C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - TCR GS5

CRL Document No. C300-BFK-C4-RGN-CRT00_ST005-51229

Contract MDL reference: C13.016

1. Contractor Document Submittal History

Revision	Date	Prepared by	Checked by	Approved by	Reason for Issue
3.0	08/02/2017	[redacted]	[redacted]	[redacted]	For acceptance

2a. Stakeholder Review Required? YES ☐ NO ☒

Stakeholder submission required: LU ☐ RfL ☐ Purpose of submission:

NR ☐ LO ☐ For no objection ☐

DLR ☐ Other: _____ 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.

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

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

2b. Review by Stakeholder (if required):

Stakeholder Organisation	Job Title	Name	Signature	Date	Acceptance
					☐
					☐

3. Acceptance by *Crossrail:*

	Crossrail Review and Acceptance Decal This decal is to be used for submitted documents requiring acceptance by *Crossrail*.
☑	Code 1. Accepted. Work May Proceed
☐	Code 2. Not Accepted. Revise and resubmit. Work may proceed subject to incorporation of changes indicated
☐	Code 3. Not Accepted. Revise and resubmit. Work may not proceed
☐	Code 4. Received for information only. Receipt is confirmed

Reviewed/Accept by: (signature) [redacted] Print Nar[redacted] Position: [redacted] Date: 23/03/17

Acceptance by Crossrail does not relieve the designer/supplier from full compliance with their contractual obligations and does not 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 Figure 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 5 at Tottenham Court Road Station (referred as TCR within this document)

As required by the Compensation Grouting Specification KC21 Clause KC21.3220(c), a written submission is required to justify the de-commissioning of compensation grouting facilities a minimum of 3 months after the completion of construction. Comparisons are made to the Compensation Grouting Performance Requirements defined in Specification for the Control of Ground Movement (C122-OVE-C2-RSP-C125-00001) Clause 3.2.5.1 and 3.2.5.2. A general location plan of the grout shafts at Tottenham Court Road (TCR) is provided in Figure 1.2.

All BFK excavation (tunnelling) works within the plan extent of the compensation grouting arrays from TCR Station Grout Shaft 5 (GS5) were completed by July 2014, although grout jacking and excavation for VEW, in the adjacent GS6 area continued until September 2014. An abridged version of this report was issued in October 2014, about 3 months after the end of tunnelling, to justify de-commissioning of the grout shaft: this report was accepted by CRL (C300-CCM-08906) and the grout shaft was subsequently de-commissioned.

This report aims to summarise the relevant construction, compensation grouting and monitoring information for GS5 at TCR Station and includes manual monitoring up to September 2015 when most of the monitoring within the GS5 area was de-scoped under C300-PMI-01858. Monitoring has continued for the HoSB and St. Patrick's Church and this report contains data up until 8th November 2016, after which all monitoring was terminated as confirmed during the I&M progress meeting on 1st December 2016.

A separate close out report is provided for the ATS prisms (C300-BFK-C4-RGN-CRT00_ST005-53008). The HLCs have been used for construction control during compensation grouting works and a separate "close-out" report is not required. Examples of data from the HLC in the GS5 area are included in Appendix B. Data from crack meters in St. Patrick's Church and 22 Soho Square are also presented in Appendix B. It is noted that some of these instruments were installed after the end of construction as instructed under C300-PMI-1692. Special monitoring of the House of St. Barnabas has been reported separately (C300-BFK-C4-RGN-CRT00_ST005_50294) and is not repeated herein.

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 remainder of the instrumentation within the GS5 area not included in other reports.

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.

