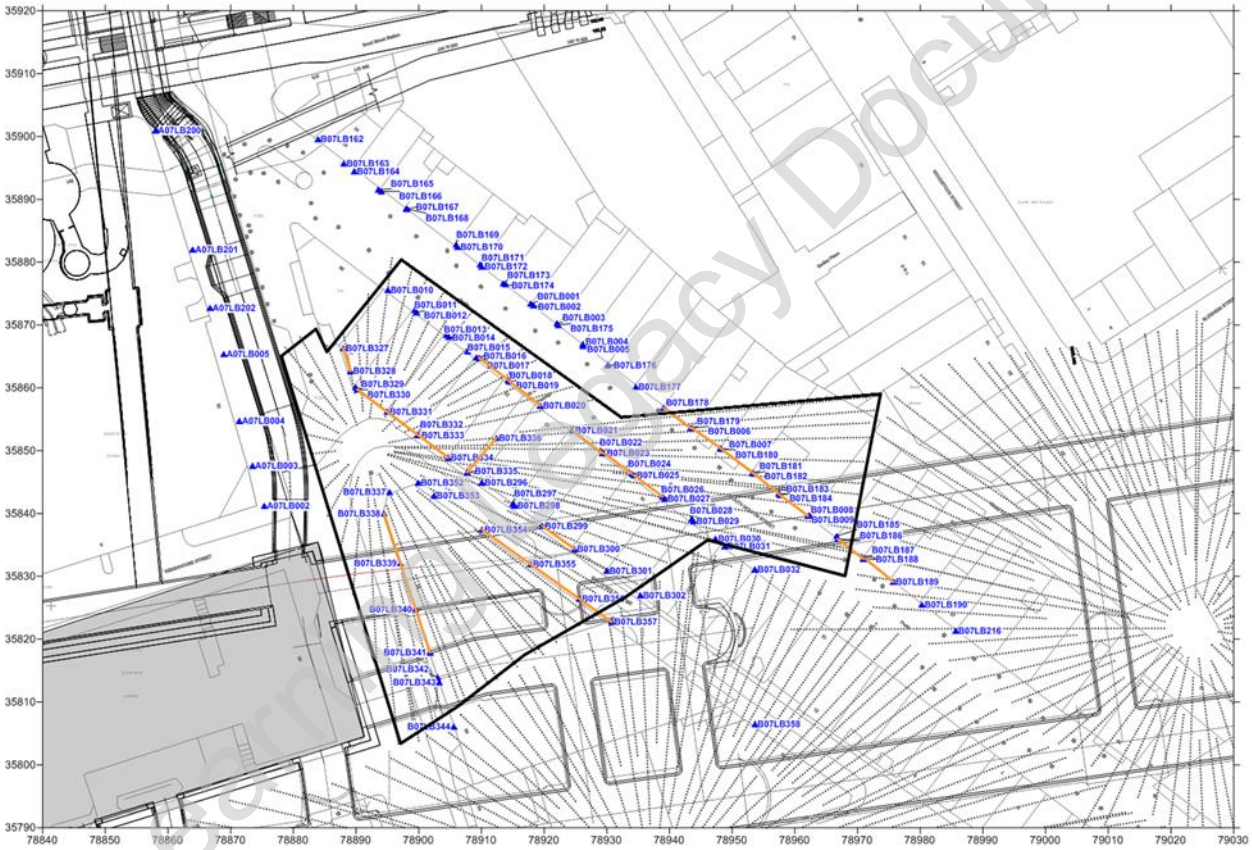


Table 4.1 Details of trigger breaches on BRE

BUILDING FACADES & PARTY WALLS		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Davies Street (NW): NONE					
Davies Street (E)					
B07LB338-B07LB339	Amber	Period F ES1	18/02/2015	1.42	1.42
B07LB339-B07LB340	Amber	marginal	03/06/2015	1.13	0.89
B07LB340-B07LB341	Amber	marginal	30/05/2015	1.19	0.97
South Molton Lane (West)					
B07LB354-B07LB355	Amber	Period G - marginal	10/08/2015	1.02	0.84
B07LB355-B07LB356	Amber	Period F	28/05/2015	1.38	1.38
B07LB356-B07LB357	Amber	Period G - marginal	13/07/2015	1.08	0.81
South Molton Lane (East)					
B07LB327-B07LB328	Amber	Period E PTE	13/08/2014	1.24	0.98
B07LB330-B07LB331	Amber	Period E PTE	20/08/2014	1.14	0.82
B07LB331-B07LB332	Amber	Period E PTE	20/10/2014	1.21	1.19
B07LB333-B07LB334	Amber	Period E PTE	25/08/2014	1.83	1.78
B07LB299-B07LB300	Amber	Period F end - CH2	04/06/2015	1.27	1.20
South Molton Street (West)					
B07LB017-B07LB018	Amber	Transitory Period D	20/01/2014	1.18	0.82
B07LB019-B07LB020	Amber	Period E PTE	16/10/2014	1.16	1.34
B07LB021-B07LB022	Amber	Period E PTE	02/01/2015	1.18	1.11
B07LB023-B07LB024	Amber	Period E PTE	30/10/2014	1.41	1.41
B07LB025-B07LB026	Amber	Period E PTE	15/07/2014	1.84	1.61
South Molton Street (East)					
B07LB178-B07LB179	Amber	Final reading only	17/09/2015	1.09	1.09
B07LB006-B07LB007	Amber	Period E PTE	02/09/2014	1.5	1.38
B07LB180-B07LB181	Amber	Period E PTE	18/09/2014	1.26	1.21
B07LB182-B07LB183	Amber	Period E PTE	13/06/2014	1.91	1.83
B07LB184-B07LB008	Amber	Period E PTE	31/07/2014	1.04	1.00
B07LB186-B07LB187	Amber	Period E PTE	09/07/2014	1.40	1.32[1]
B07LB188-B07LB189	Amber	Period E PTE	09/07/2014	1.51	1.43[1]
South Molton Passage					
B07LB335-B07LB336	Amber	End of Period E	04/02/2015	1.18	1.15

[1] ***Readings relate to 19/08/15, whereas values in GS2 report (C300-BFK-C4-RGN-CRT00_ST005-51179 are from 20/05/15)***

BRE monitoring data from the facades within the footprint of GS4 are presented in the following sections, namely, South Molton Street east and west, South Molton Lane east and west, Davies Street east and west and South Molton Passage.

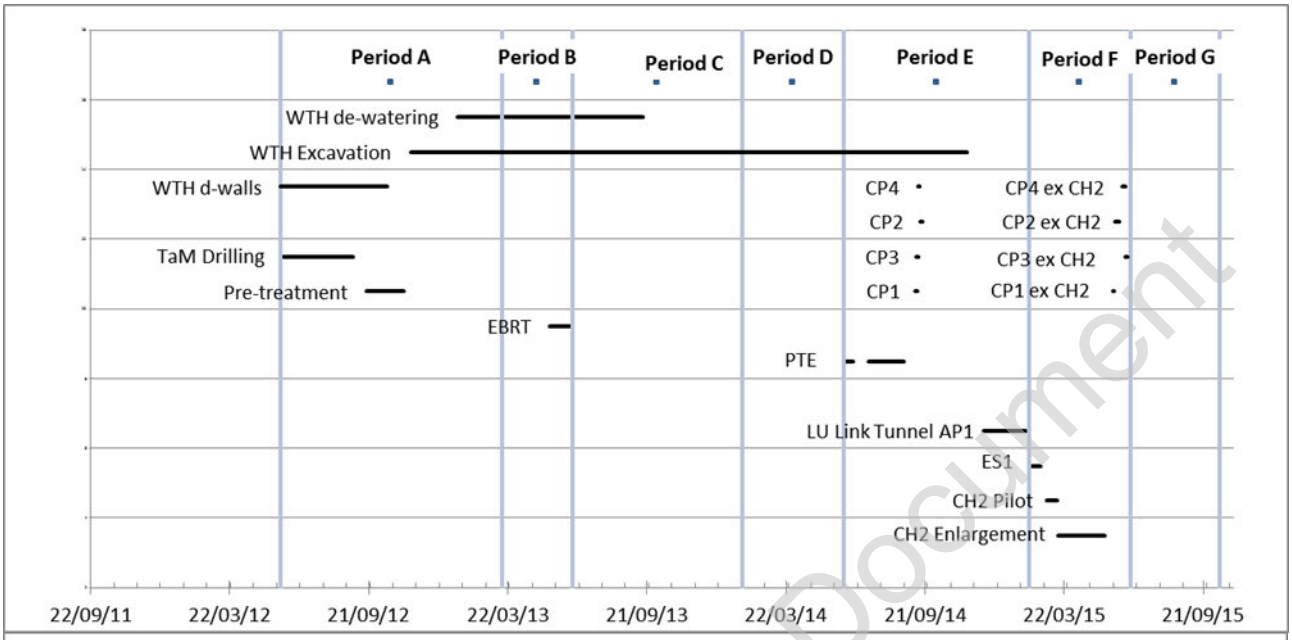
The plots presented, as appropriate, for each façade comprise:

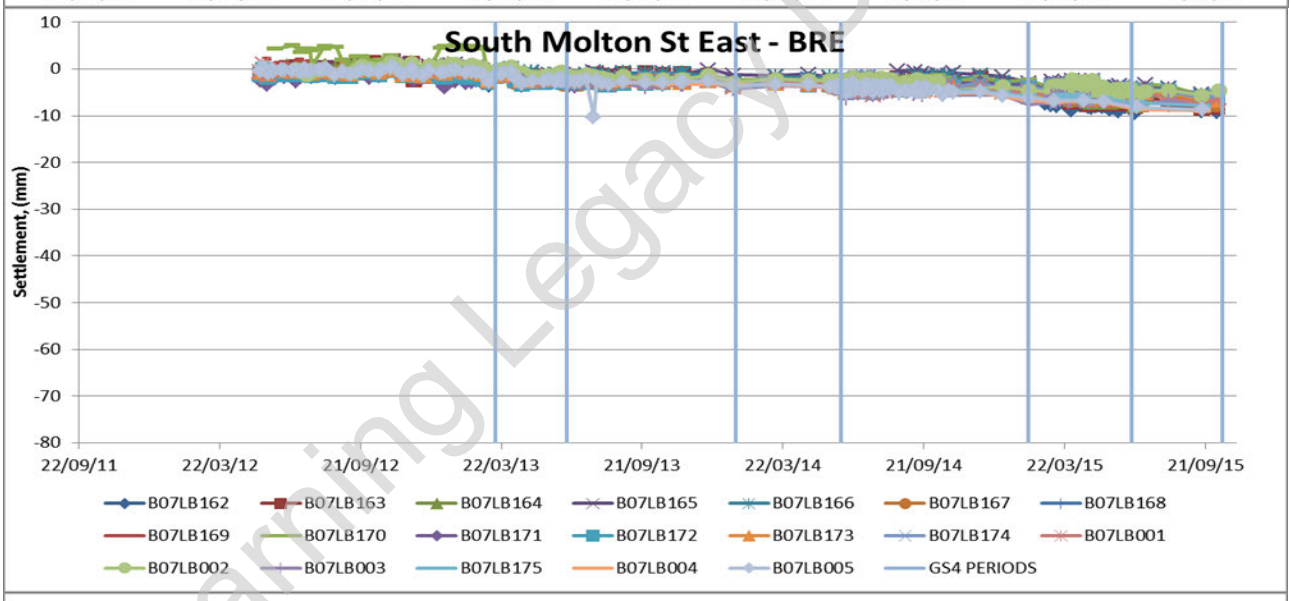
1. Summary of tunnel construction and associated construction periods.
2. Time settlement history.

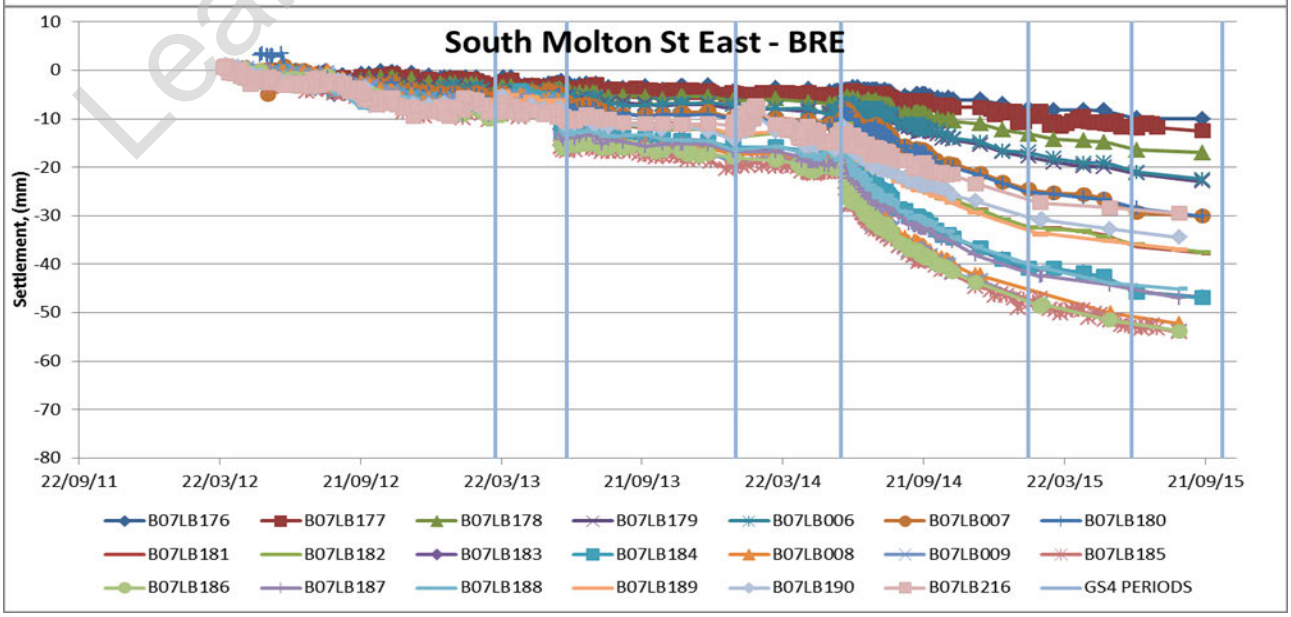
3. Settlement profile plots with a series as close as possible to the date of the end of each construction period.
4. Time slope history over the full construction period with the distances between the points in metres shown in the legend in square brackets.

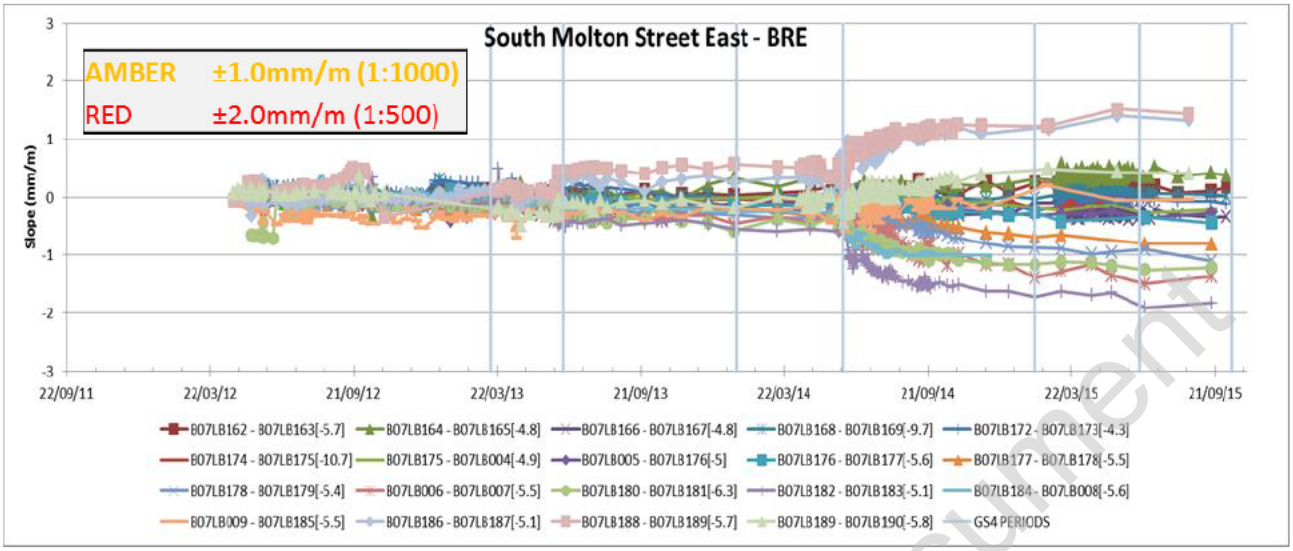
All available data is plotted in these figures.

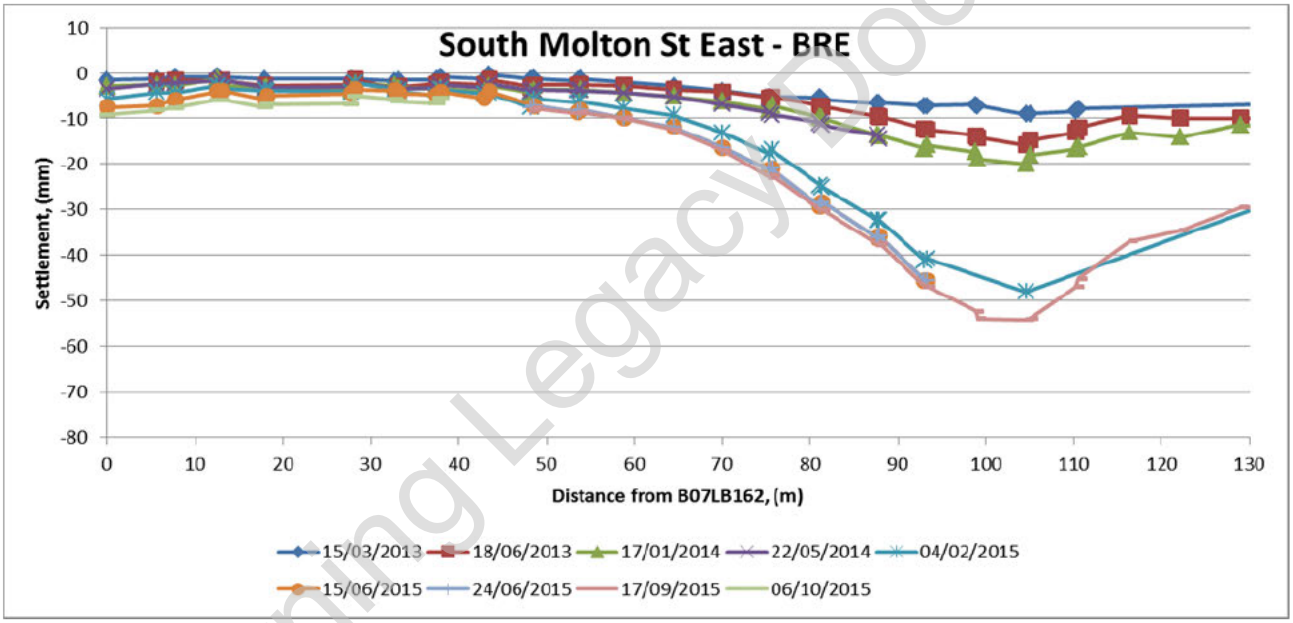
4.2. South Molton Street- East











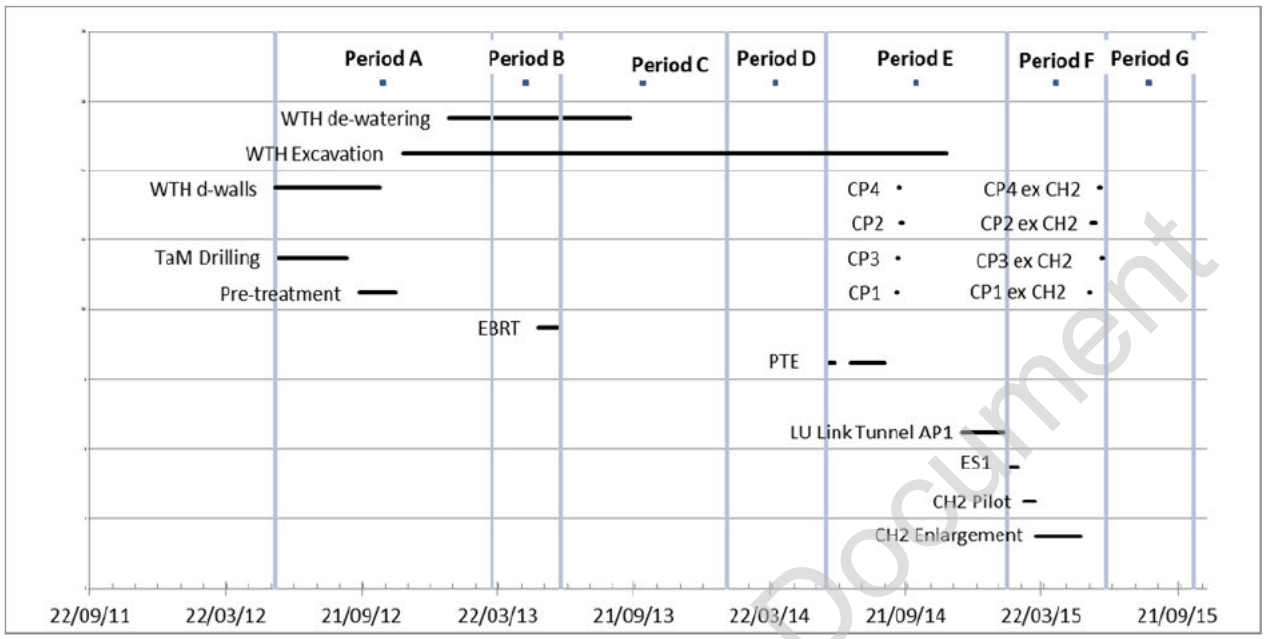
The following points are noted:

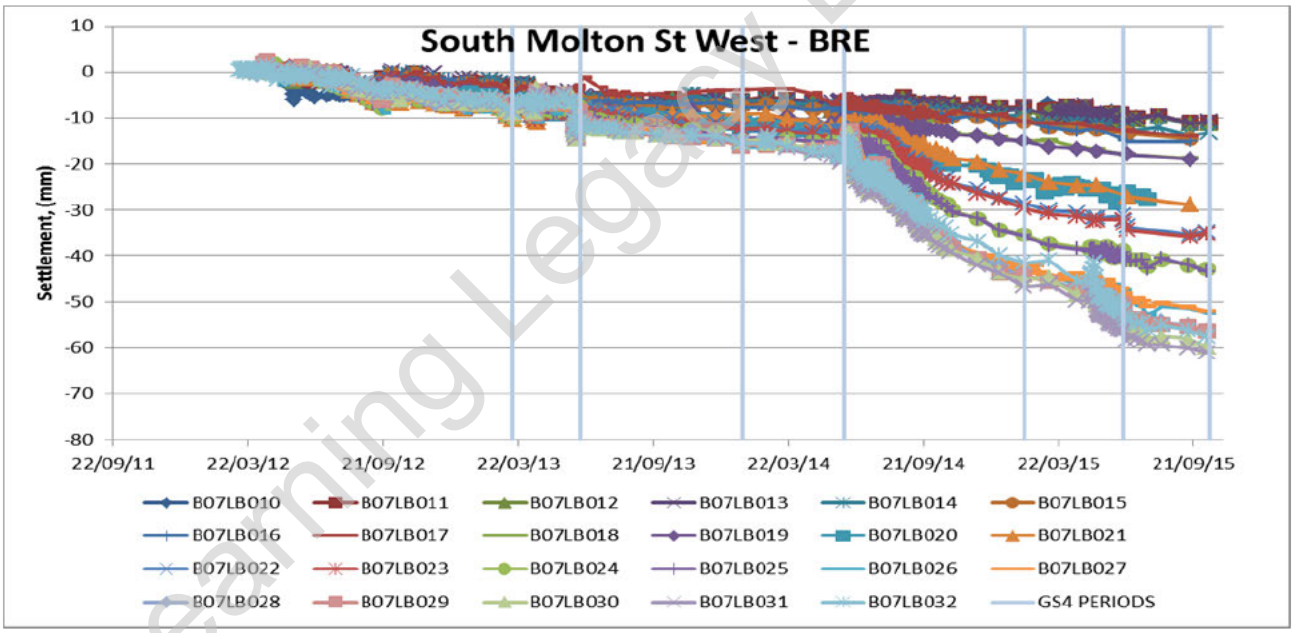
- The northern part of the South Molton Street east façade lies partly within the plan extent of the GS4 array (from distance 70 to 105m): data from all points shown on Figure 4.1.1 are presented.
- The South Molton Street east façade traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable event was however the construction of PTE in Period E (see Section 3.7).
- 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, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of 7mm with a trough extending from distance 70m to 130m.
- In Periods C and D (no tunnelling or grouting) there was little change: time-related movement resulted in a small increase in settlement to 21mm by the end of Period D.
- The construction of the PTE in Period E 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 nearly 30mm,

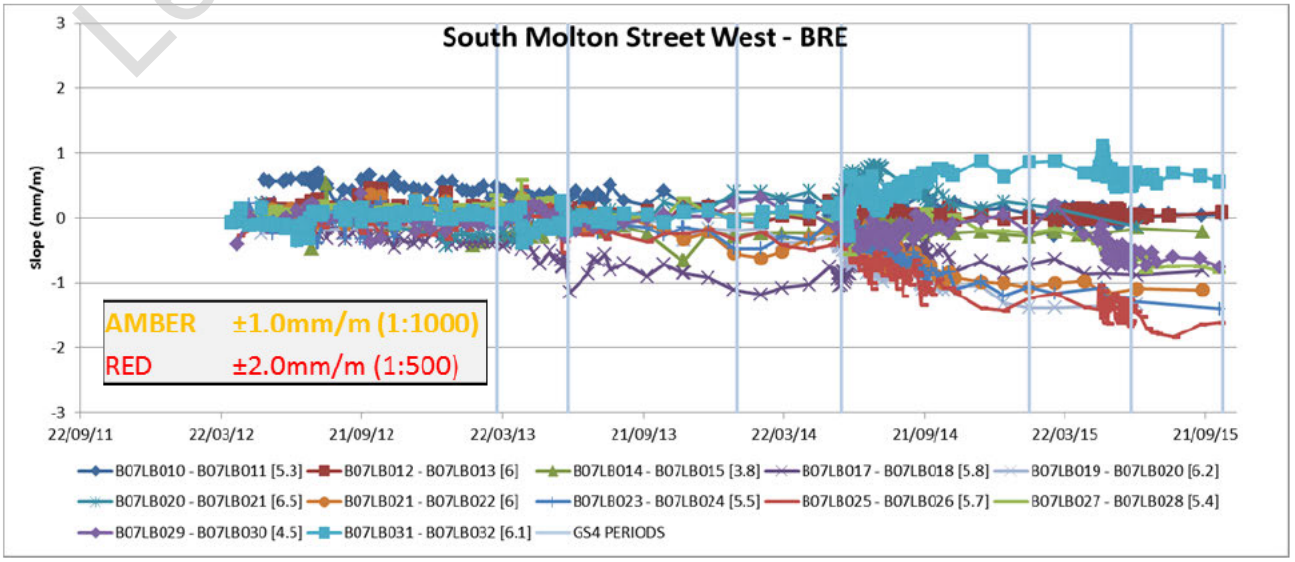
producing a total settlement of almost 50mm. 6 Amber triggers were generated either during or following tunnelling, as detailed in Table 4.1.

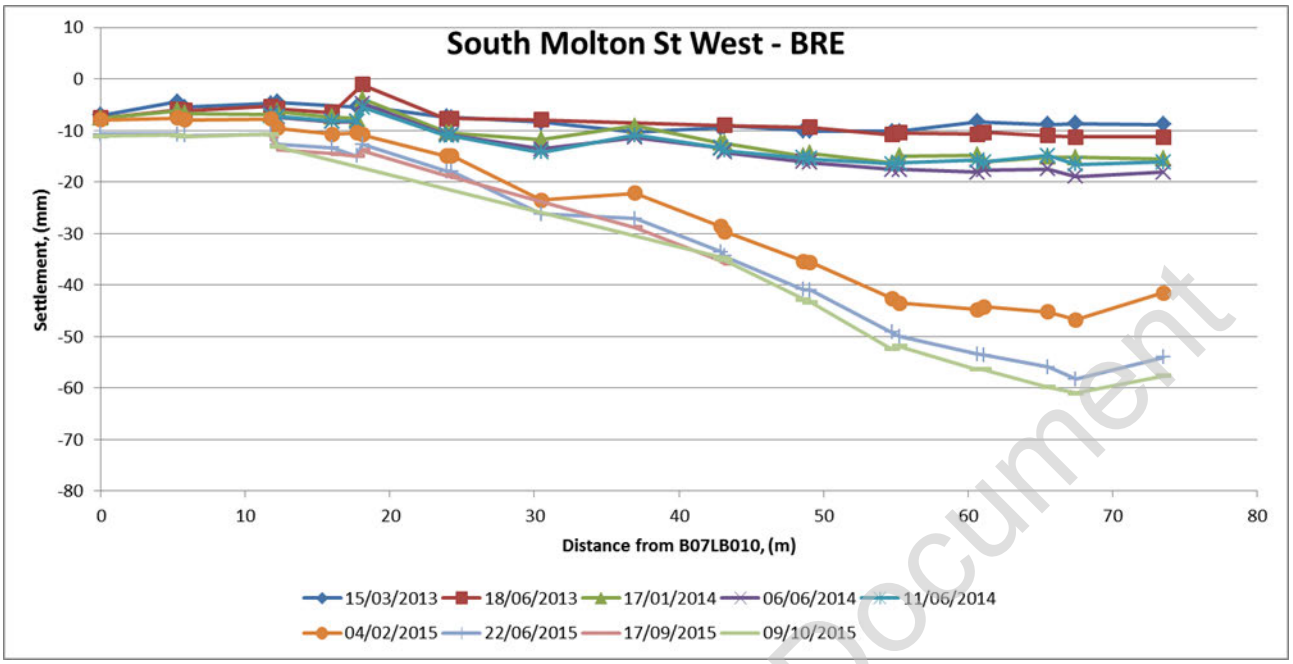
- Consolidation continued at a decreasing rate through Periods F and G, resulting in total settlement of ~55mm. As expected the movements became relatively uniform and hence the impact on slopes became minor, albeit one further Amber trigger was recorded on the final reading, as detailed in Table 4.1.
- By inspection, there were no Deflection Ratio trigger breaches.

4.3. South Molton Street - West





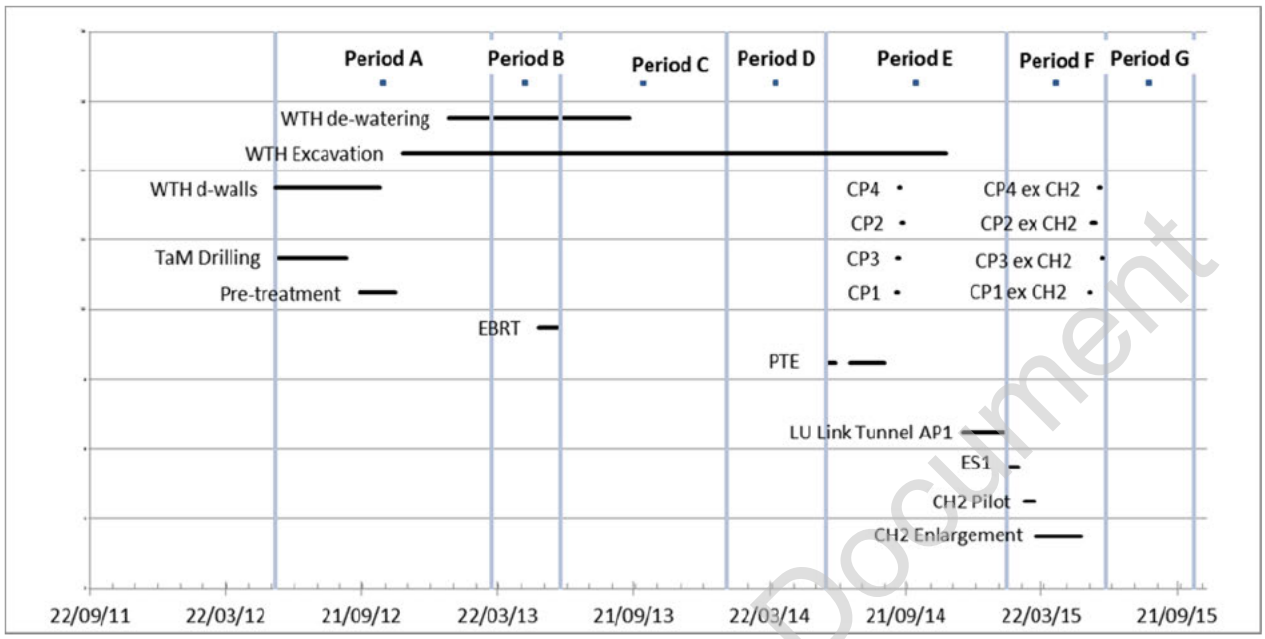


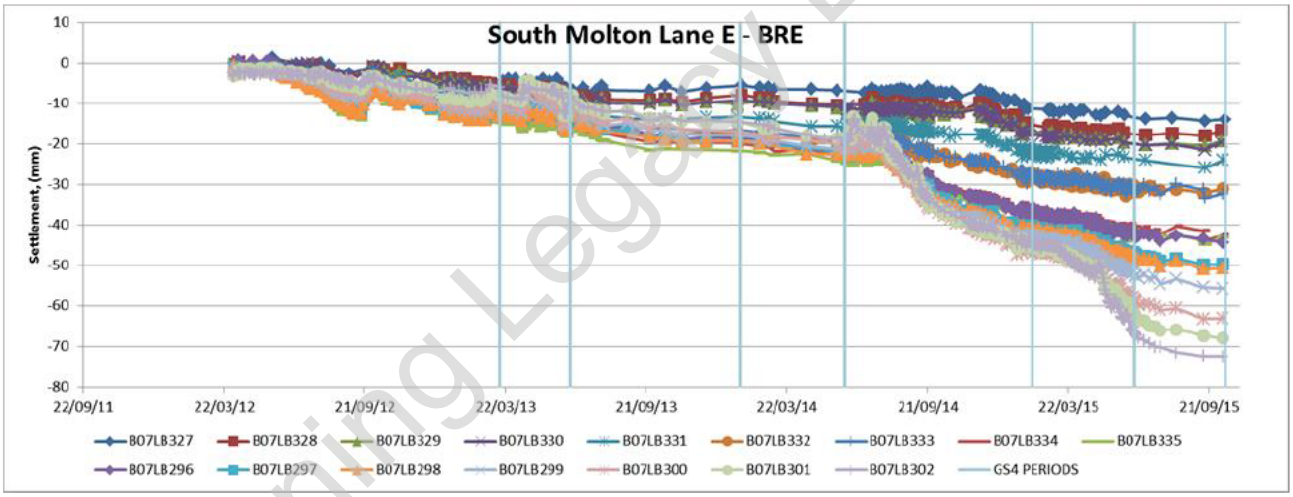


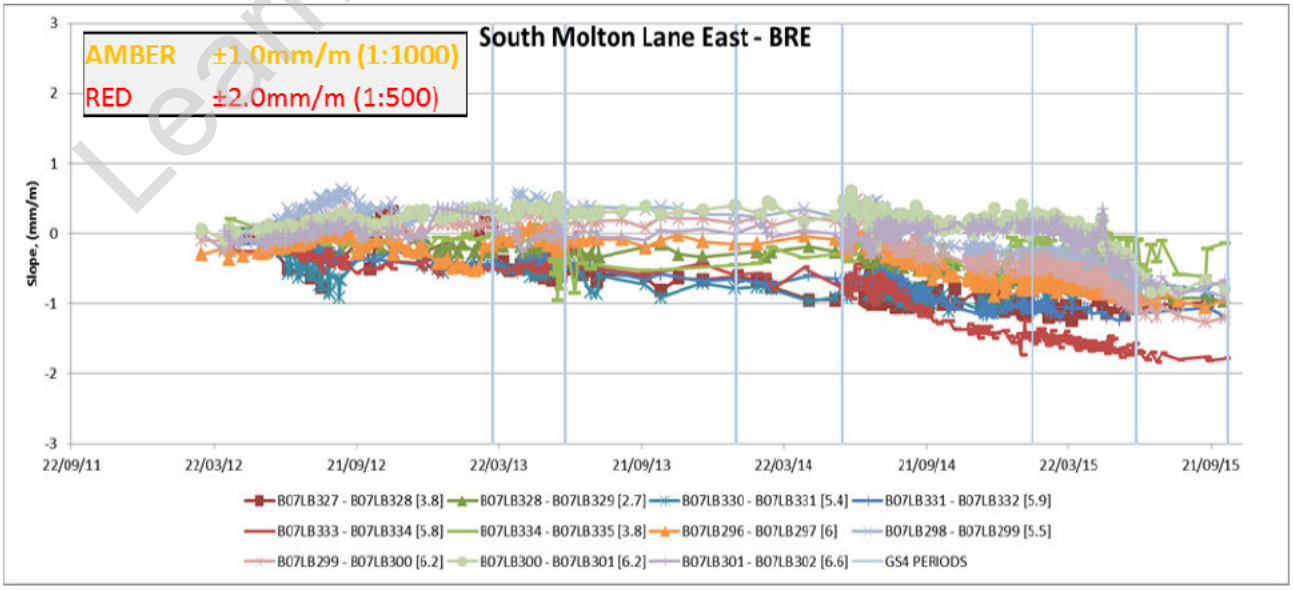
The following points are noted:

- The northern part of the South Molton Street west façade lies partly within the plan extent of the GS4 array (from distance 0 to 70m): data from all points shown on Figure 4.1.1 are presented. It is noted that 28 South Molton Street had recently been redeveloped with a piled building: the original extent of the compensation grouting zone was curtailed by CRL.
- 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 PTE in Period E (see Section 3.7).
- 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, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of less than 5mm.
- In Periods C and D (no tunnelling or grouting) there was little change: time-related movement resulted in a small increase in settlement to 18mm by the end of Period D. Nevertheless, one Amber trigger was recorded although this was transitory and had reduced below the trigger level by the end of the Period.
- The construction of the PTE in Period E 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 nearly 30mm, producing a total settlement of almost 50mm. 4 Amber triggers were generated either during or following tunnelling, as detailed in Table 4.1.
- In Period F, construction of CH2 with concurrent grouting and the completion of the cross passage connection produced a further 10mm increase in maximum settlement to ~60mm.
- A reduced rate of long term settlement is shown in Period G, resulting in total settlement of exceeding 60mm. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection, there were no Deflection Ratio trigger breaches.

4.4. South Molton Lane - East



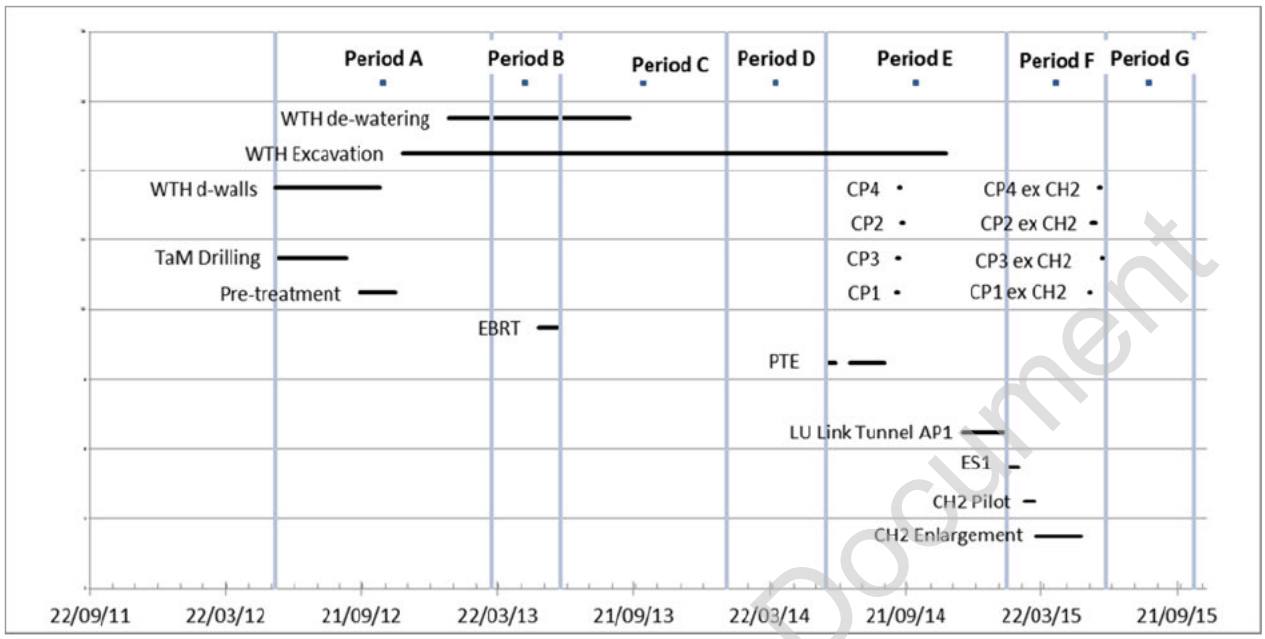


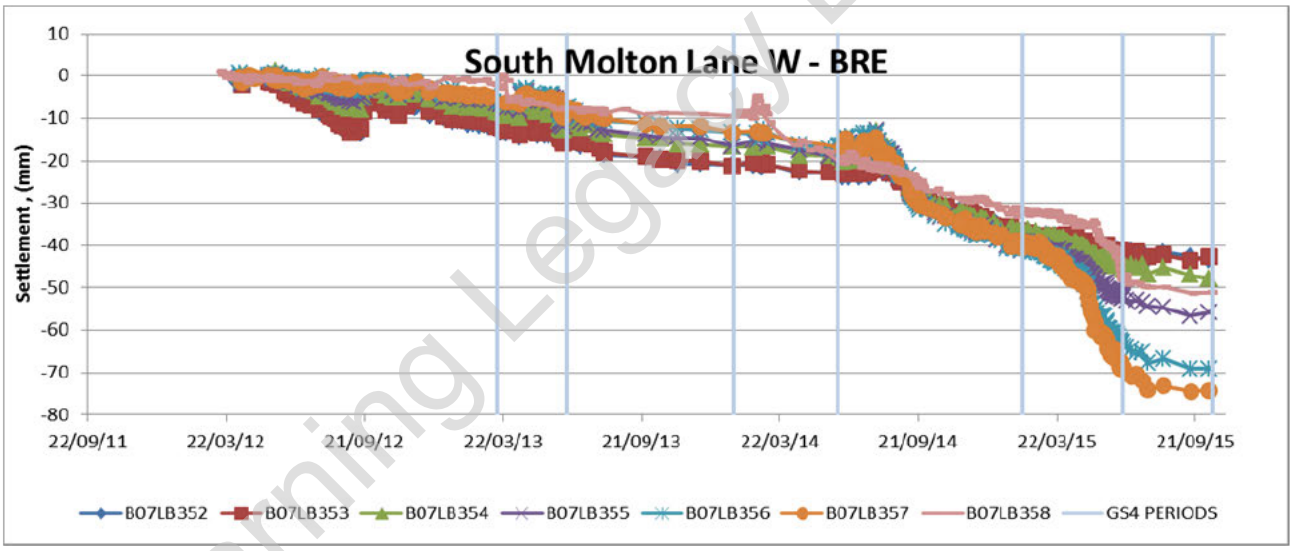


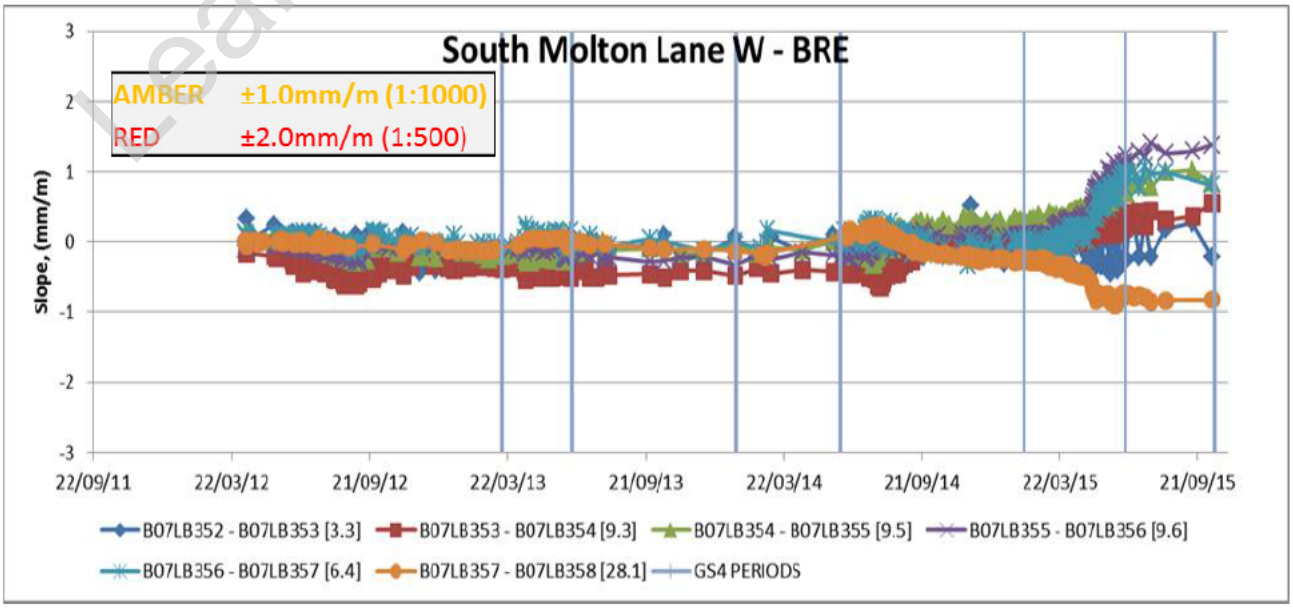
The following points are noted:

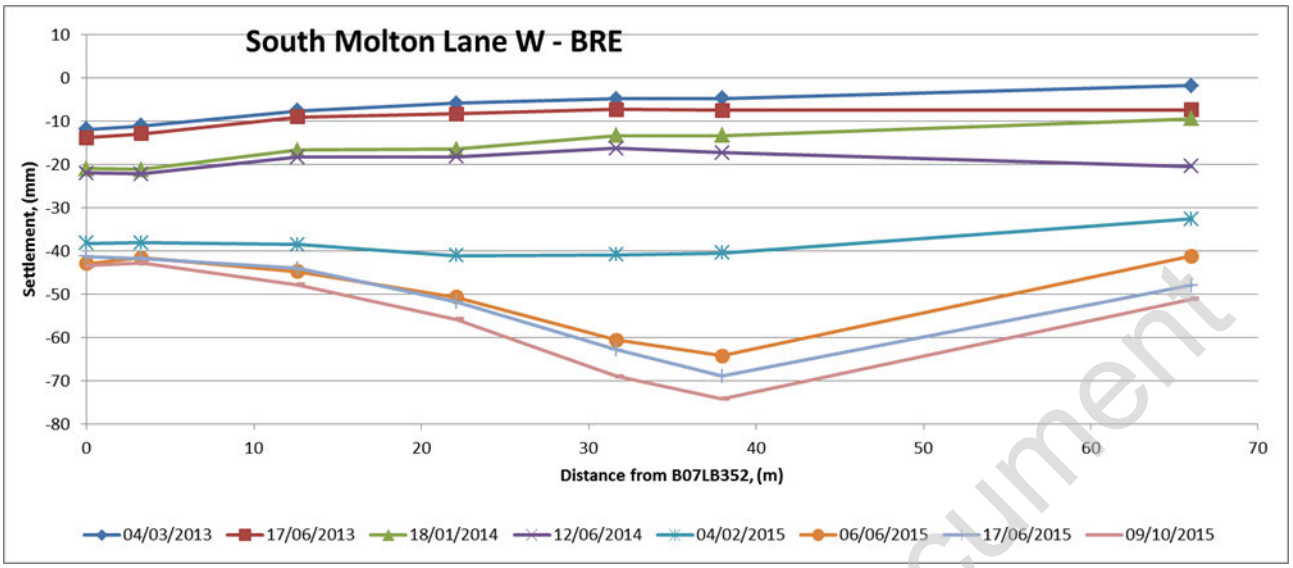
- The northern part of the South Molton Lane east façade is within the GS4 array (up to distance 60m): data from all points shown on Figure 4.1.1 are presented.
- The South Molton Lane east façade is the rear of the buildings on South Molton Street West which are approximately 15m apart: consequently the behaviour was similar to that described in Section 4.3. The exception to this is that there was 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 PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~15mm but there was only minor variation over the full length of the façade.
- In Period B, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of less than 5mm.
- In Periods C and D there was little change: time-related movement resulted in a small increase in total settlement to ~22mm by the end of the Period D.
- The construction of the PTE in Period E 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 45mm. 4 Amber triggers breaches were generated either during or following tunnelling as detailed in Table 4.1.
- 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 further Amber trigger was generated at the end of the period by movements following completion of CH2. Also two of the earlier Amber triggers reduced to below the limiting value.
- Post construction, in Period G, settlement has continued to increase but at a decreasing rate. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection of the settlement profiles, there were no Deflection Ratio trigger breaches.