Figure 1.1 Extracts from Works Information

KC21.3220 Compensation Grouting - General Requirements

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

KC21.3228 Reporting

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

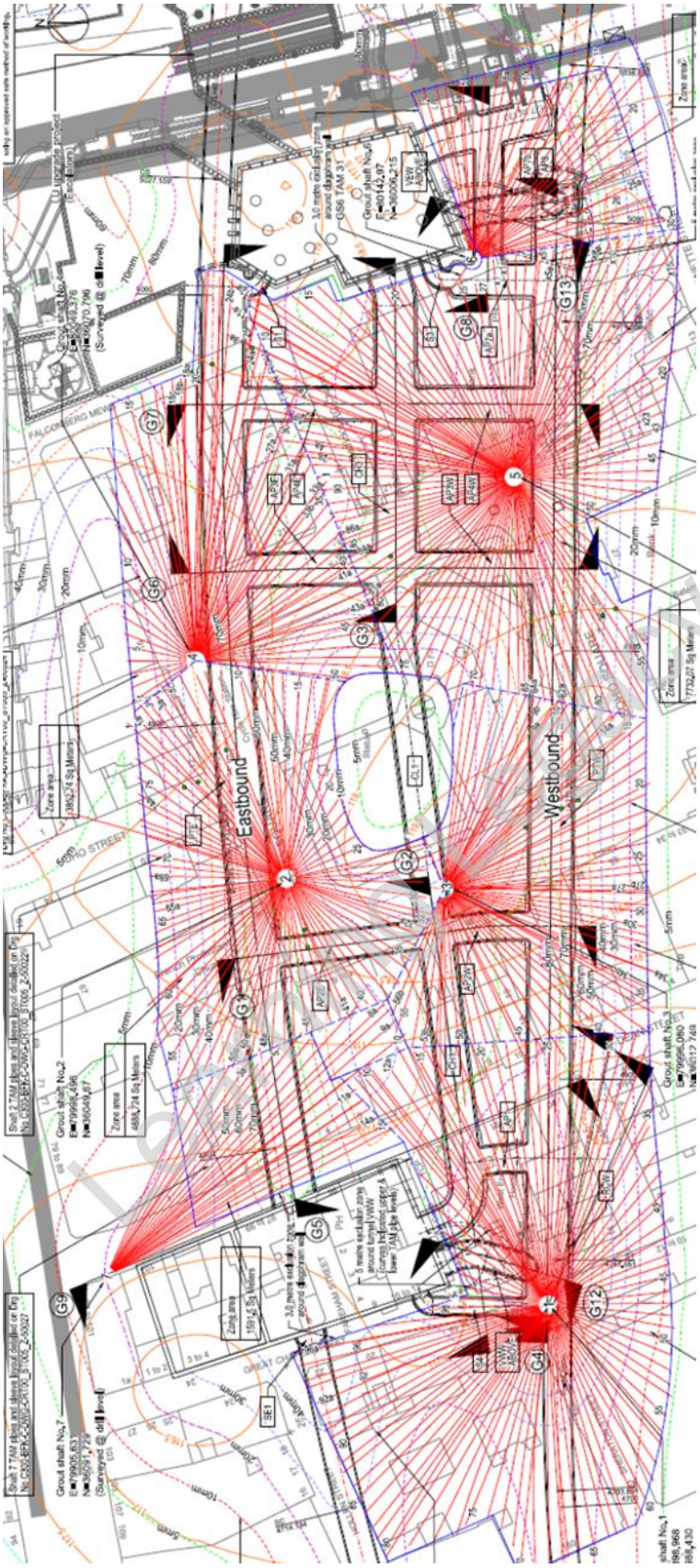
f) A final version of the report will be prepared to incorporate the justification for de-commissioning, as required by Compensation Grouting - general requirements, and as-built records of the reinstatement of grout shafts and arrays including H&S closeout reporting.

KX10.2113 Final Report

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

KX10.2114	Close-Out Reports Prior to the de-commissioning of any instrumentation, the *Contractor* shall produce a "close-out" report which summarises the data from the instrumentation the *Contractor* wishes to remove and relates it to the construction activities which produced any observed changes. The report shall demonstrate that the rate of change in the data has reached an acceptably small rate either in accordance with specified rates or, where no rate is specified, in relation to trigger values and an evaluation of any potential residual risks.

Figure 1.2 General Shafts Location Plan (reproduced from C300-BFK-C-DWG-CRT00_ST005_Z-50020)