4.5. South Molton Lane - West





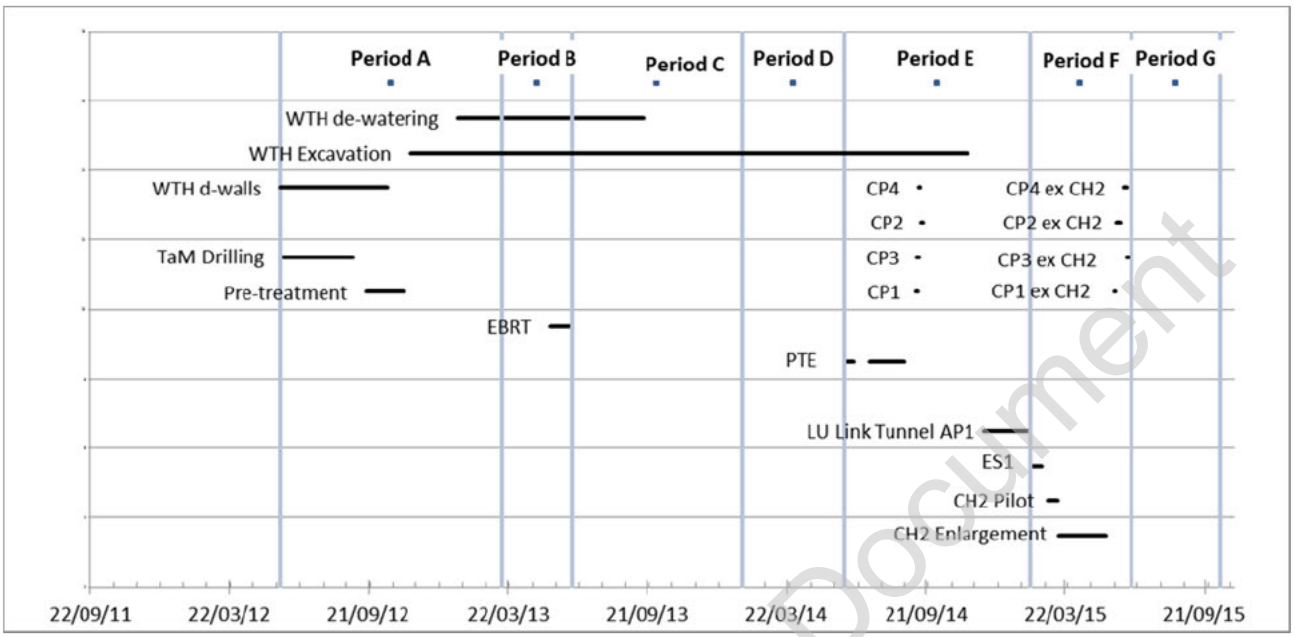


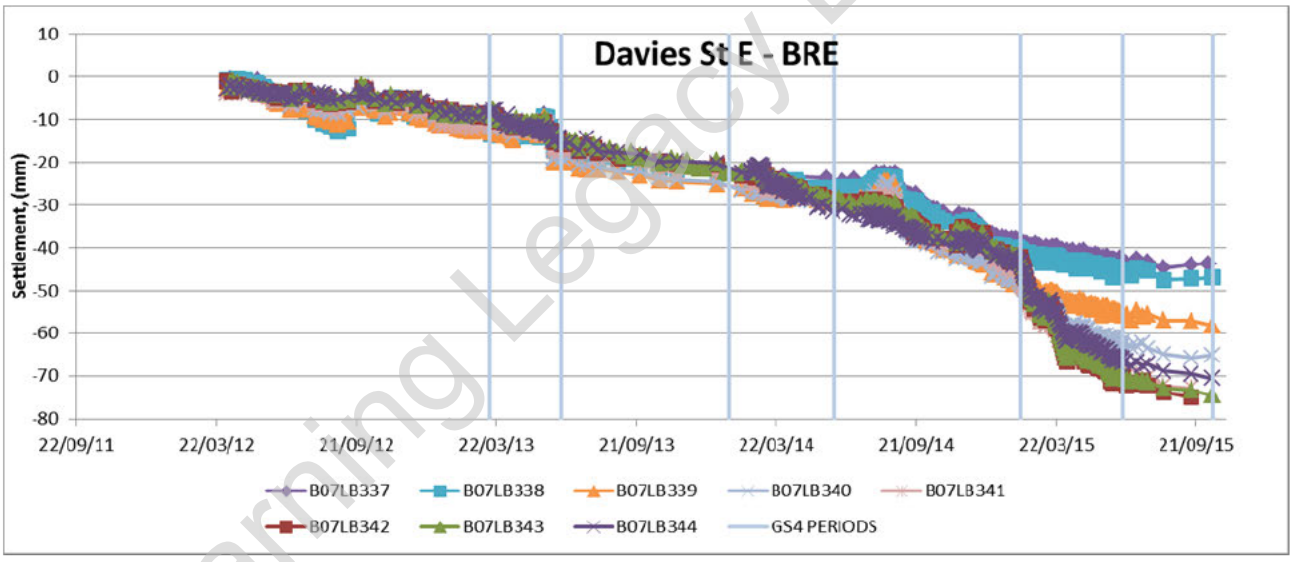


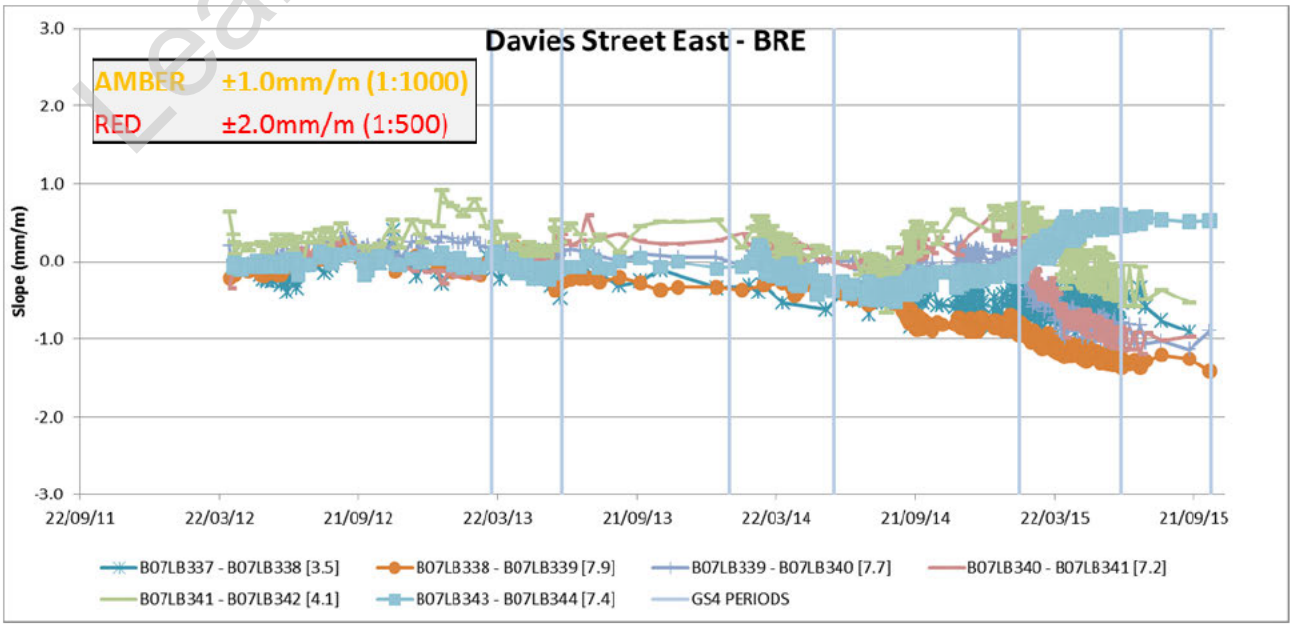
The following points are noted:

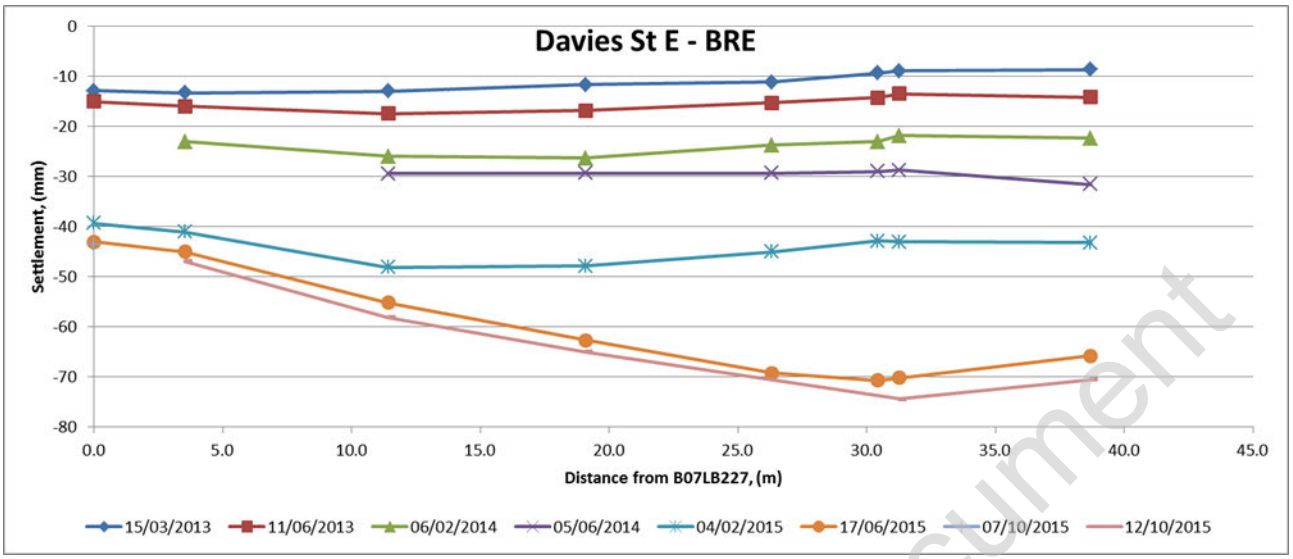
- The northern part of the South Molton Lane west façade is within the GS4 array (up to distance 35m): data from all points shown on Figure 4.1.1 are presented.
- The South Molton Lane west façade is parallel to the east façade and separated by only about 6m: consequently the behaviour is similar to that described in Section 4.4.
- 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 PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was more than 10mm but there was only minor variation over the full length of the façade.
- In Period B, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of less than 5mm.
- In Periods C and D there was little change: time-related movement resulted in a small increase in total settlement to ~22mm by the end of the Period D.
- The construction of the PTE in Period E 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 41mm.
- 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 Amber trigger (B07LB355-B07LB356) was generated due to post construction movements some time after the tunnelling. The adjacent slopes also had occasional readings in excess of 1mm/m during Period G, but the final readings on both were below the trigger value. Details are given in Table 4.1.
- Post construction, in Period G, settlement has continued to increase, but at a decreasing rate. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection of the settlement profile, there were no Deflection Ratio trigger breaches.

4.6. Davies Street - East





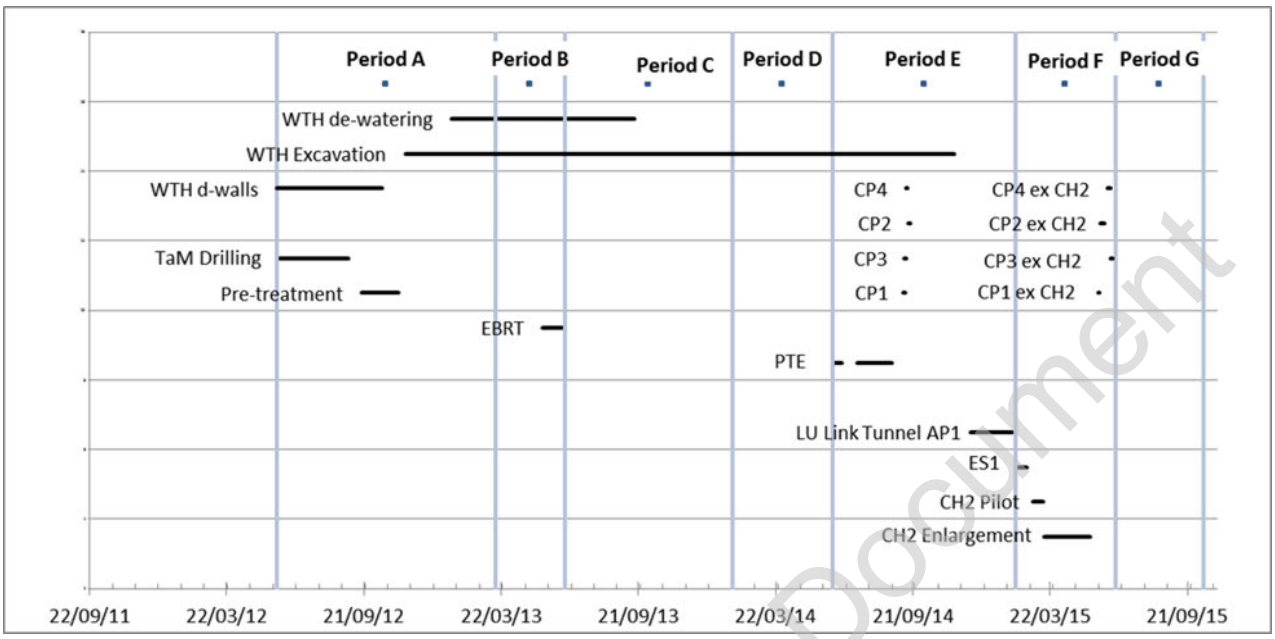


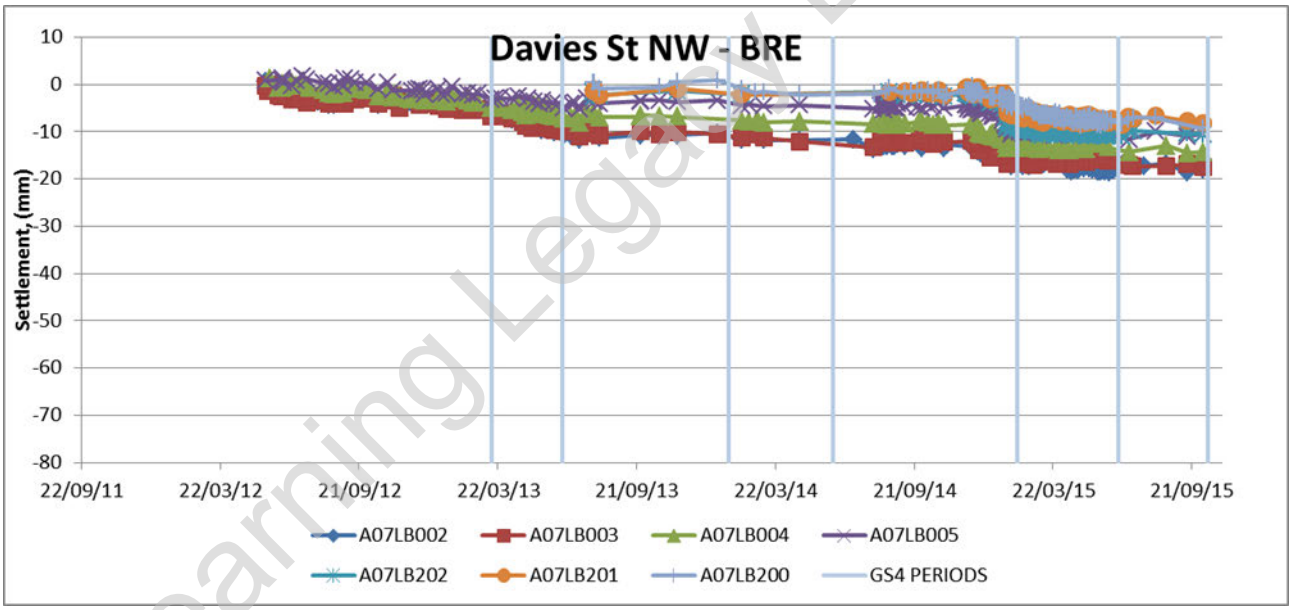


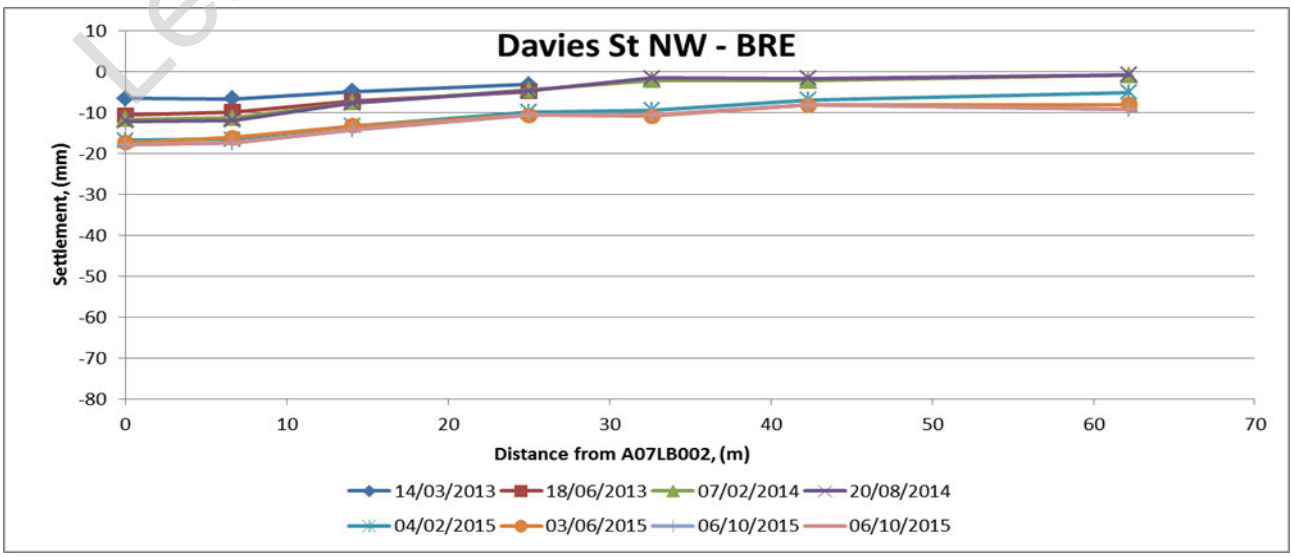
The following points are noted:

- The northern part of the Davies Street east façade is within the GS4 array: data from all points shown on Figure 4.1.1 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 PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was greater than 10mm but there was only minor variation over the full length of the façade.
- In Period B, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of 6mm producing a maximum total settlement of ~20mm.
- In Periods C and D there was little change: time-related movement resulted in a small increase in total settlement except at the southern end of the transect where the construction of PTW in February 2014 had a small influence. By the end of the Period D, the maximum total settlement was over 30mm.
- The construction of the PTE in Period E had a major effect, not just during construction where settlement increased by <10mm, but also by significant consolidation settlement which increased the total settlement within the Period to about 20mm, producing a total settlement of 48mm..
- 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 PTE to the southern end of the transect adjacent to CH2. Associated with this change, three Amber trigger levels were exceeded (two of which were marginal). Details are given in Table 4.1
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection of the settlement profile, there were no Deflection Ratio trigger breaches.

4.7. Davies Street - West



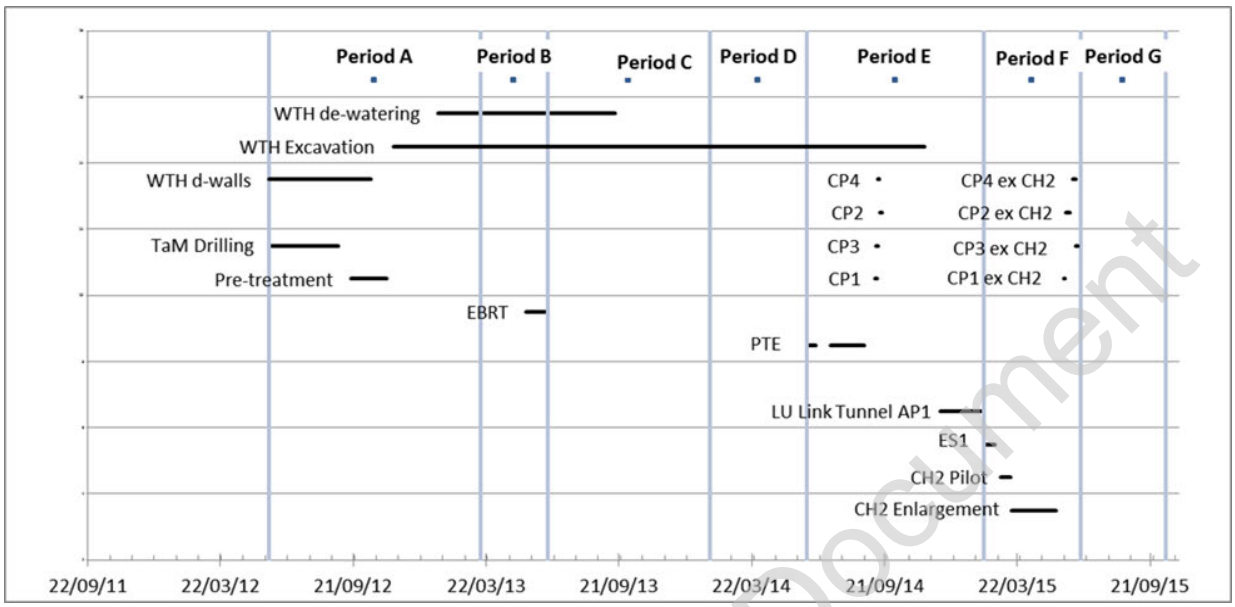


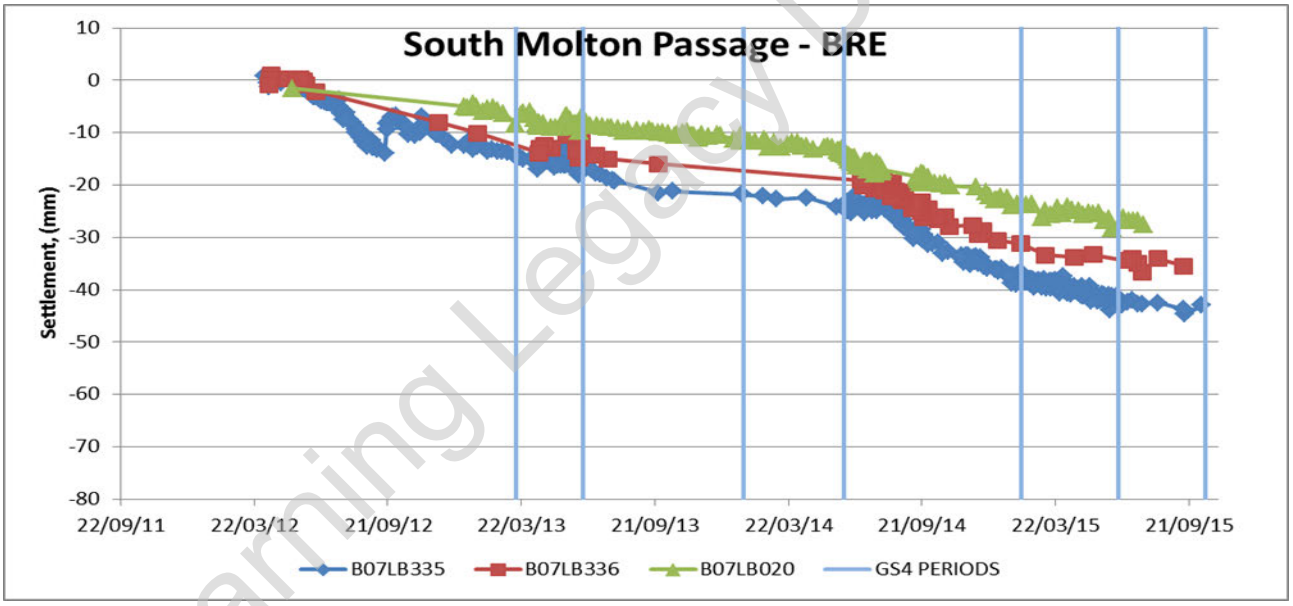


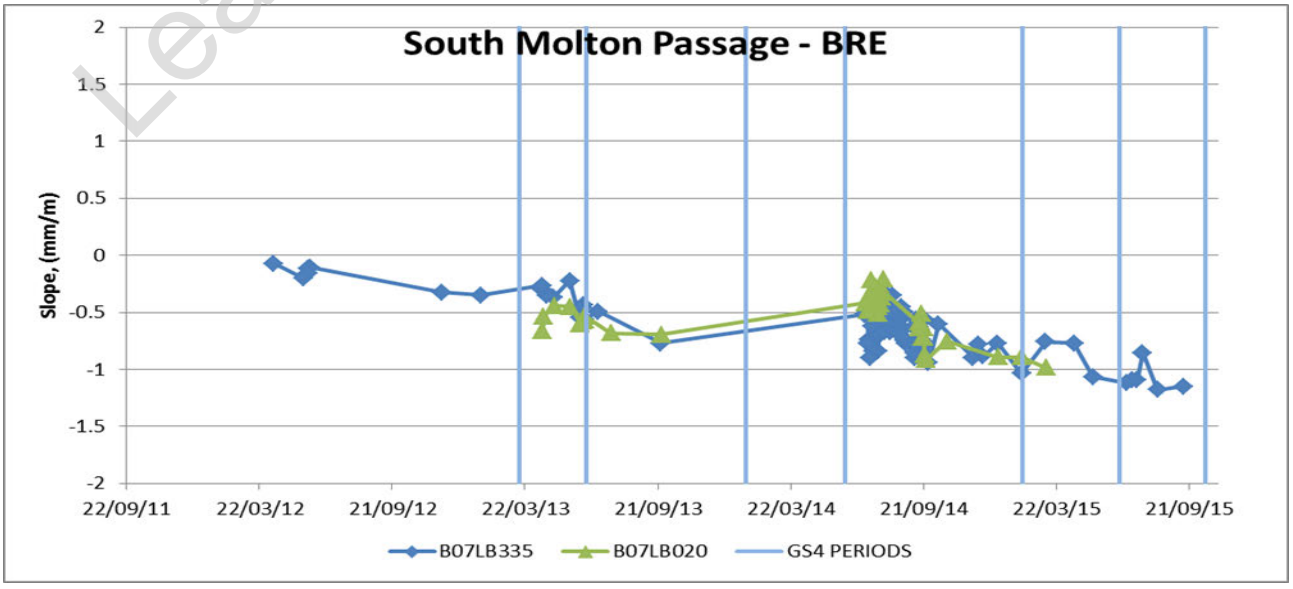
The following points are noted:

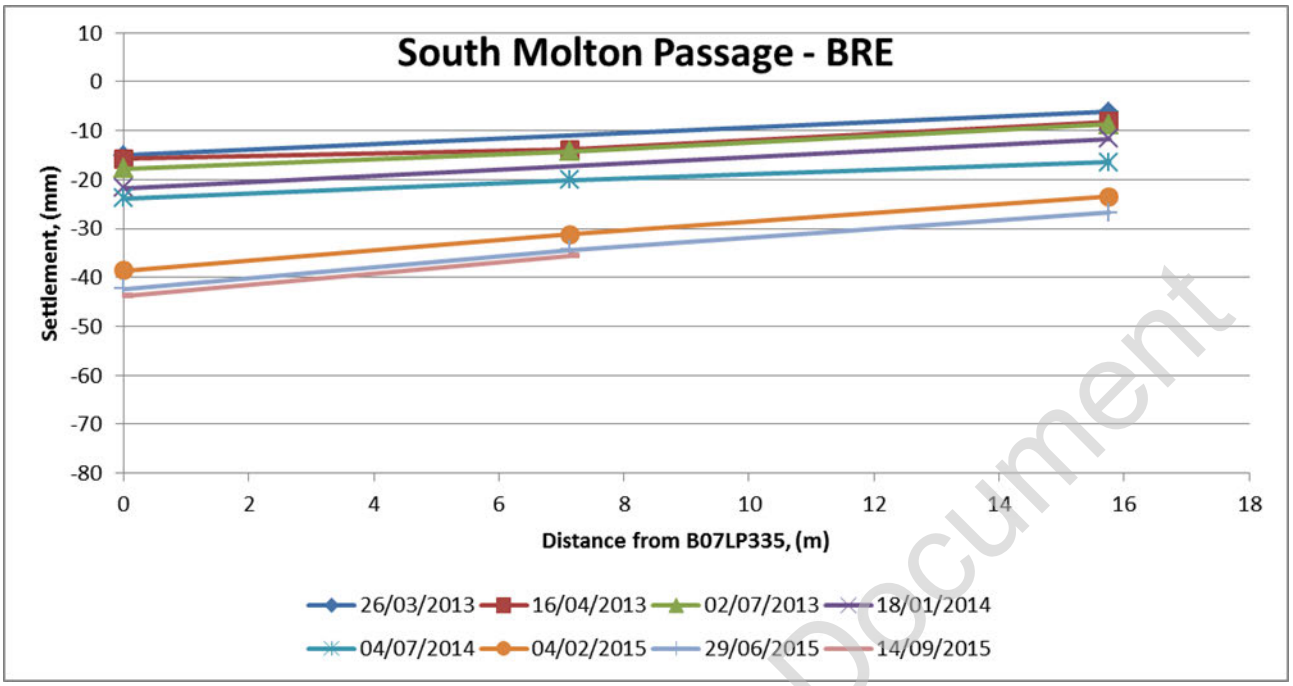
- The west façade of Davies Street to the north of Weighhouse Street is a piled structure (West One). The full extent of the façade is just outwith the GS4 array.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~7mm and there was only minor variation over the full length of the façade.
- In Period B, the EBRT generated a further 3mm settlement. Maximum settlement was about 10mm at the end of Period B.
- In Periods C and D there was little change: time-related movement resulted in a small increase in total settlement to ~12mm by the end of the Period D.
- The construction of the PTE in Period E had no significant effect. However AP1, which runs parallel to the façade, increased the total settlement to about 18mm.
- In Periods F and G there was little or no change in settlement.
- By inspection of the time and profile plots, there are no slope trigger breaches.

4.8. South Molton Passage









The following points are noted:

- South Molton Passage gives access to South Molton Lane through a building on the west side of South Molton Street.
- The most significant event was the construction of PTE in Period E.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~15mm but there was only minor variation over the full length of the façade.
- In Period B, movements from the EBRT were reduced by uplift generated by grout jacking producing a net increase in settlement of less than 5mm.
- In Periods C and D there was little change: time-related movement resulted in a small increase in total settlement to ~23mm by the end of the Period D.
- The construction of the PTE in Period E had a major effect, not just during construction where settlement was controlled to <5mm 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 about 40mm. An Amber trigger breach was generated following tunnelling as detailed in Table 4.1.
- Post construction, in Periods F and G, settlement has continued to increase but at a decreasing rate. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection of the settlement profiles, there were no Deflection Ratio trigger breaches

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5. GROUND SETTLEMENT AND SLOPES

5.1. Slope Triggers

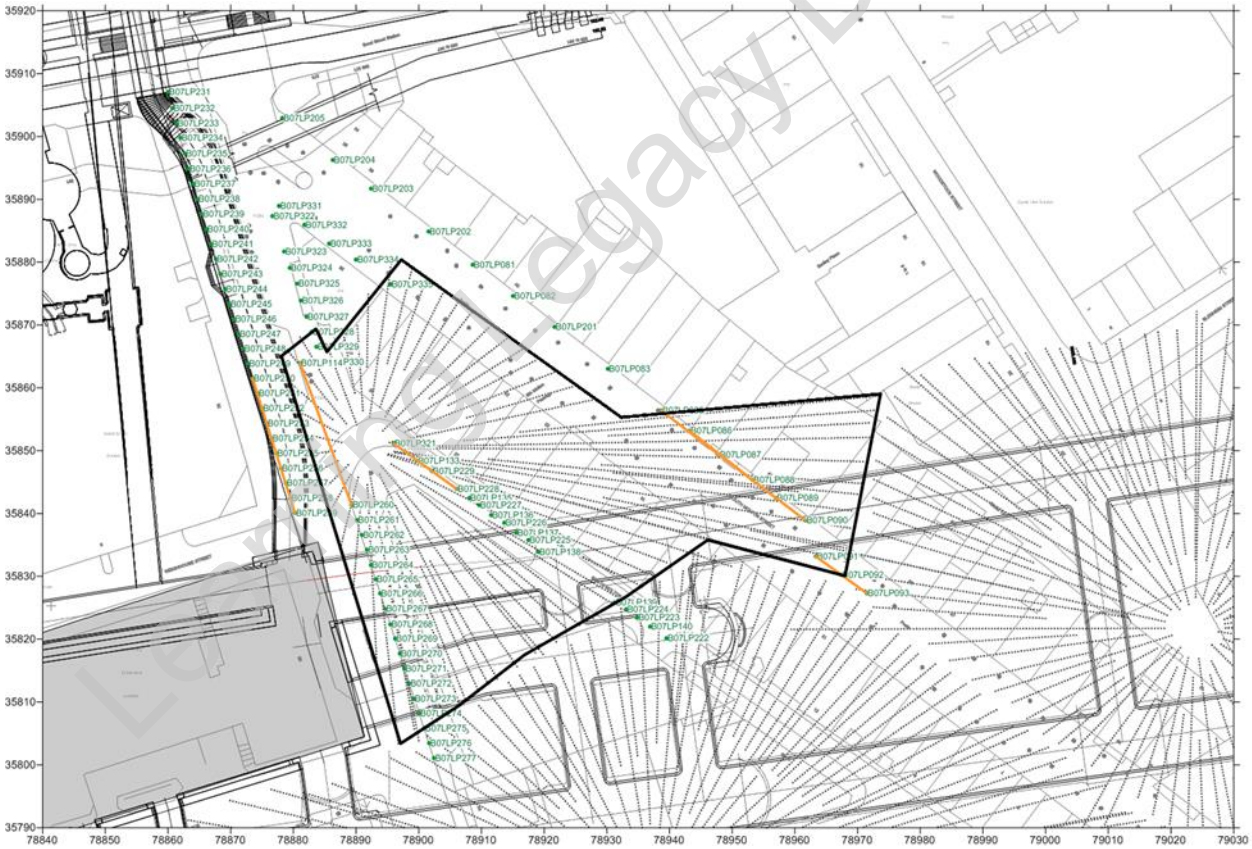
The locations where slope triggers have been exceeded are shown for PLP monitoring of ground level on Figure 5.1.1. A larger version of Figure 5.1.1 is included in Appendix C. Details are given in Table 5.1.

Slope triggers are as follows:

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

Comparison of Figures 4.1.1 and 5.1.1 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.



PLP monitoring data from the kerb lines within the footprint of GS4 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. Time slope history since the completion of tunnelling i.e. construction Period G.

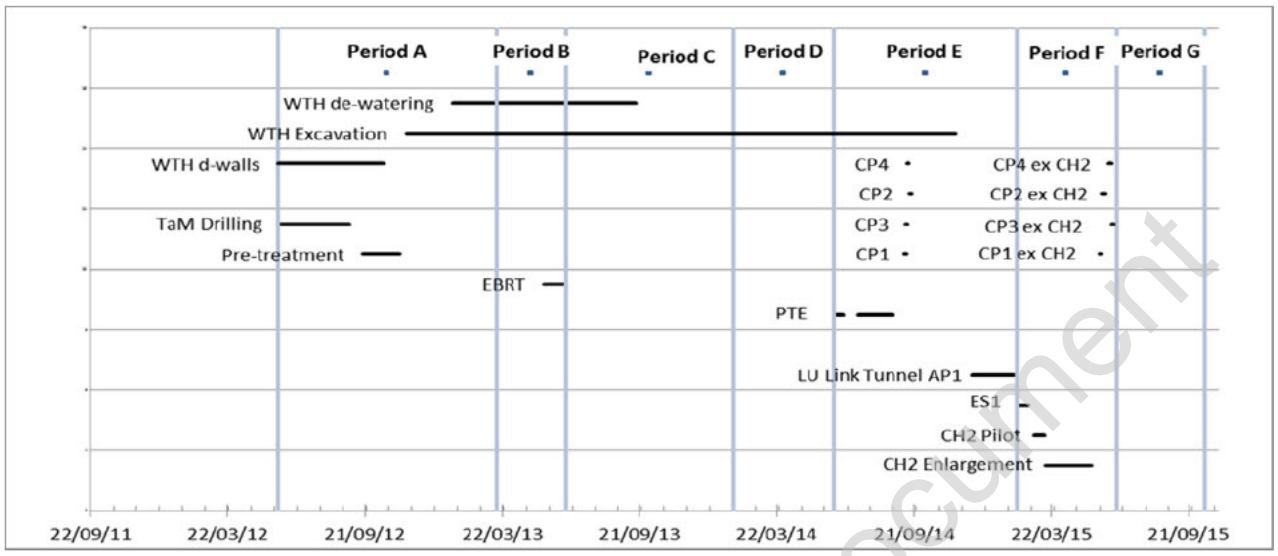
6. Deflection ratio plots are provided as necessary.

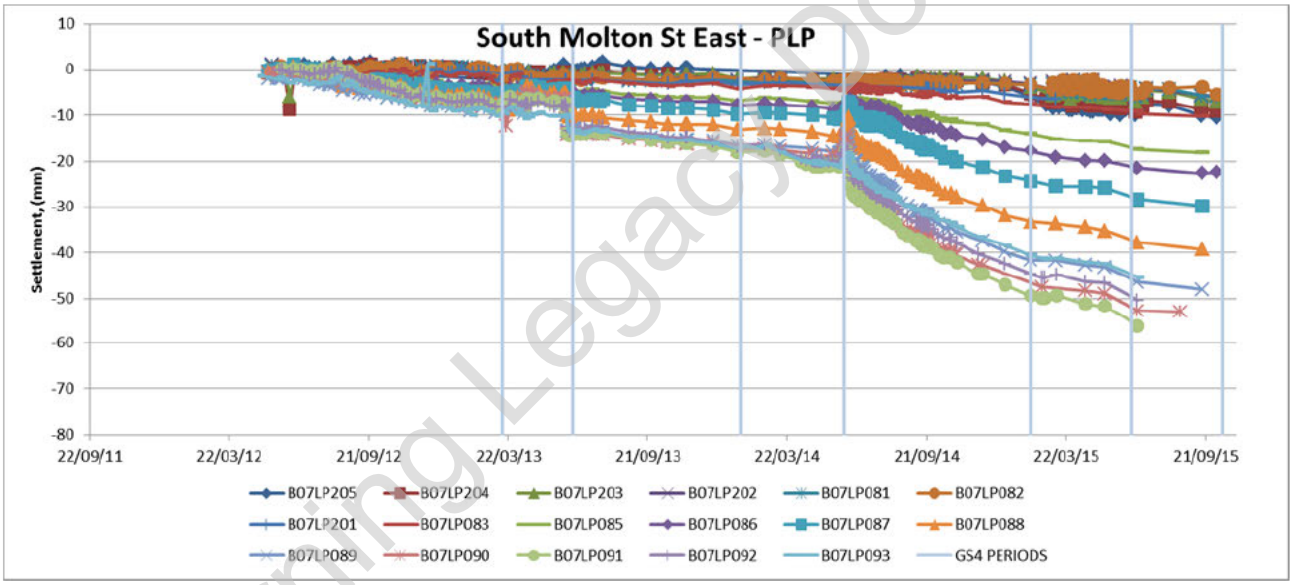
All available data is plotted in these figures.

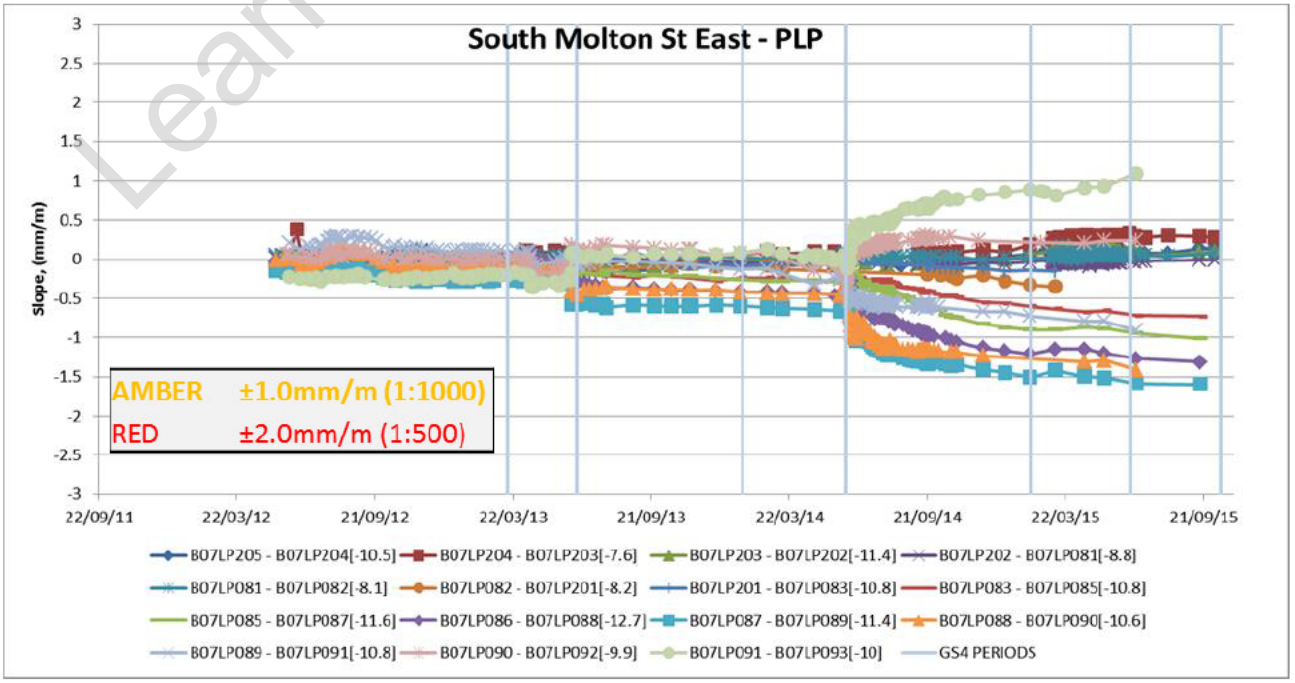
Table 5.1 Details of trigger breaches on PLP

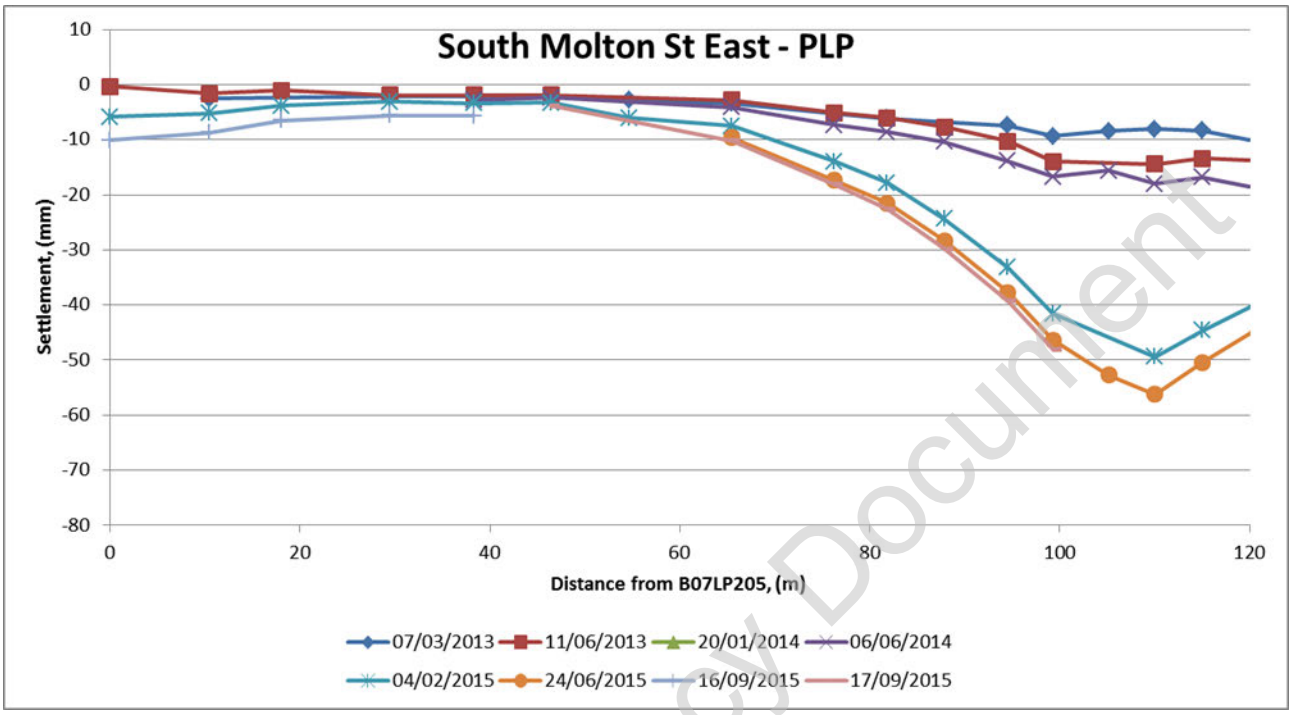
GROUND POINTS		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Davies Street (NW):					
B07LP259-B07LP255	Amber	Period E AP1 transitory (to 14/12/14)	08/12/2014	1.49	0.70
B07LP258-B07LP254	Amber	Period E AP1 transitory (to 15/01/15)	08/12/2014	1.43	0.98
B07LP257-B07LP253	Amber	Period E AP1 transitory (14/01/15)	13/12/2014	1.17	1.00
B07LP256-B07LP252	Amber	Period E AP1 transitory (to 14/01/15)	14/12/2014	1.12	0.95
B07LP255-B07LP251	Amber	Period E AP1 transitory (to 14/01/15)	14/12/2014	1.03	0.70
B07LP254-B07LP250	Amber	Period E AP1 transitory (to 16/01/15)	14/12/2014	1.2	0.98
Davies Street (E)					
B07LP114-B07LP260	Amber	Period E PTE	16/11/2014	1.28	1.10
South Molton Lane					
B07LP321-B07LP228	Amber	Period F ES1 / CH2	11/05/2015	1.11	0.95
South Molton Street					
B07LP085 - B07LP087	Amber	Period G - final reading only	17/09/2015	1.01	1.01
B07LP086 - B07LP088	Amber	Period E PTE	16/10/2014	1.31	1.31
B07LP087 - B07LP089	Amber	Period E PTE	19/06/2014	1.60	1.59
B07LP088 - B07LP090	Amber	Period E PTE	19/06/2014	1.41	1.41
B07LP091 - B07LP093	Amber	Period G - final reading only	24/06/2015	1.09	1.09
South Molton Street West (NONE)					