2. CONSTRUCTION WORKS PROGRESS

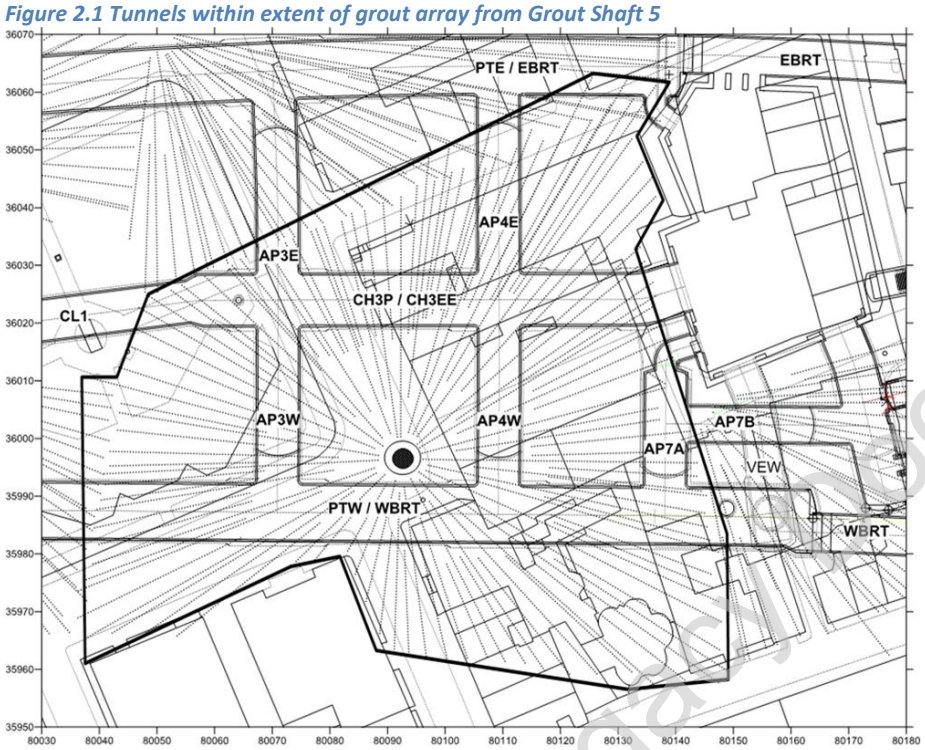
2.1. Tunnels

Table 2.1 and Figure 2.1 show the tunnel construction works undertaken within the footprint of the compensation grouting arrays installed from GS5 at TCR Station. Tunnel excavation commenced with WBRT in June 2013 and was completed with the junction between AP7A and PTW in June 2014 and the final section of PTE in July 2014. The VEW is located just to the east of the GS5 area but was constructed after the other tunnels and has been included to define the date of the completion of excavation (the end of Period E). 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, C, D & E) as shown in Table 2.1. The main construction activities in each period are summarised in Table 2.2.

Table 2.1 Progress of C300/C410 & TCRSU works at TCR GS5 area.

PERIOD	TUNNEL	ABB.	START DATE	END DATE
A	Shaft sink		31/07/2012	22/08/2012
	TaM drilling		02/10/2012	26/03/2013
	TCRSU Goslett Yard Box	TCRSU_GYB	pre-31/07/2012	02/06/2013
B	Westbound Running Tunnel	WBRT	02/06/2013	16/06/2013
	Central Link Tunnel	CL1	10/06/2013	21/06/2013
	Lower Concourse 3 Pilot Tunnel	CH3P	22/06/2013	08/07/2013
	Lower Concourse 3 Enlargement	CH3E	09/07/2013	17/08/2013
	Eastbound Running Tunnel	EBRT	10/08/2013	09/09/2013
	TCRSU Goslett Yard Box	TCRSU_GYB	02/06/2013	12/08/2013
C	Access Passage 4 West	AP4W	08/09/2013	23/09/2013
	Access Passage 3 West	AP3W	15/09/2013	26/09/2013
	Access Passage 4 East	AP4E	24/09/2013	07/10/2013
	Access Passage 3 East	AP3E	28/09/2013	07/10/2013
	Access Passage 7 A	AP7A	22/10/2013	01/11/2013
	Access Passage 7 B	AP7B	08/11/2013	14/11/2013
D	Platform Tunnel Westbound	PTW	20/01/2014	15/04/2014
	Access Passage 4 West junction	AP4W	03/04/2014	07/04/2014
	Access Passage 3 West junction	AP3W	28/03/2014	31/03/2014
	Access Passage 7 A junction	AP7A	10/06/2014	14/06/2014
E	Platform Tunnel Eastbound	PTE	10/07/2014	25/07/2014
	Ventilation Tunnel East Westbound pre grouting	VEW pre-grouting	16/07/2014	16/08/2014
	Ventilation Tunnel East Westbound excavation	VEW excavation	16/08/2014	07/09/2014

Figure 2.1 Tunnels within extent of grout array from Grout Shaft 5



2.2. Other construction works

Works by BFK prior to the commencement of tunnelling included:

- Sinking of Grout Shaft 5
- Drilling for installation of TaMs
- Pre-treatment grouting

Works by Others prior to the start of tunnelling included:

- TCRSU (Tottenham Court Road Station Upgrade) works (see Appendix C)

Works by Others during tunnelling comprised:

- TCRSU works (Goslett Yard Box level -3 to -5)

2.3. Compensation Grouting

The volume of grout injected from TCR GS5 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 30m^3 injected prior to tunnelling, concurrent grouting over 350m^3 and grout jacking 50m^3. Concurrent grouting was undertaken with all tunnels except the WBRT, CL1 and the various junctions between Access Passages (AP). A VE proposal (C300-CCM-01519) was implemented to avoid any delays to the running tunnel drive which allowed grouting to be undertaken pre- and post-tunnelling – the volume of grout associated with this is included under grout jacking. The AP junctions are short lengths of tunnel and the extent of the exclusion zones over the tunnel face, as defined in the Specification for Control of Ground Movements (SCoGM), rendered concurrent

grouting impractical. CL1 is a temporary tunnel below the centre of Soho Square and CRL deemed that concurrent compensation grouting was not mandatory (C300-PMI-00434).

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 TCR GS5 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.

Table 2.2 Construction Periods for works in TCR GS5 area.

PERIOD	START DATE	END DATE	MAIN WORKS
A	01/04/2012	02/06/2013	Shaft sink, TaM drilling, Pre-treatment, TCRSU_GYB
B	02/06/2013	08/09/2013	WBRT, CL1, CH3P, CH3E, EBRT, TCRSU_GYB
C	08/09/2013	20/01/2014	AP4W, AP3W, AP4E, AP3E, AP7A, AP7B
D	20/01/2014	10/07/2014	PTW, AP3W, AP4W & AP7a junctions
E	10/07/2014	07/09/2014	PTE (VEW)
F	07/09/2014	25/09/2015	General post construction monitoring
G	25/09/2015	08/11/2016	HoSB & St. Patrick's Church monitoring

Figure 2.2 Volume of grout injected from TCR GS5 by grouting type.