5.2. South Molton Street – East





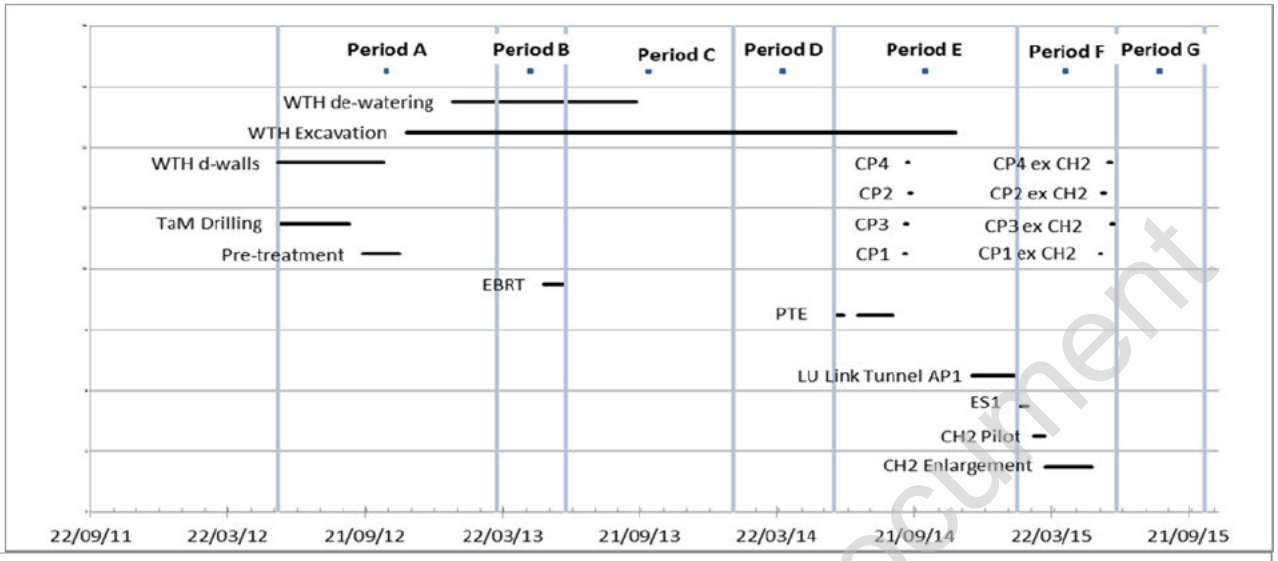


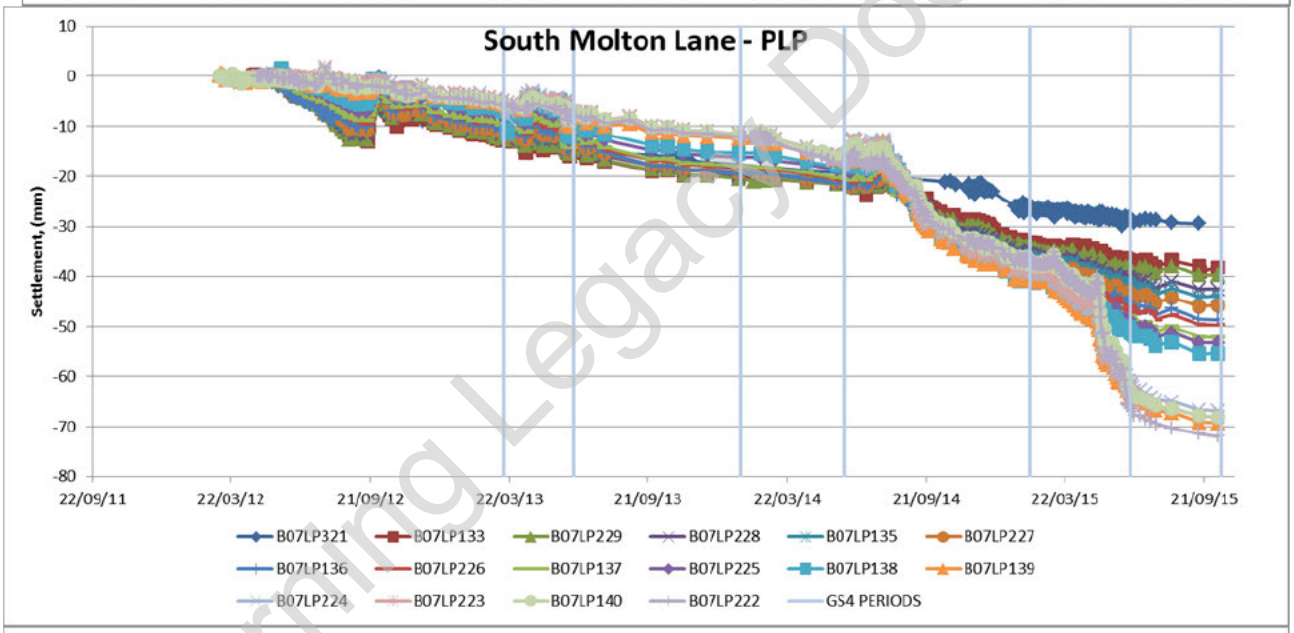


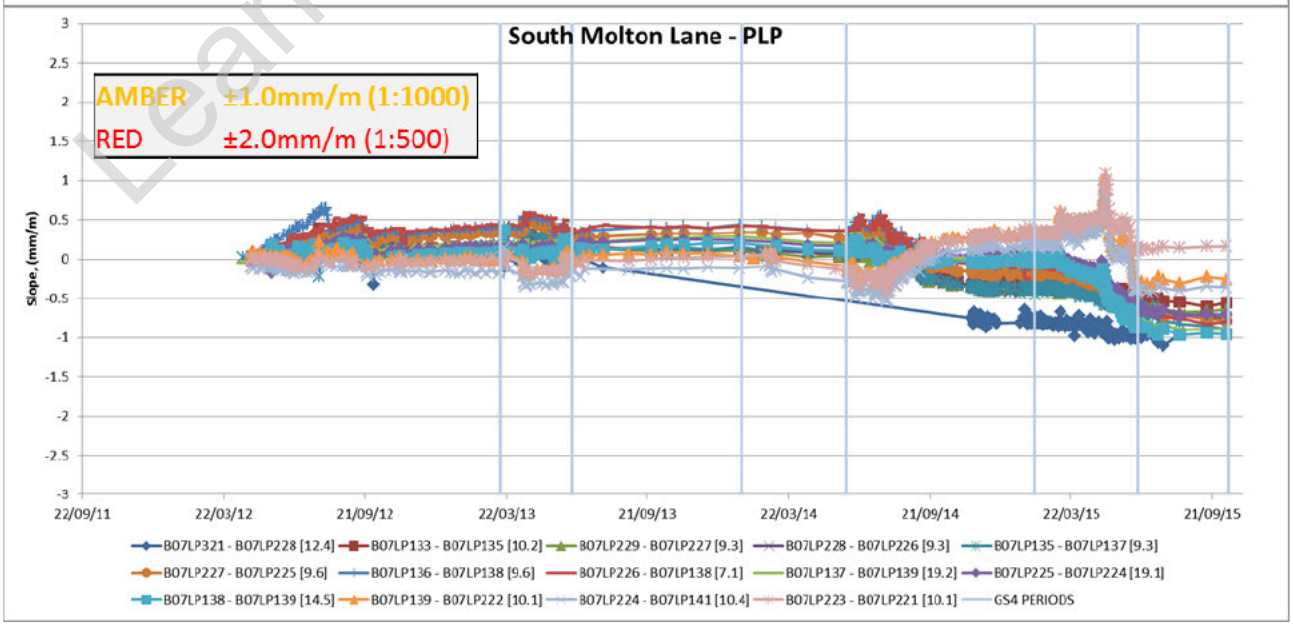
The following points are noted:

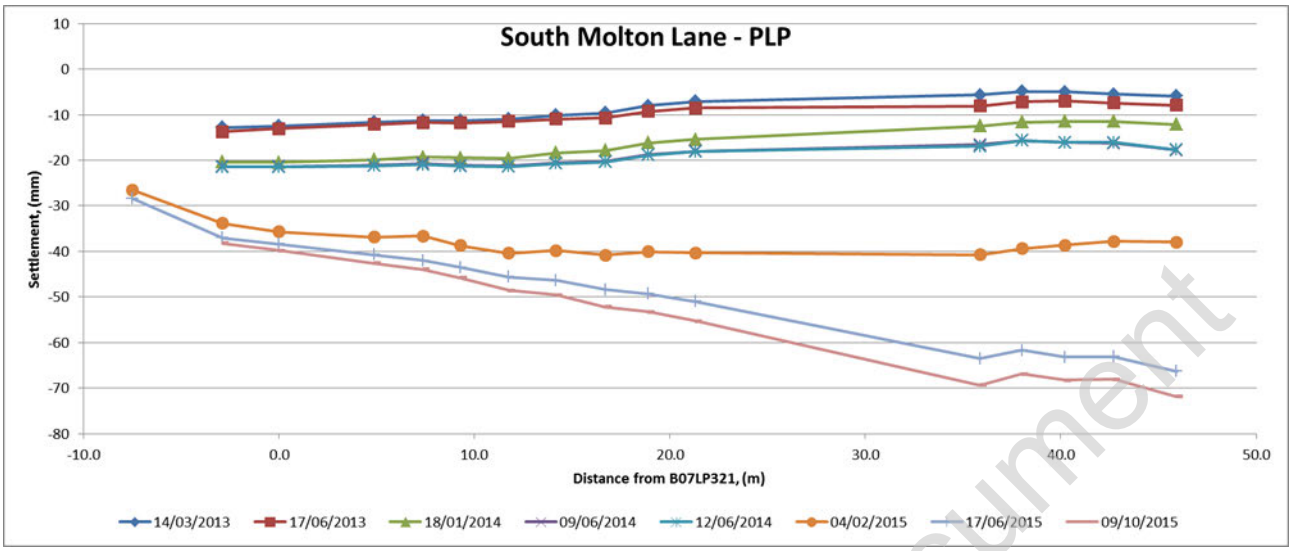
- The northern part of South Molton Street is partly within the GS4 array (from distance 70m to 110m). The section of the PLP transect from 0m to 70m is just outside the plan extent of the GS4 arrays which terminate below the centre of South Molton Street: data from all points shown on Figure 5.1.1 are presented.
- South Molton Street traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were the construction of PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm.
- In Period B, the EBRT together with grout jacking produced about 5mm increase in settlement.
- There was little change In Periods C and D indicating small time related movements following the TBM drives, giving a maximum settlement of ~20mm.
- The construction of the PTE in Period E 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 30mm, producing a total settlement of 50mm. Three Amber triggers were generated due to movements both during and after tunnelling. Details are given in Table 5.1.
- In Period F, there was a further increase in total settlement to ~55mm associated with the construction of CH2 and an increased rate of consolidation settlement.
- Post construction, in Period G, settlement has continued to increase. As expected the movements became relatively uniform and hence the impact on slopes became minor. However two further Amber triggers (slope <1.1mm/m) were recorded on the final reading.

5.3. South Molton Lane





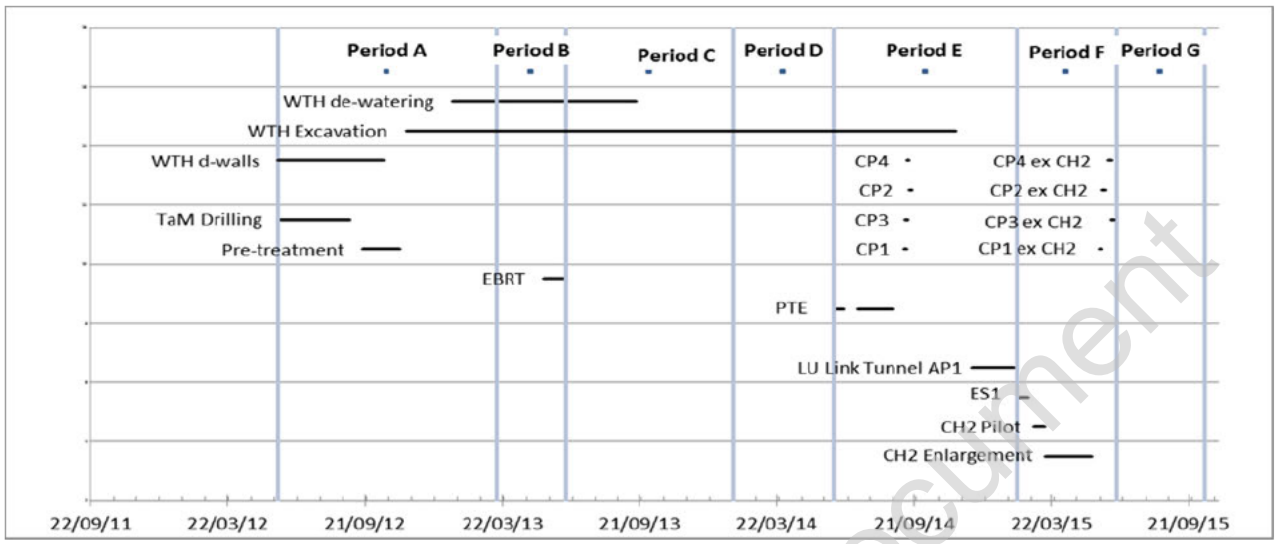


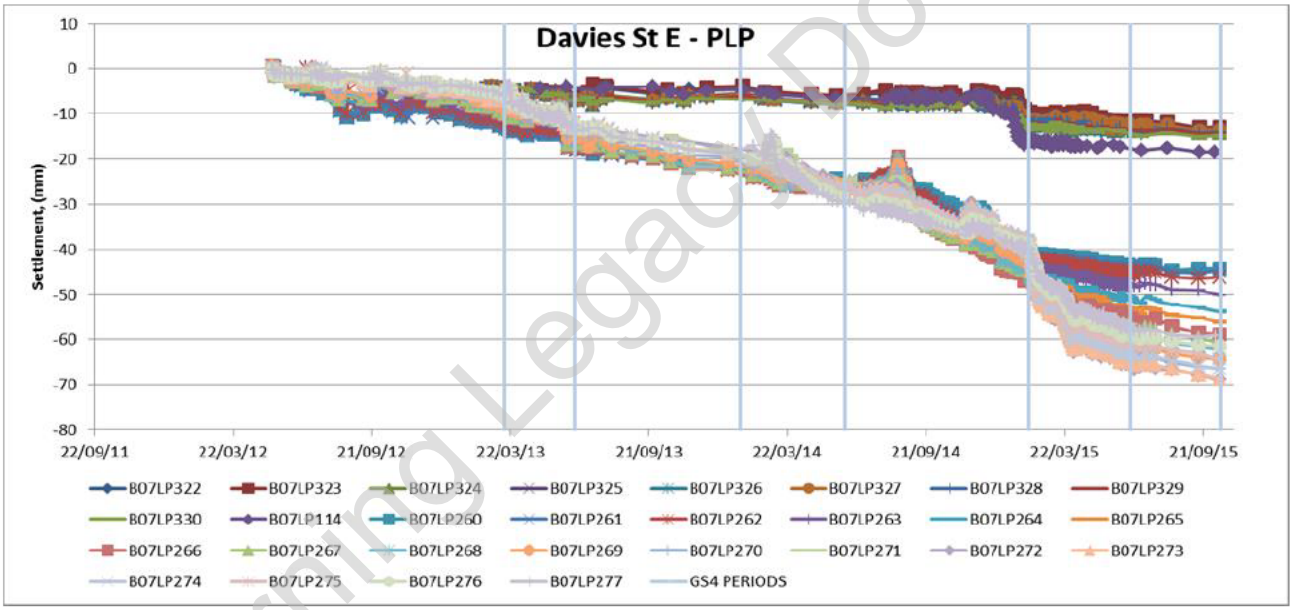


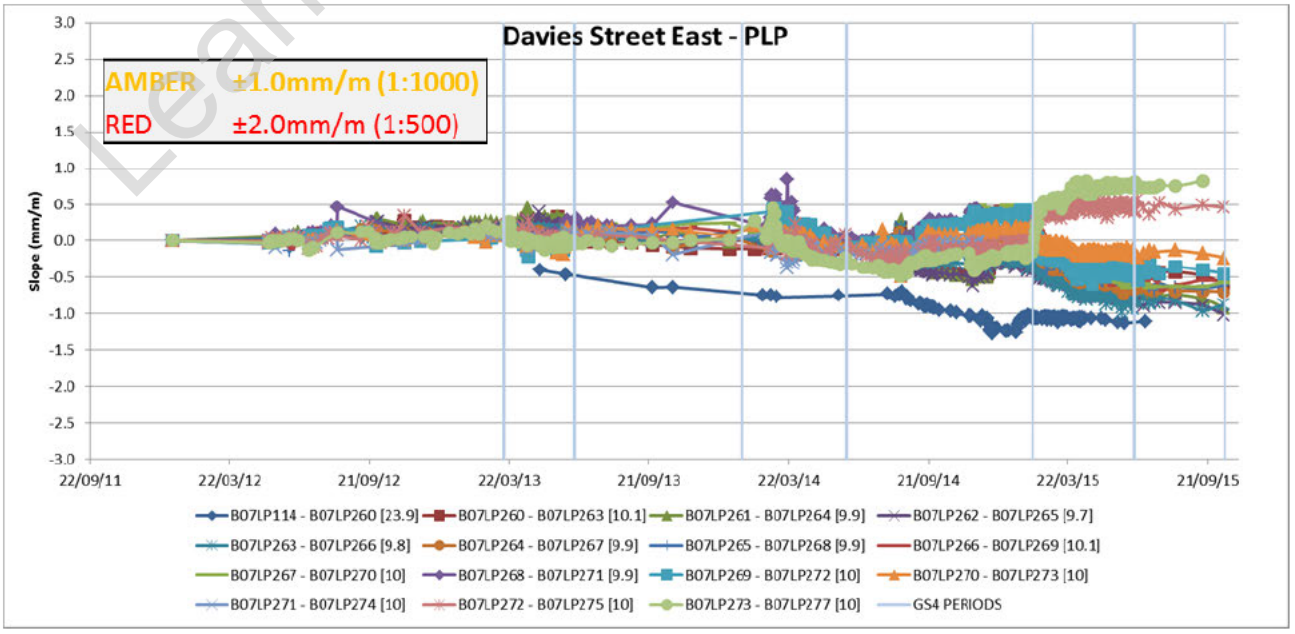
The following points are noted:

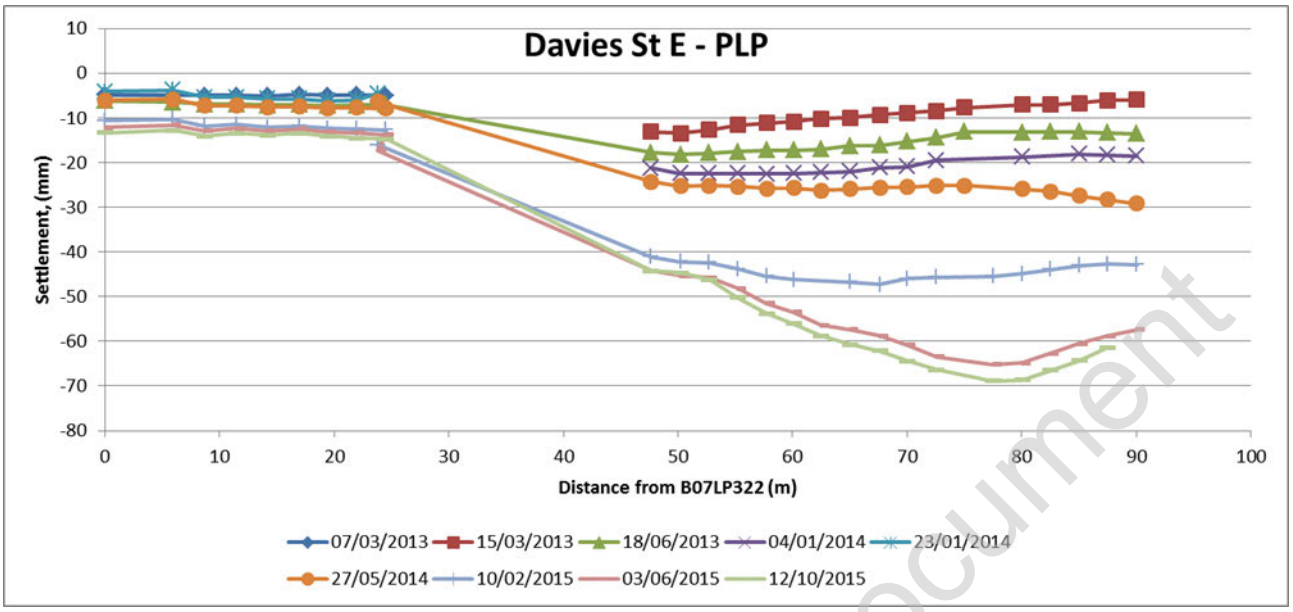
- The northern part of the South Molton Lane is within the GS4 array (up to distance 35m): data from all points shown on Figure 5.1.1 are presented.
- South Molton Lane traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~12mm but there was only minor variation over the full length of the façade.
- In Period B, the EBRT together with grout jacking produced a minor (<5mm) increase in settlement.
- There was little change In Periods C and D indicating small time related movements following the TBM drives, giving a maximum settlement of ~20mm.
- The construction of the PTE in Period E 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 maximum total settlement within the Period to ~20mm, producing a total settlement of 40mm.
- In Period F, there was a further increase in total settlement to 63mm at the southern boundary of the GS4 array associated with the construction of ES1 and CH2 and a subsequent increased rate of consolidation settlement.
- Post construction, in Period G, settlement has continued to increase (maximum 69mm). As expected the movements became relatively uniform and hence the impact on slopes became minor. However one marginal Amber trigger (slope <1.1mm/m) was recorded albeit the final reading was below the trigger level.