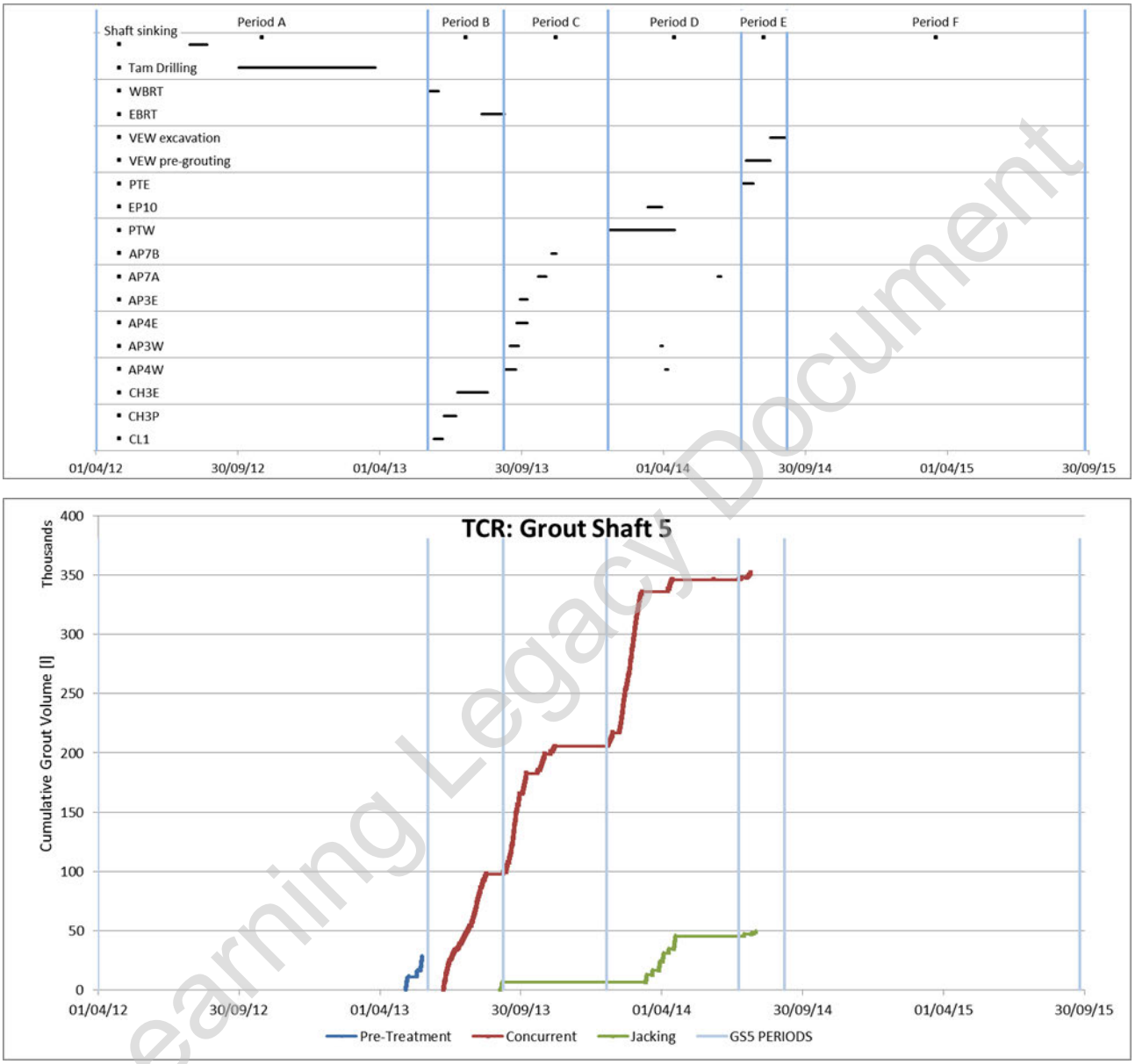


Figure 2.3 Distribution of grout injected from TCR GS5: Pretreatment grouting. Grout Intensity (mm).