5.4. Davies Street - East





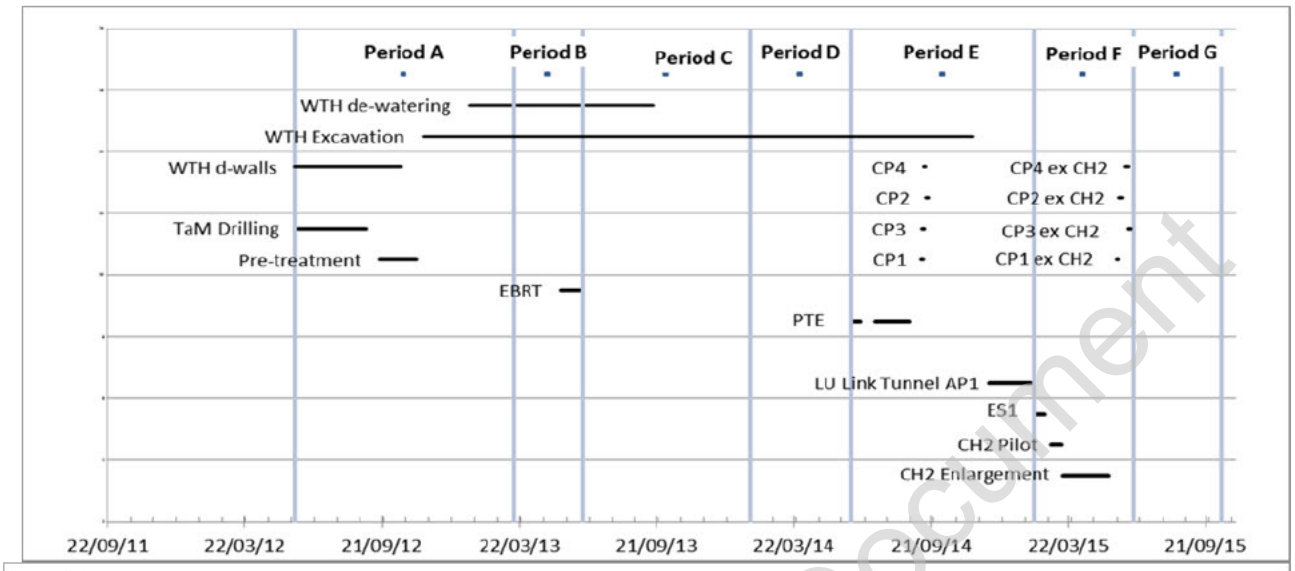


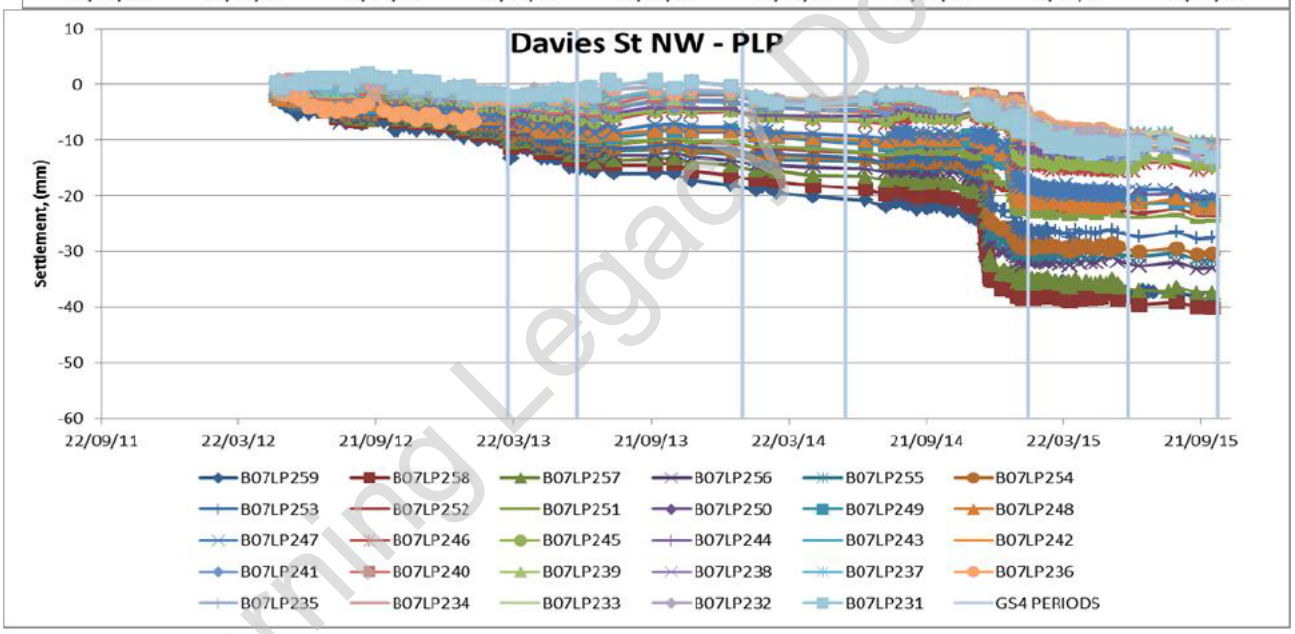


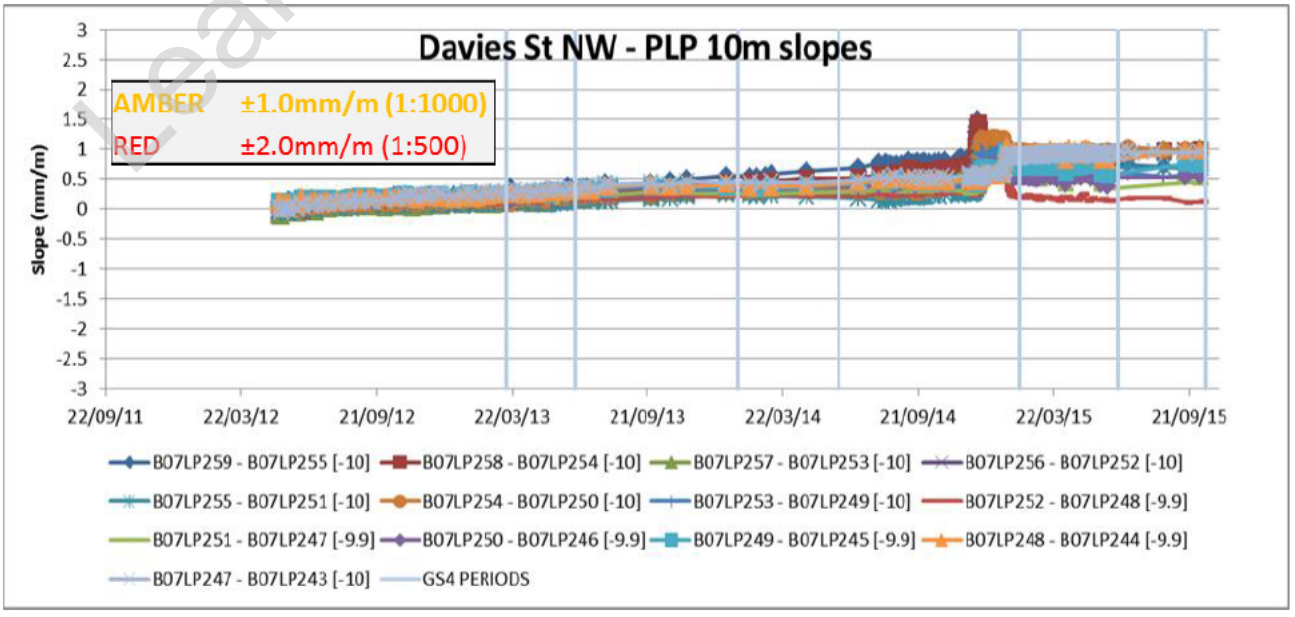
The following points are noted:

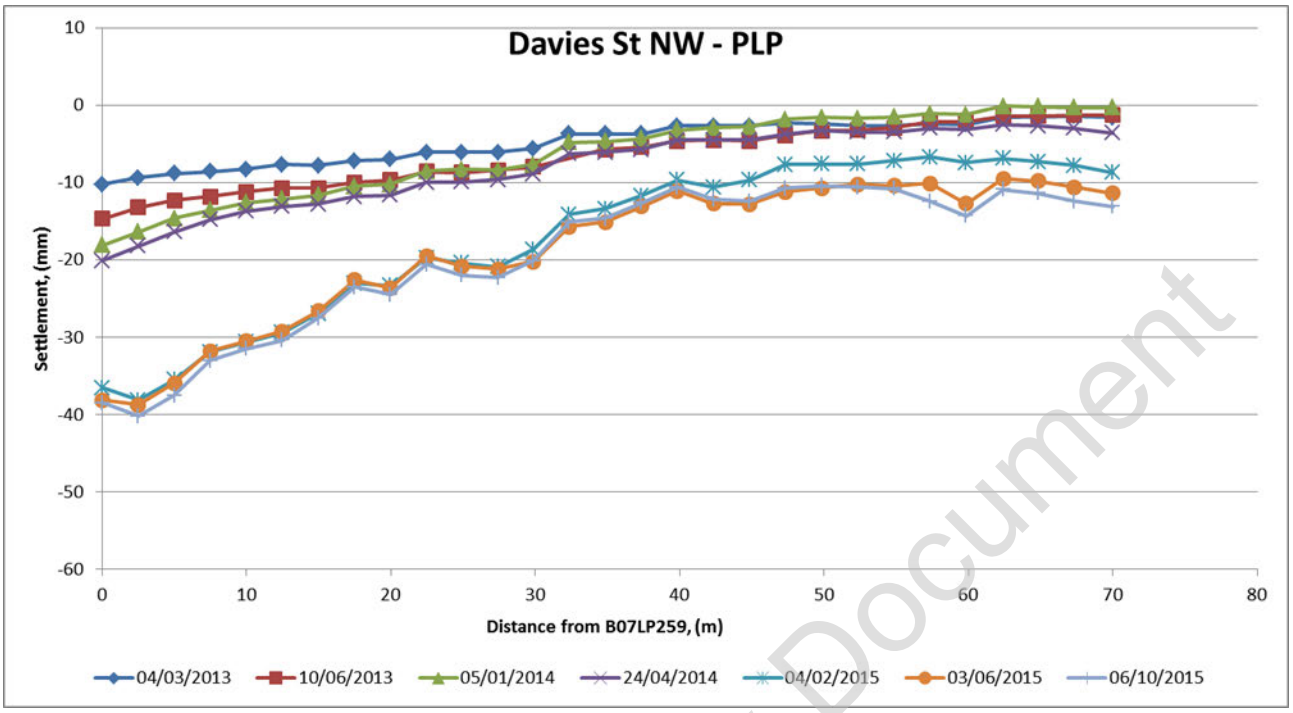
- The northern part of Davies Street is within the GS4 array (from distance 25m to 85m): data from all points shown on Figure 5.1.1 are presented.
- Davies Street traverses the entire extent of the tunnels and consequently the key events vary with location. The most notable events were however the construction of PTE in Period E and CH2 in Period F.
- At the end of Period A, prior to tunnelling, the maximum settlement was over 10mm but there was only minor variation over the full length of the façade.
- In Periods B and C, the EBRT and subsequent consolidation generated a further ~10mm settlement.
- In Period D the construction of PTW had a minor effect at the southern end of the profile (from distance 75m) which increased settlement by up to 10mm, giving a maximum of 30mm. However, there was ongoing consolidation throughout the transect.
- The construction of the PTE in Period E had a major effect, not just during construction where settlement increased by ~10mm, but also by significant consolidation settlement which increased the total settlement within the Period to almost 20mm, producing a total settlement of ~47mm. One Amber slope trigger (B07LP122-B07LP260) resulted from these movements.
- The construction of AP1 generated settlement on the points to the north of South Molton Lane (up to distance of 25m). These PLP were installed immediately adjacent to the redeveloped building at 28 South Molton Street, in lieu of BRE. A uniform settlement of ~5mm in shown.
- In Period F, there was a further increase in the maximum total settlement to ~65mm associated with the construction of ES1 and CH2 and an increased rate of consolidation settlement.
- Post construction, in Period G, settlement continued to increase slowly. As expected the movements became relatively uniform and hence the impact on slopes became minor, although a further slope (B07LP262-B07LP265) had a single reading of 1.02mm/m.

5.5. Davies Street – West





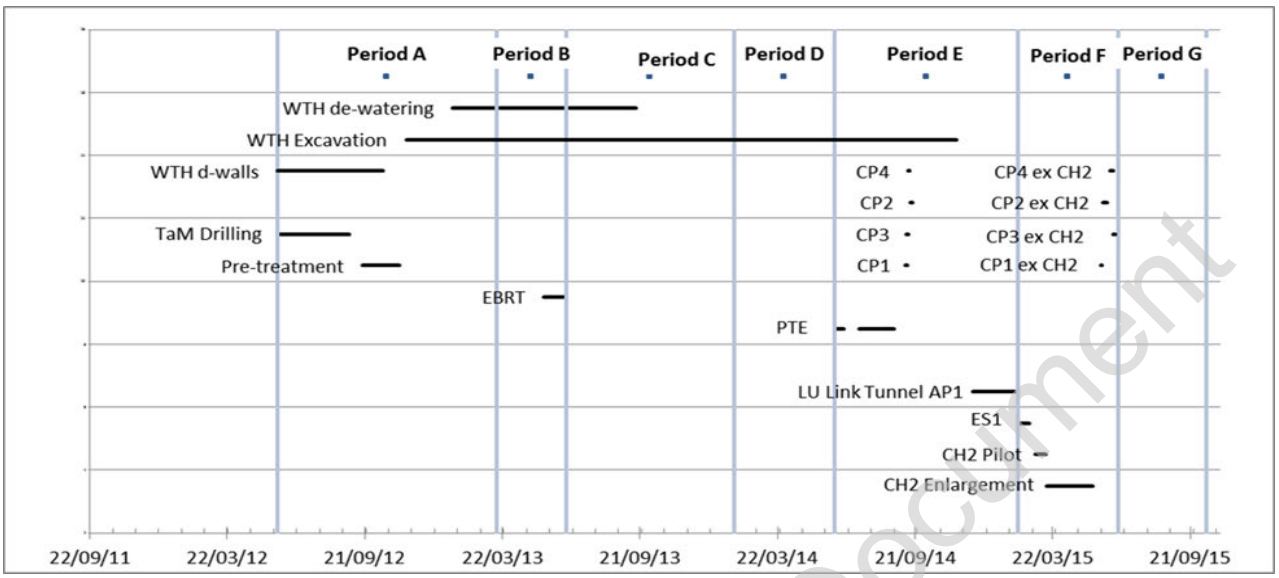


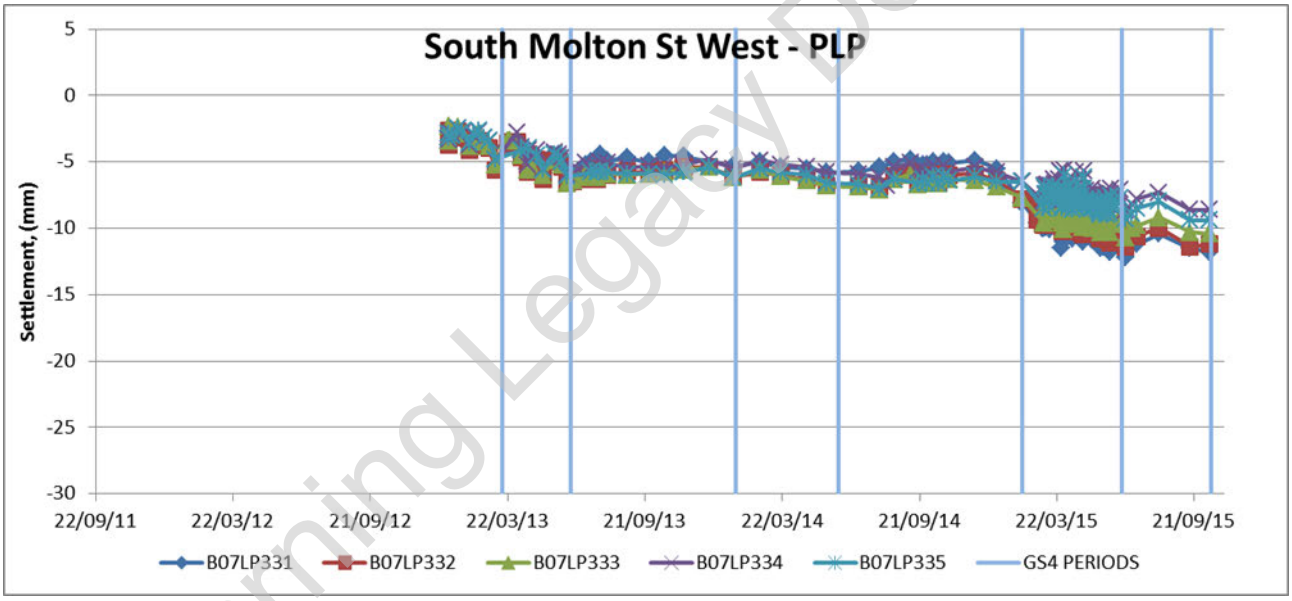


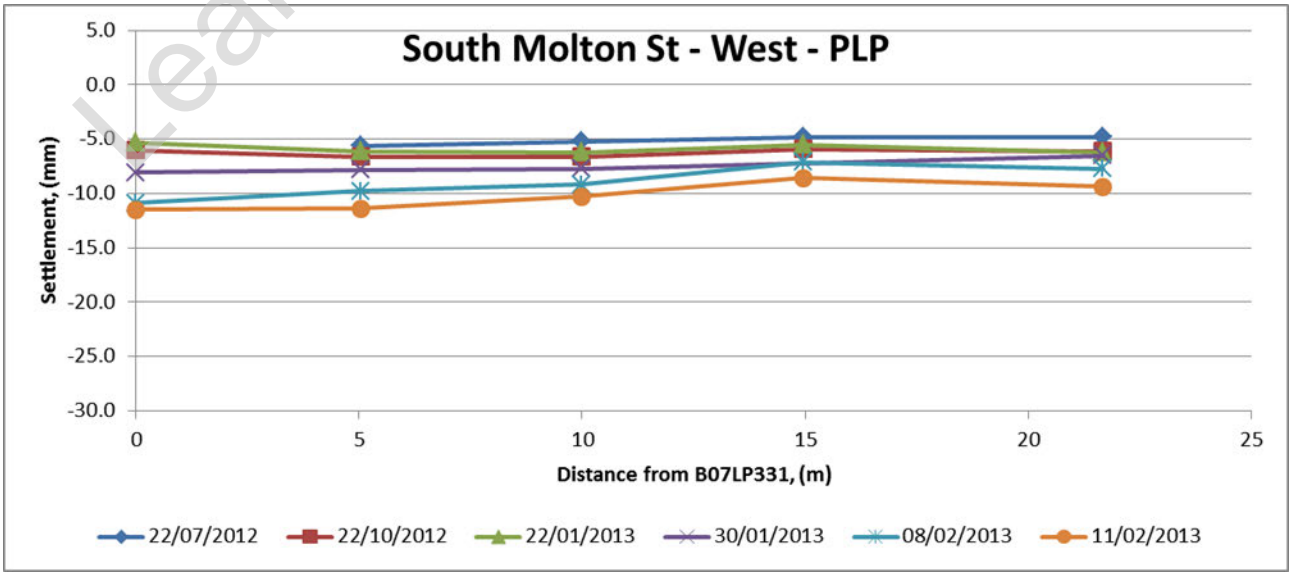
The following points are noted:

- The west kerbline of Davies Street is on the extremity or outwith the GS4 array: data from all points shown on Figure 5.1.1 are presented.
- At the end of Period A, prior to tunnelling, the maximum settlement was ~10mm but there was a gradual variation over the full length of the transect.
- In Periods B, C and D, the EBRT and subsequent consolidation generated a further ~10mm settlement.
- In Period E, the construction of PTE had no discernible effect. The construction of AP1 (Ch. 0 to 61m) generated settlement of up to 20mm adjacent to the WTH decreasing gradually to the north. Six transient Amber triggers were generated as the tunnel advanced. All reduced to below the Amber level, albeit, they remained close to the limiting value.
- In Period F, the final 20m of AP1 and the LU vent tunnel diversion were completed producing only a minor impact (<5mm) at the northern end of the transect (from distance 40m).
- Post construction, in Period G, settlement has continued to increase slowly. As expected the movements became relatively uniform and hence the impact on slopes became minor.

5.6. South Molton Street West







The following points are noted:

- The PLP installed on the west side of South Molton Street adjacent to number 28, are additional points following re-development of this building. The compensation grouting arrays were curtailed at the boundary of this property since the new building is piled.
- An initial settlement of ~4mm was estimated for these points based on adjacent data points. There was no significant change (maximum settlement of 7mm) troughout Periods B, C and D.
- In Period E, the construction of PTE had no discernible effect. The construction of AP1 (Ch. 0 to 61m) in Period E and the final 20m of AP1 and the LU vent tunnel diversion in Period F produced only a minor impact (<5mm).
- Post construction, in Period G, settlement has continued to increase slowly with a maximum recorded settlement of 12mm. As expected the movements became relatively uniform and hence the impact on slopes became minor.
- By inspection of the profile plot, there were no slope trigger values 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 4. 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:

- Significant movements occurred prior to the commencement of tunnelling due to installation of the compensation grouting TaMs as well as from works by others.
- 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 such that the TaMs were located within the exclusion zone above the tunnel. No TaMs were required above the LU Link Tunnel (AP1).
- 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 structures is not a linear elastic situation, there is the potential for significant damage to occur even if the recorded 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: a maximum of 125l/m^2 was injected below the TA Centre, 56 Davies St.

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 4. This was accepted by CRL and the grout shaft was subsequently de-commissioned.

The post-construction monitoring was terminated under C300-PMI-01858. 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

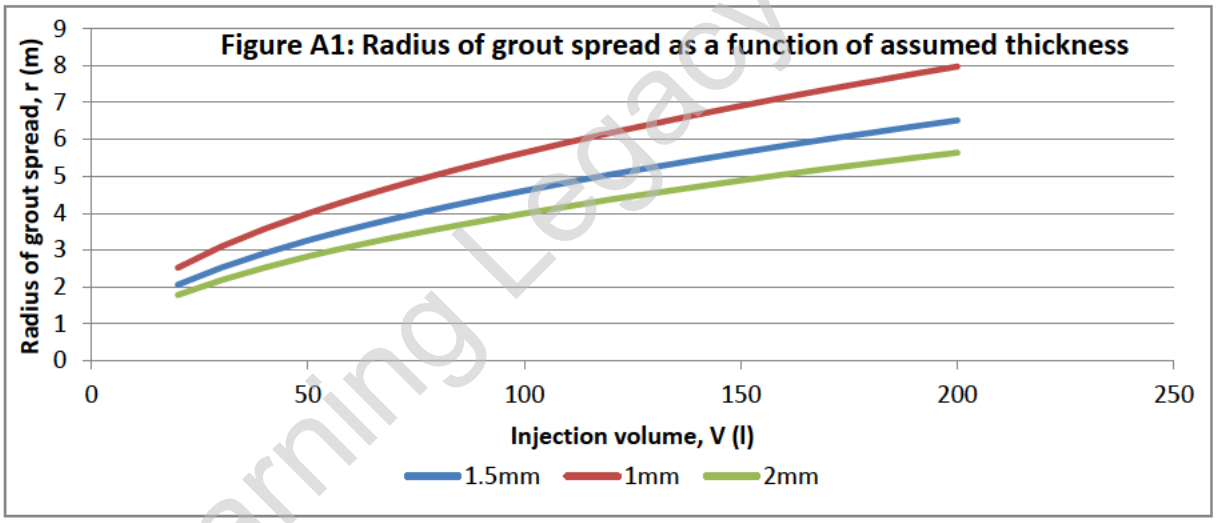
A method of producing a visualisation of the quantity and distribution of grout injected during compensation grouting is useful in interpreting performance. For each injection the volume and the location of the port used are known. The model used is intended to approximate the distribution of grout within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

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



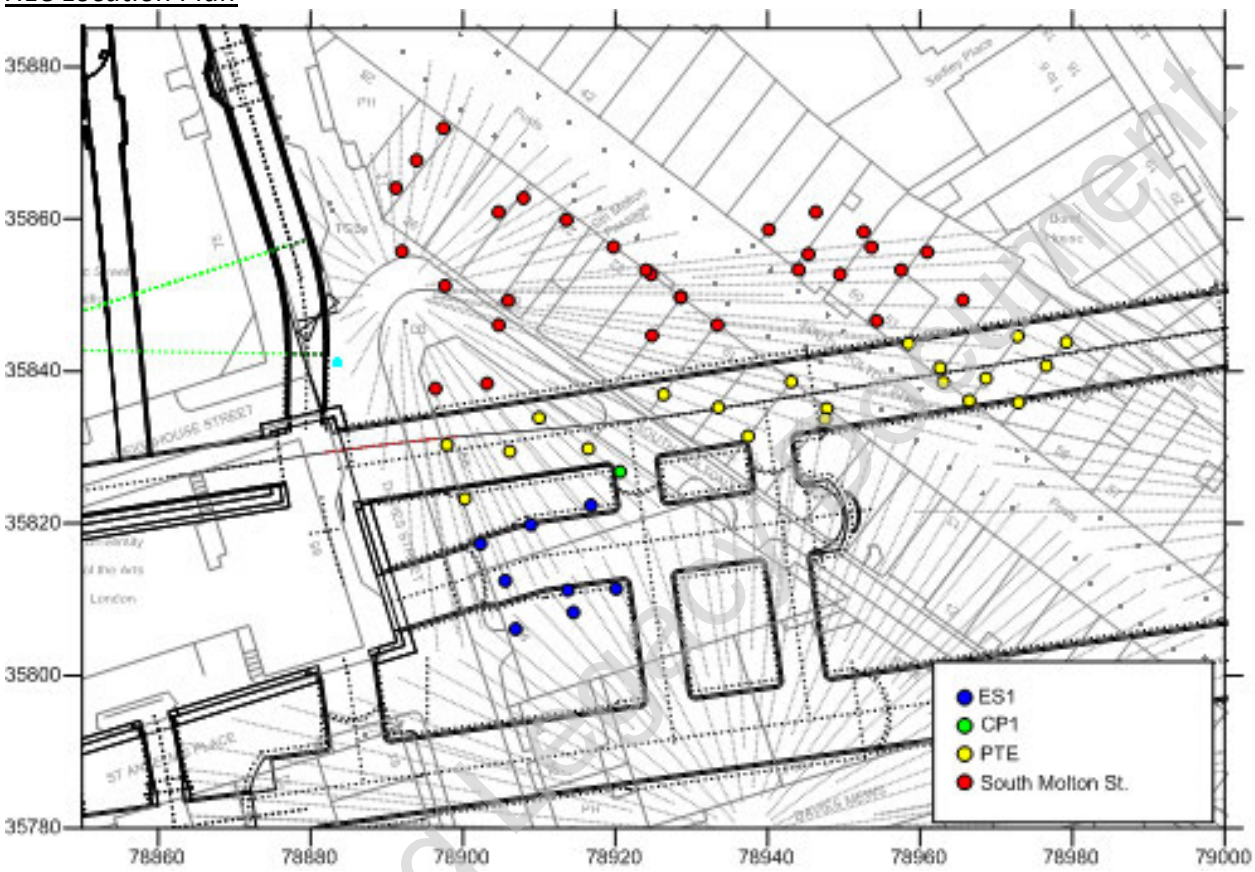
Observation of grout in the ground suggests that a thickness of 1 – 2mm is predominantly achieved. All of the plots included in this report are based on an assumed thickness of 1.5mm. Figure A1 shows the variation in radius for thicknesses of 1.0, 1.5 and 2.0mm.

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.

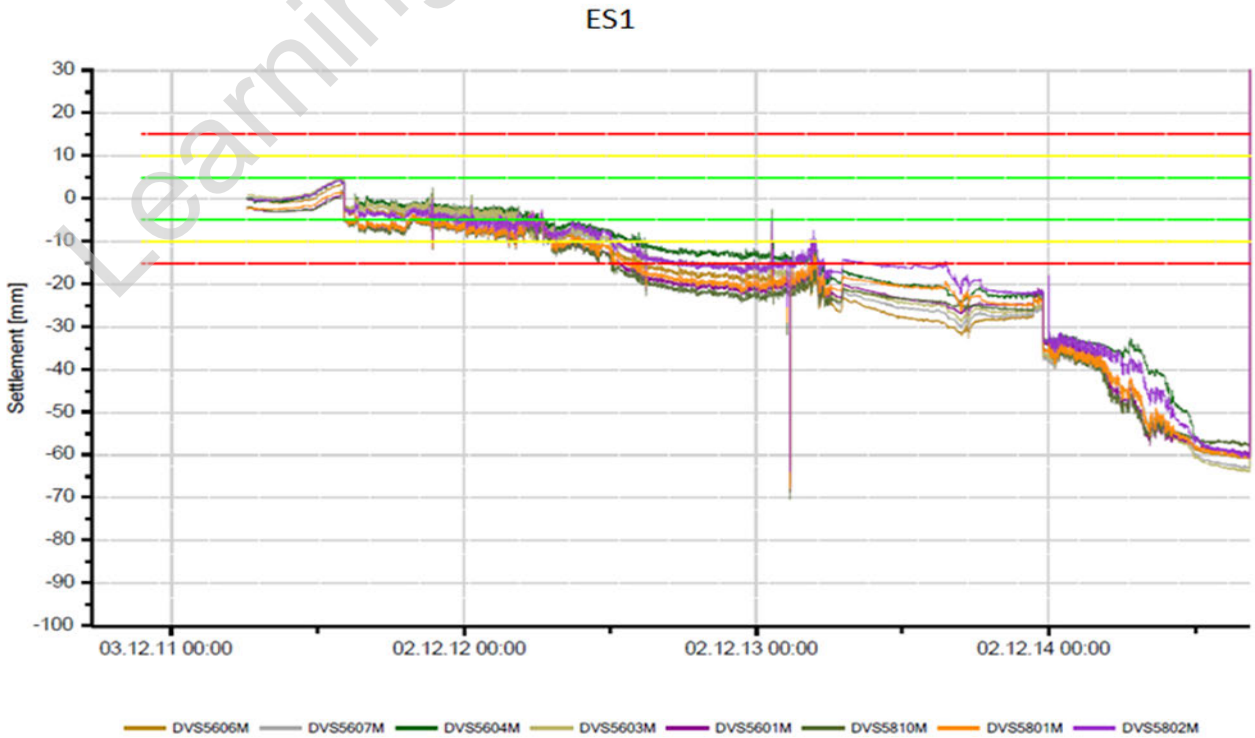
Appendix B

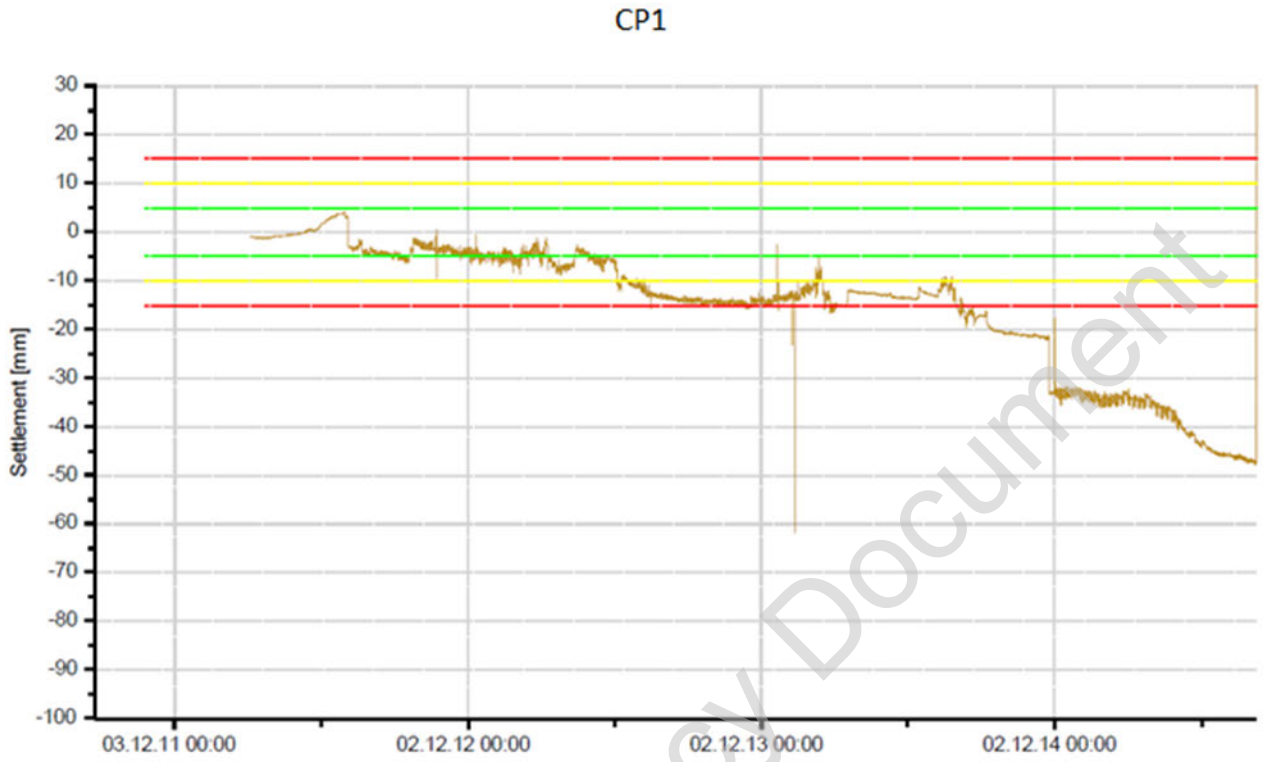
HLC & SAA data

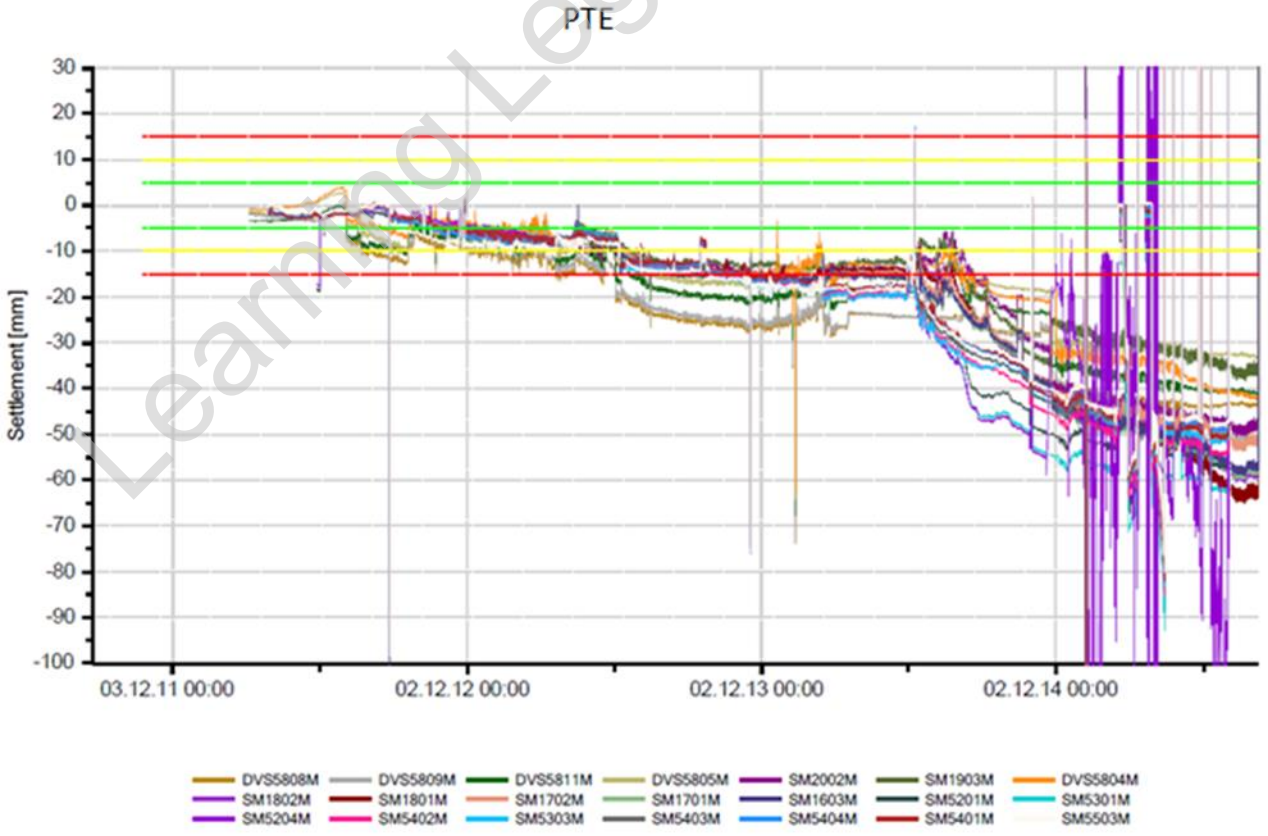
HLC Location Plan



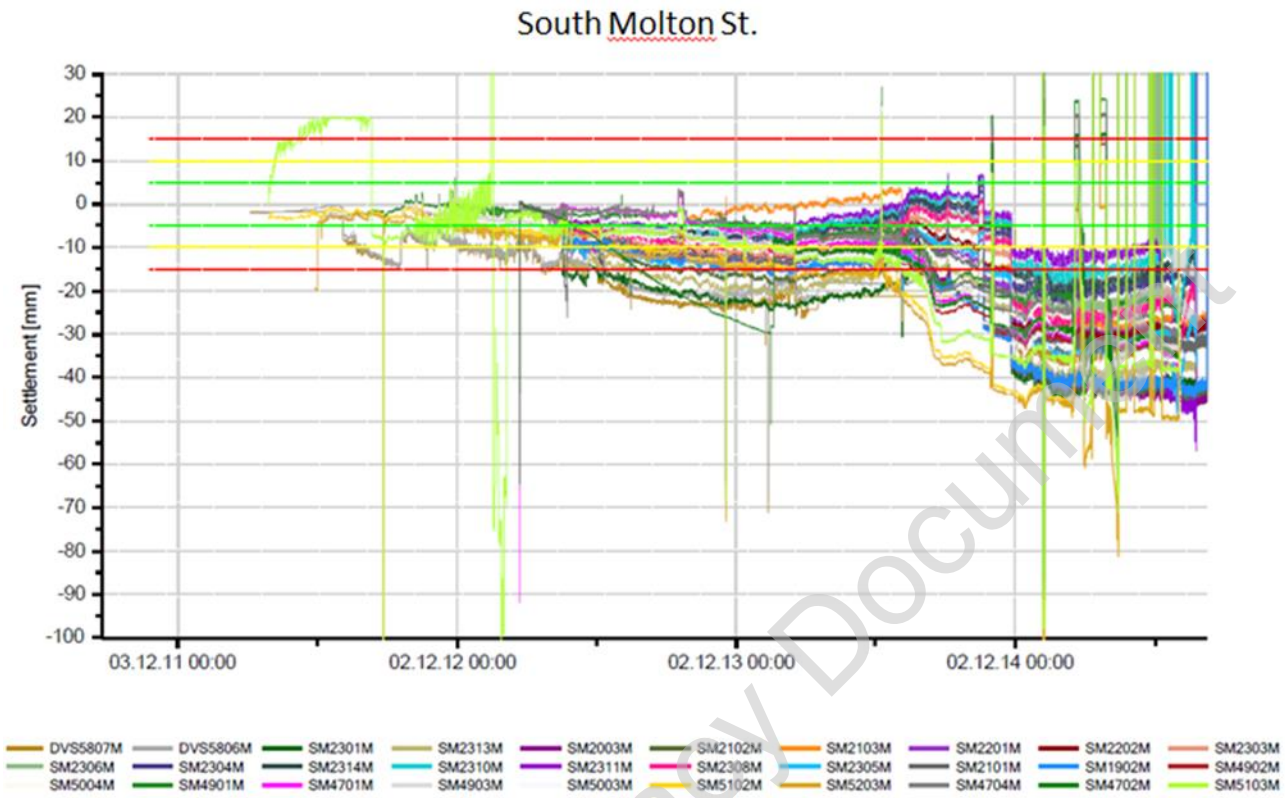
HLC Data Plots







N.B. Cells not required for Construction Control following completion of PTE in July 2014



N.B. Cells not required for Construction Control following completion of PTE in July 2014

Horizontal Inclinometers

The Works Information required a horizontal inclinometer to be drilled along the alignment of AP1 from the WTH approximately 1m above the crown of the tunnel. However this was not practicable due to the limited access to get a drilling rig in position within the WTH. As an alternative it was agreed to drill and install six horizontal Shape Accel Arrays (SAA) from Grout Shaft 4.

The SAA provide a settlement value at 0.5m intervals along their length and this data has been used to produce contour plots showing the development of settlement as the tunnel was progressively excavated.

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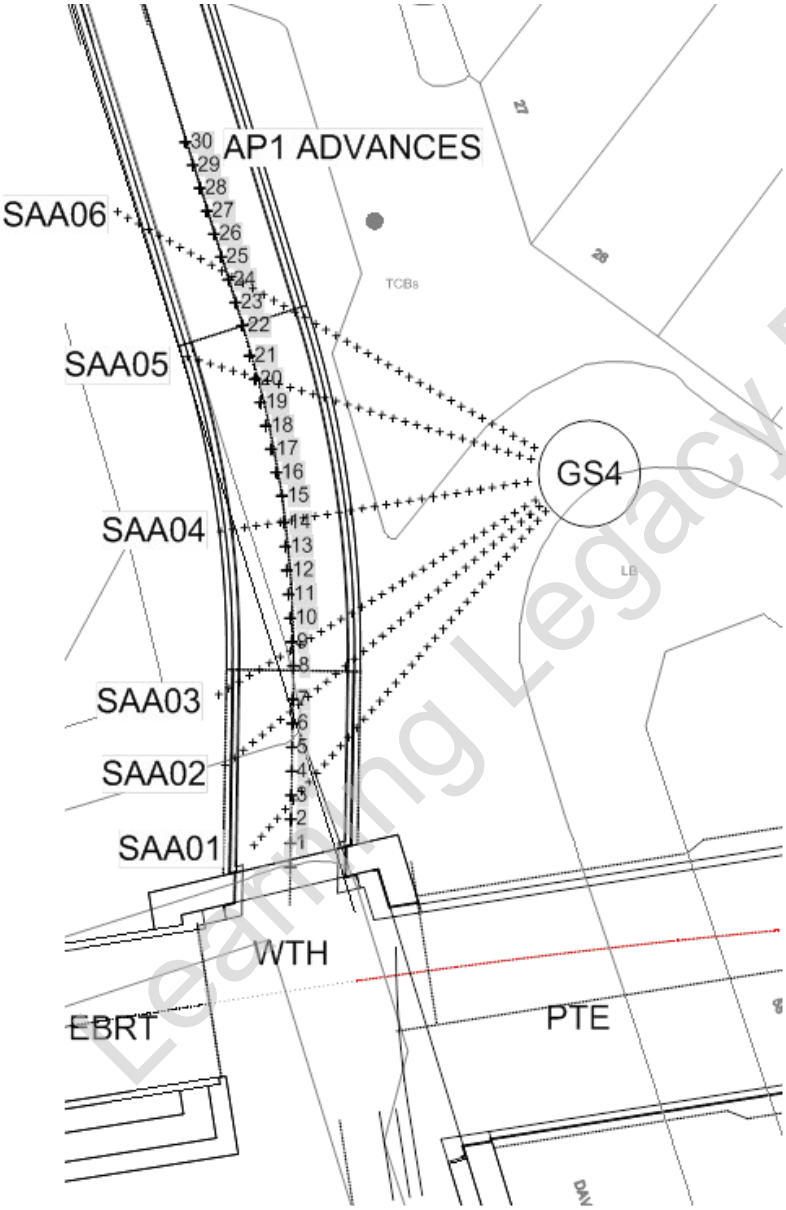