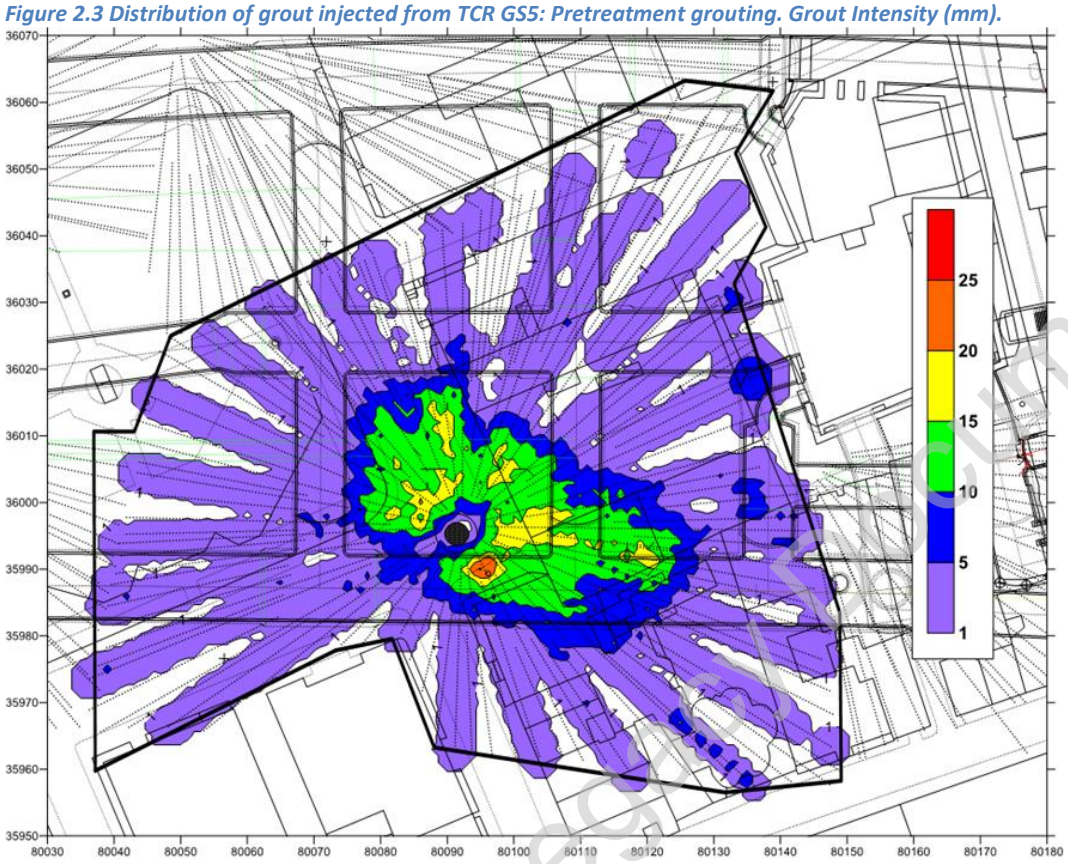


Figure 2.4 Distribution of grout injected from TCR GS5: Concurrent grouting. Grout Intensity (mm).

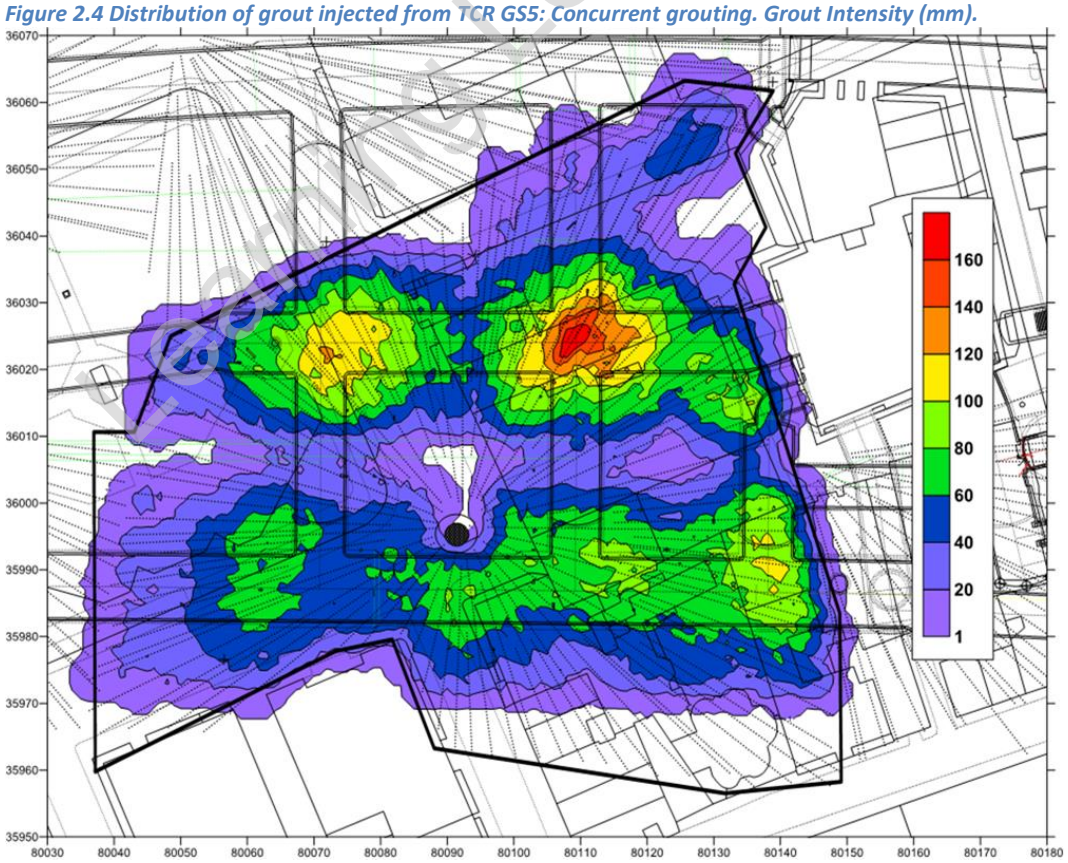


Figure 2.5 Distribution of grout injected from TCR GS5: Jack grouting. Grout Intensity (mm).

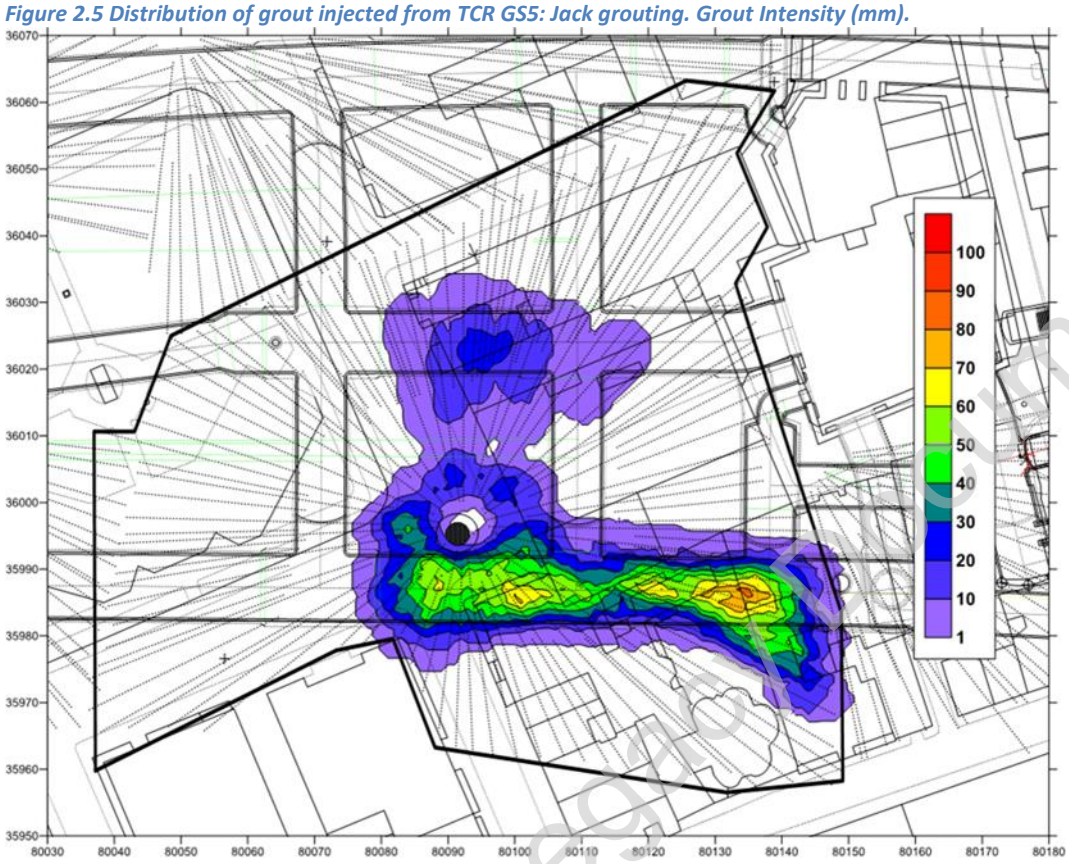
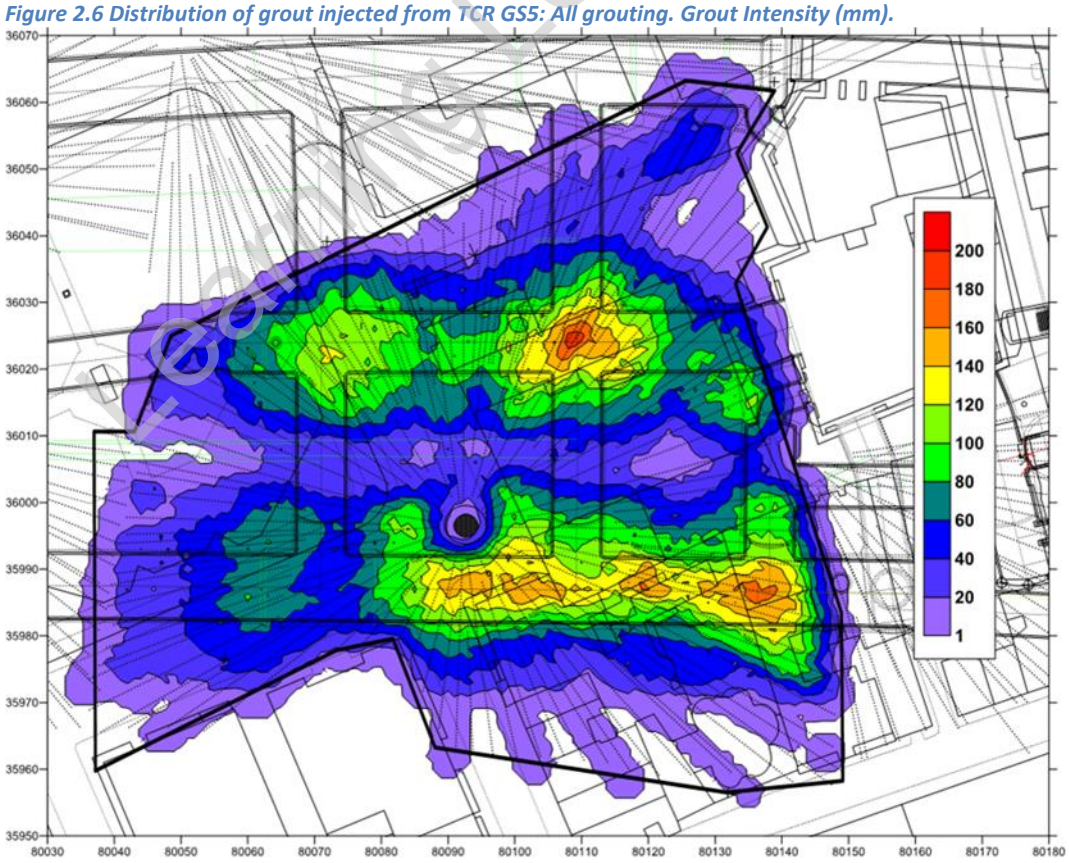