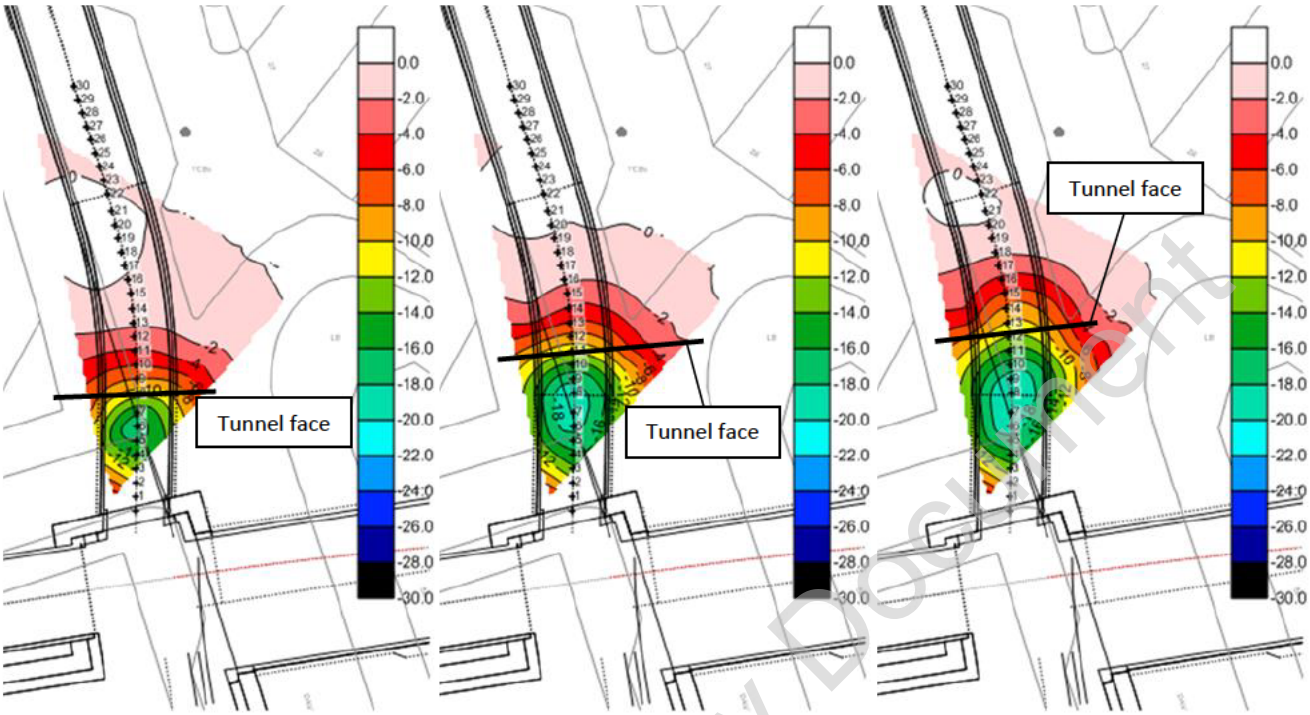

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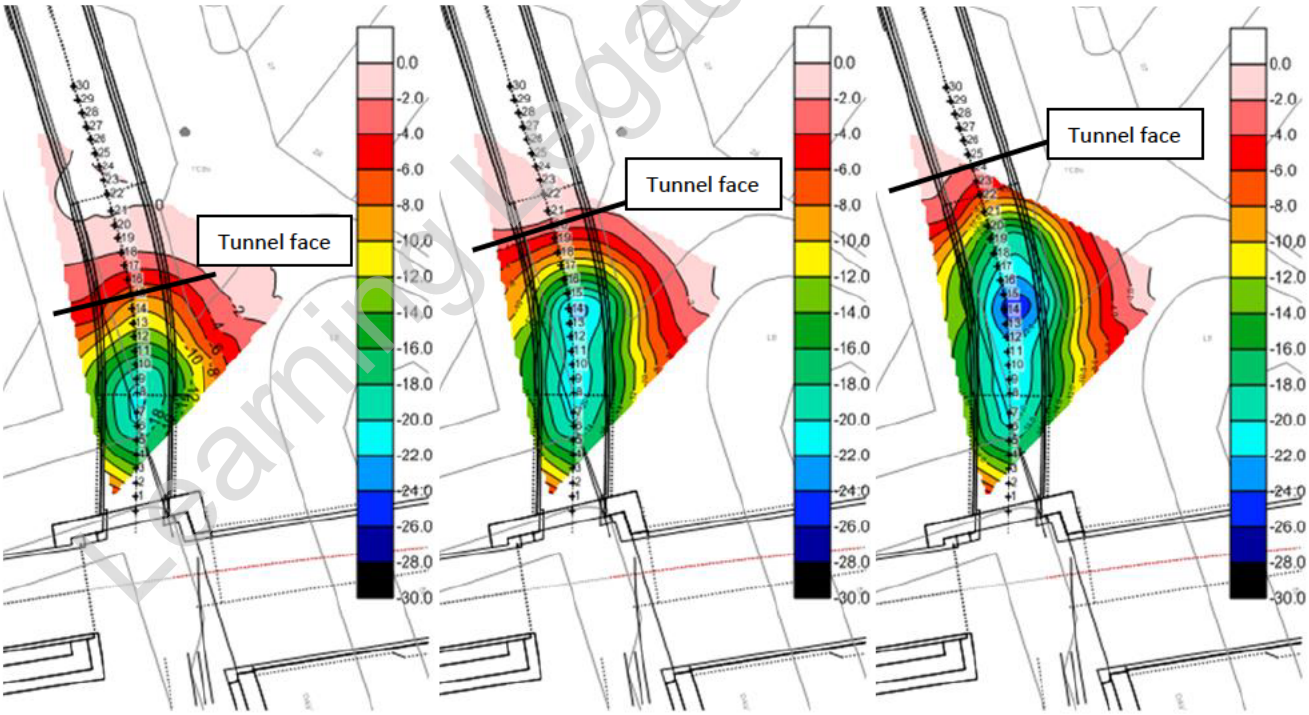

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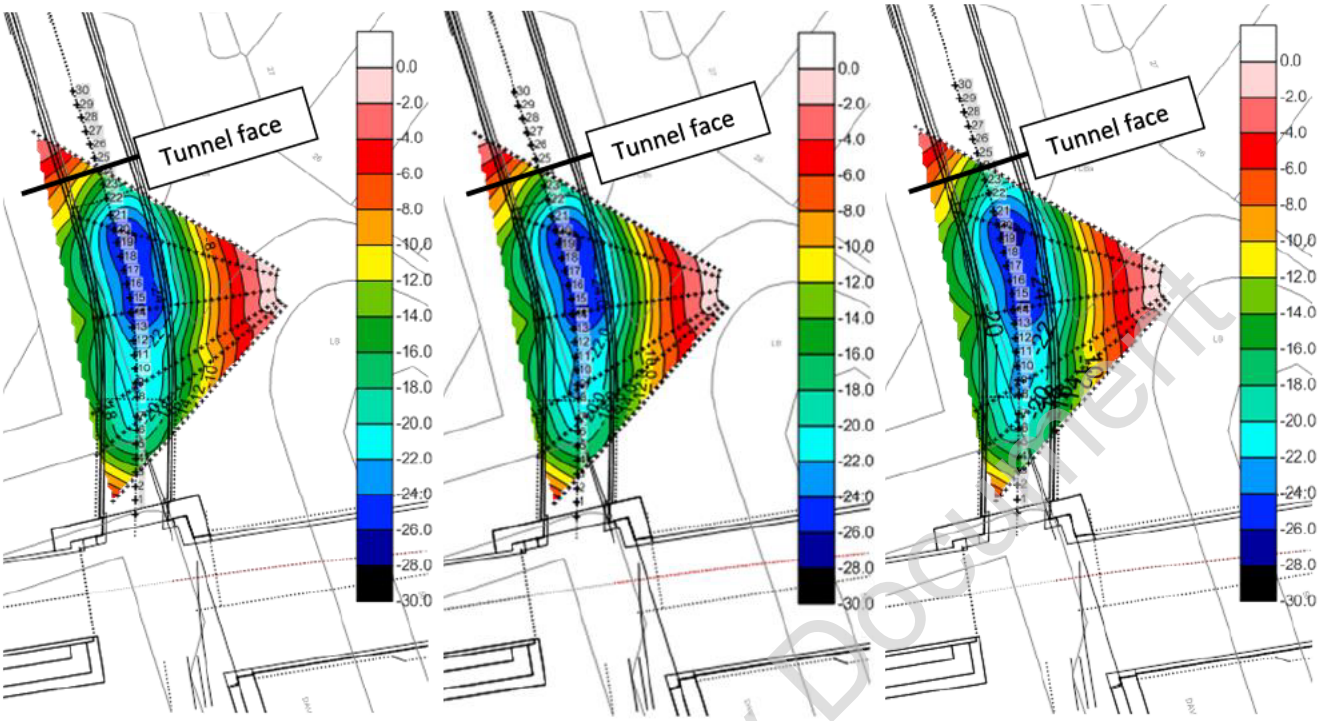

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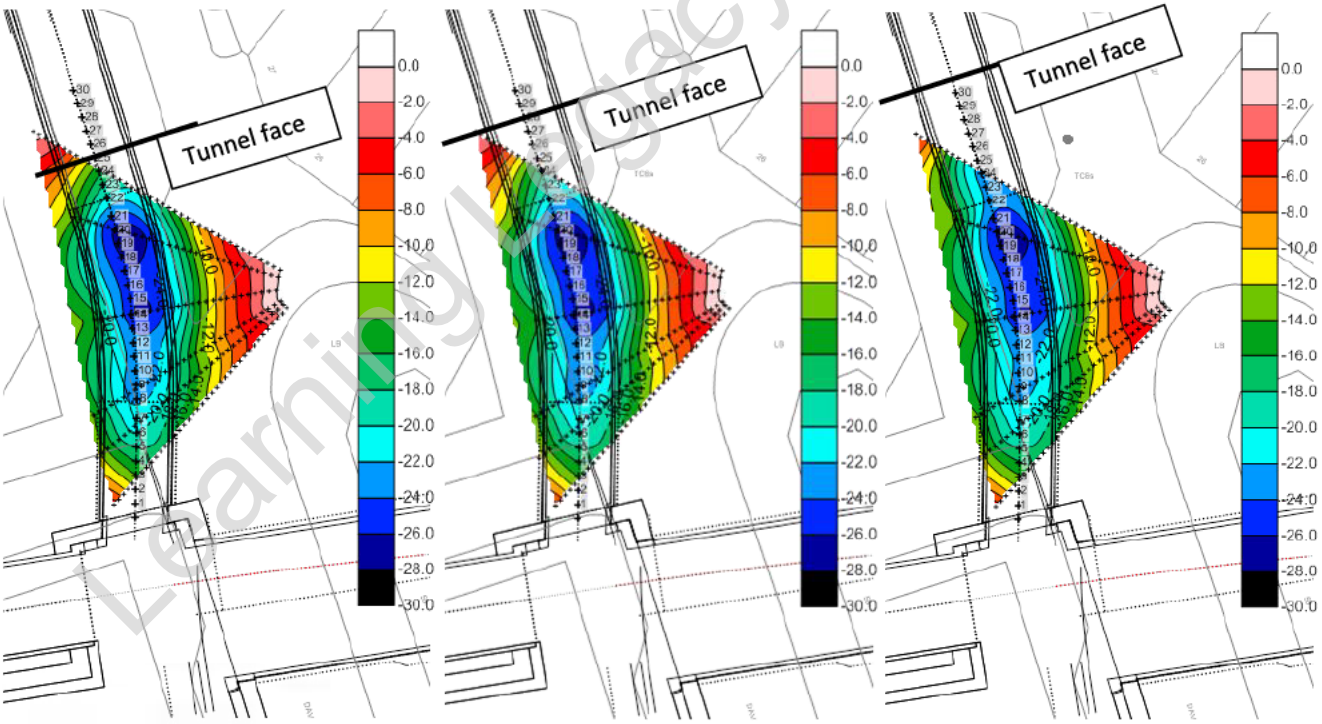

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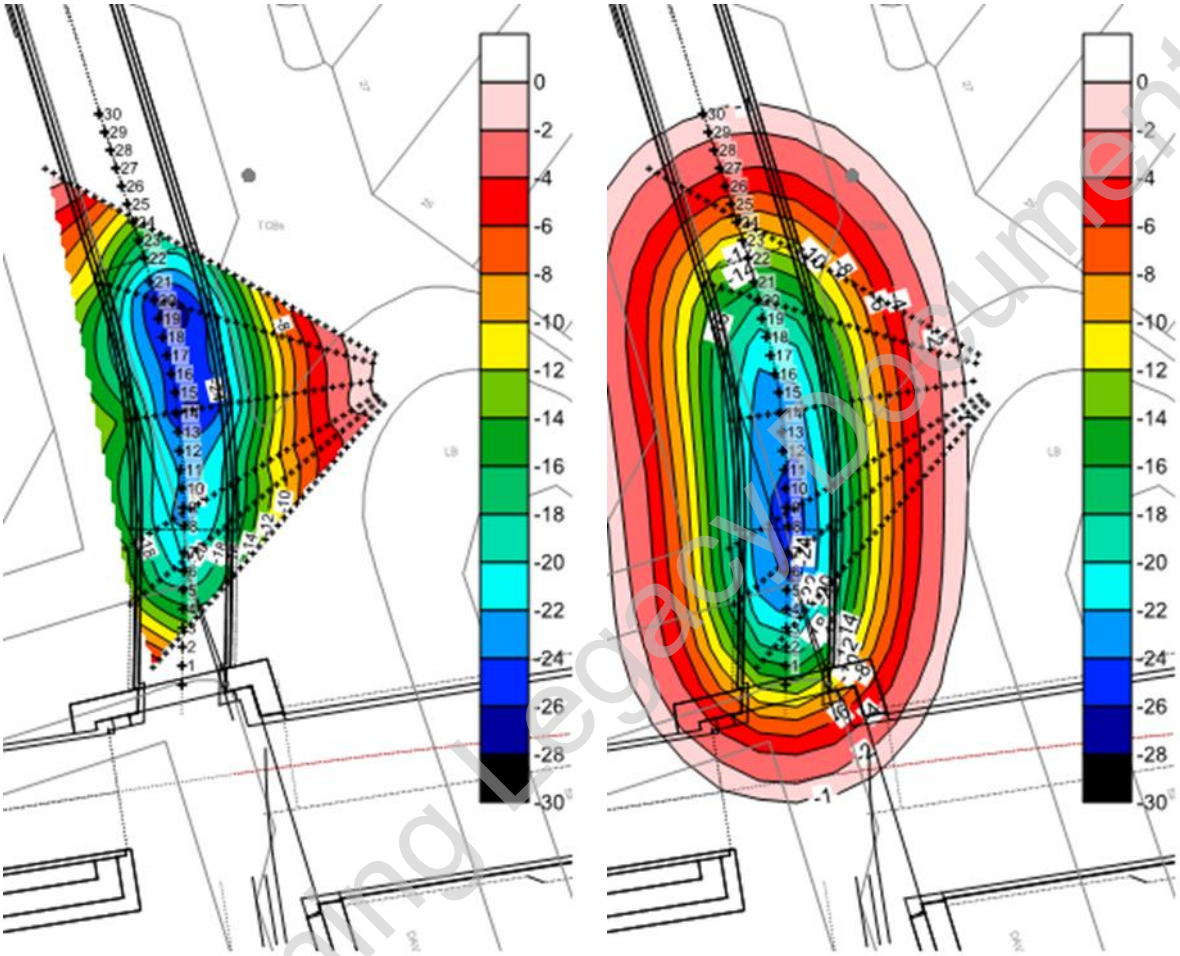
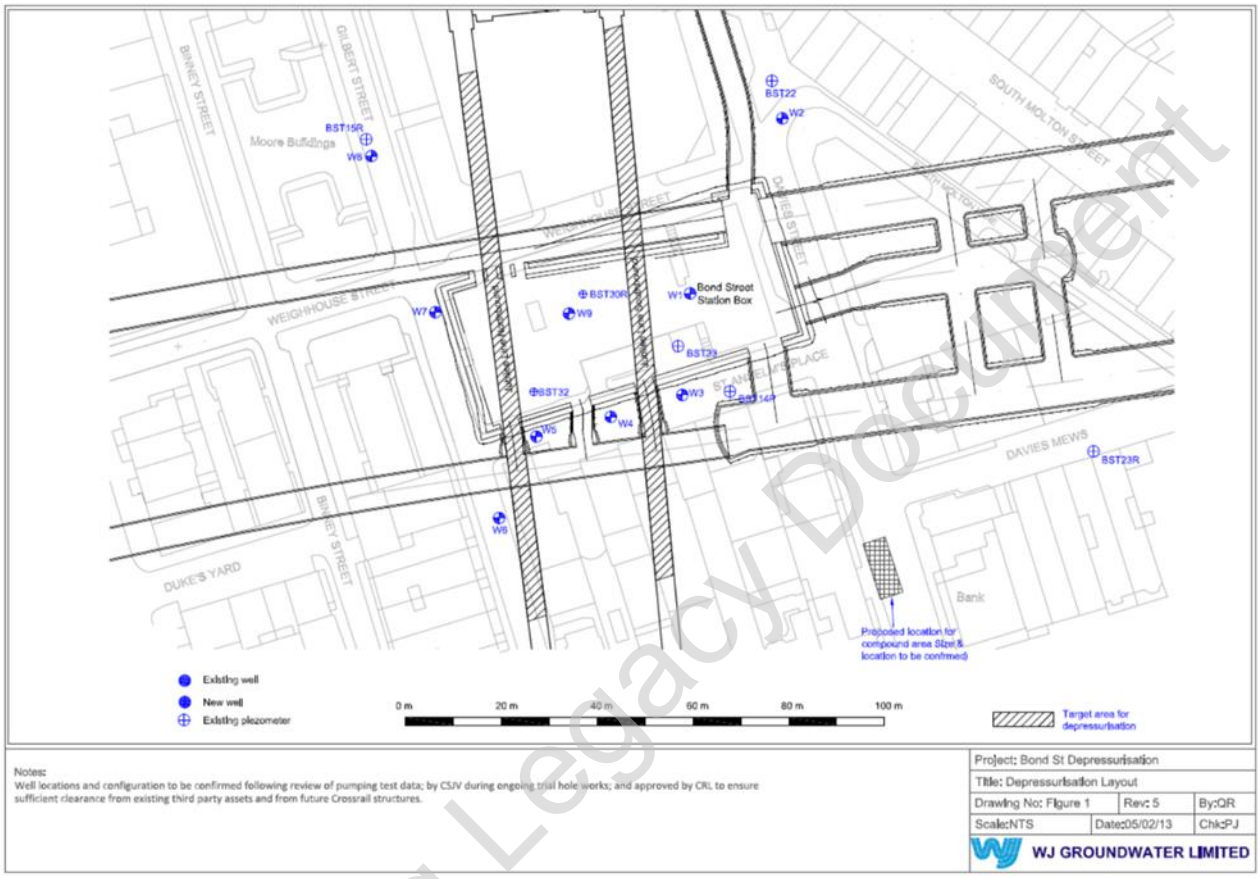
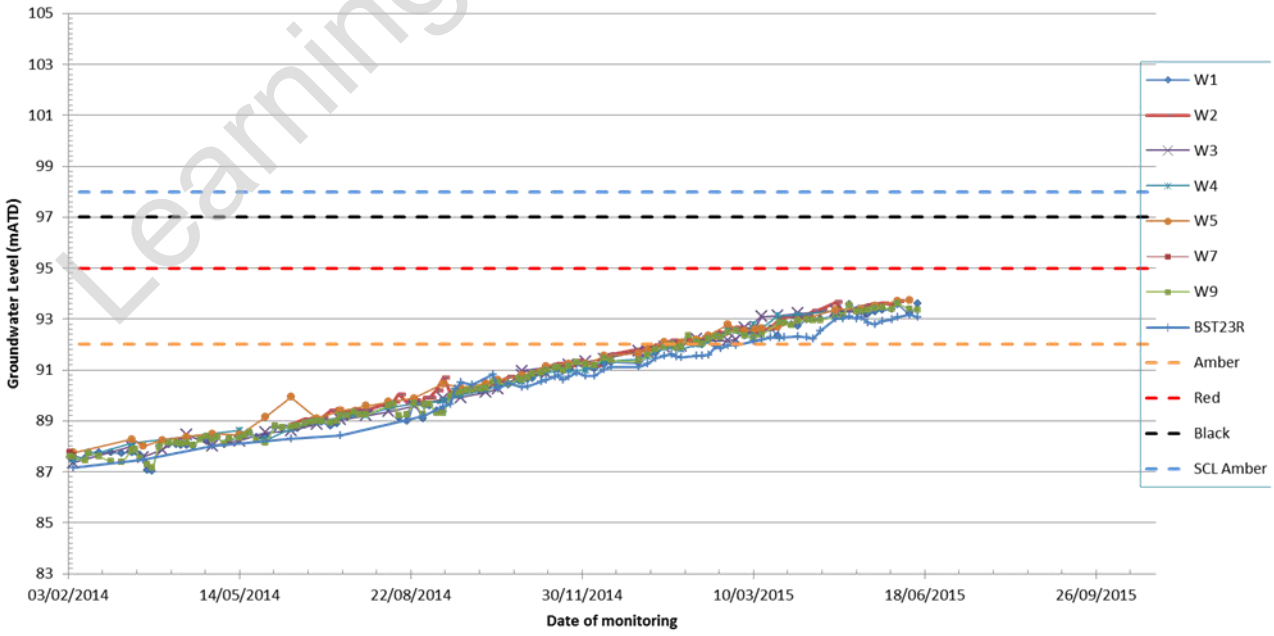
A comparison between the measured and calculated greenfield settlement at the elevation of the SAA has been undertaken: the volume loss used in the calculation (0.9%) was based on back-analysis of the observed movement after 24 advances. The plots show the effect of the diaphragm wall of the WTH in reducing movements over the first advances of the tunnel, whereas from approximately 12m from the wall the observed centreline settlements are slightly greater than calculated.



Groundwater Monitoring

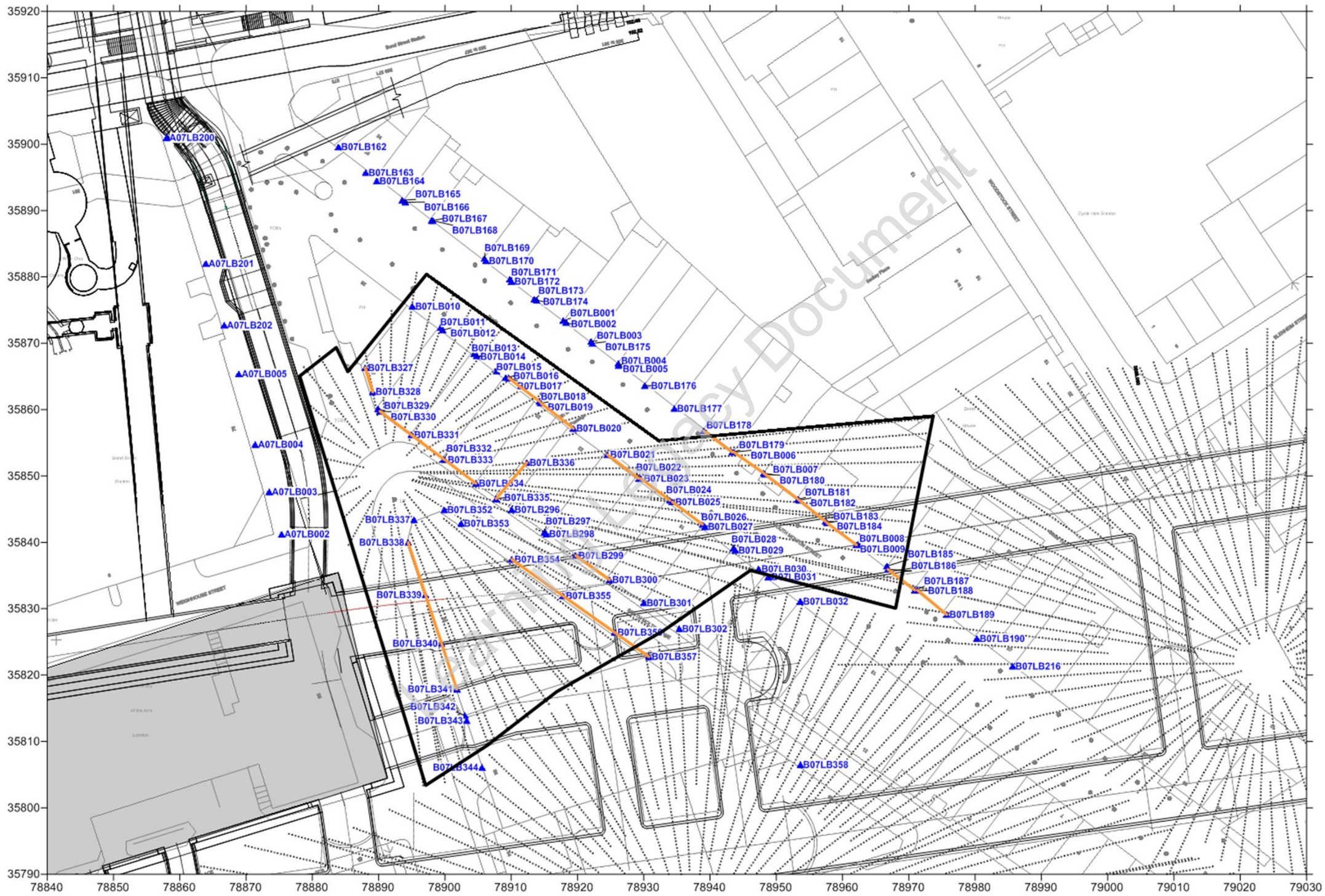
C411 undertook de-watering of the Lambeth Group sand channel below the WTH between January and September 2013. BFK took over monitoring of the recovery in water level in February 2014 about 5 months after the cessation of pumping. The data collected by BFK are presented. Trigger levels set by C411 and for BFK SCL tunnelling are shown on the plot.





Appendix C

Enlarged version of Figures 4.1.1 and 5.1.1 showing location of monitoring points and slope triggers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