Figure 2.6 Distribution of grout injected from TCR GS5: All grouting. Grout Intensity (mm).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. Settlement Overview

Contours of total predicted short term greenfield settlement (supplied by C122) calculated using simple empirical methods are shown in Figure 3.1.1. It is noted that the effect of compensation grouting has not been considered. The measured settlement at the end of construction (Period E) in September 2014, including consolidation settlement during the period of construction is shown in Figure 3.1.2.

The following points are noted:

- Settlements were generally significantly less than 50% of the predicted values, notwithstanding that the observed movements include a significant proportion of consolidation settlement over the 2½ year construction period.
- The most obvious differences between the predictions and the observations are:
    - the maximum observed settlement contour in Figure 3.1.2 is 30mm within the GS5 TaM array compared to the maximum predicted greenfield settlement of over 90mm in Figure 3.1.1;
    - the spacing of the contours implies that actual slopes were much less than those associated with the volume loss prediction;
    - the extent of the zone of settlement is similar to that predicted with any differences in the locations of the 1mm contour attributable to the tolerances on the survey data;
    - there is no major impact on the contours from the piled building at 26 Soho Square.

Figure 3.1.1 Predicted greenfield settlement contour (supplied by C122)

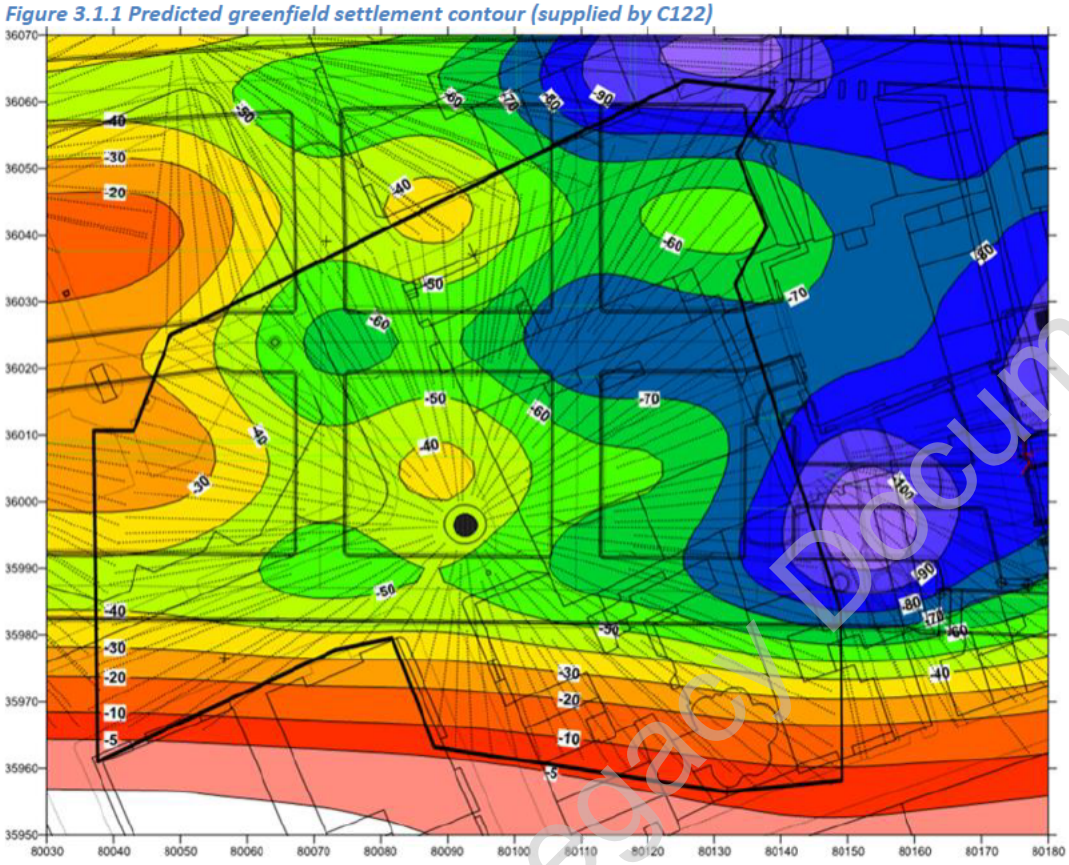
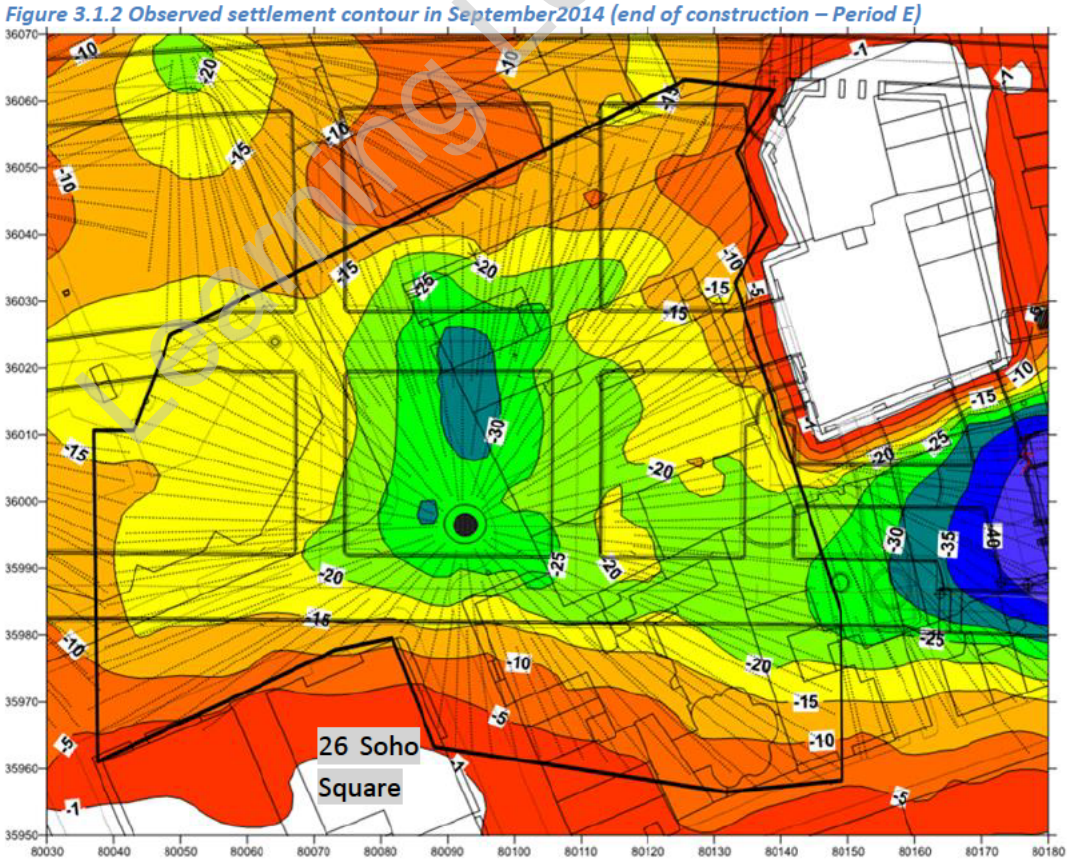


Figure 3.1.2 Observed settlement contour in September2014 (end of construction – Period E)



In order to compare the predicted and actual movements at various stages of construction, the overall monitoring period from April 2012 to the cessation of general monitoring (under C300-PMI-01858) in September 2015 has been divided into a number of periods, based largely on tunnel excavation progress. The construction activities completed in each period are summarised in Table 2.2. Note that excavation for the TCRSU Goslett Yard Box was ongoing throughout Period A and was completed during Period B.

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

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

3.2. Period A: 01/04/12 – 02/06/13 Shaft sinking, TaM drilling, Pre-treatment, TCRSU_GYB

Period A includes all of the preparatory work prior to the commencement of tunnelling. BFK works comprised shaft sinking and the drilling of TaMs from TCR GS5. Significant movements were generated prior to and during BFK works by the adjoining London Underground TCR Station Upgrade project (TCRSU). Adjustments have been applied to the BFK monitoring based on the contour shown in Figure 3.2.1. The TCRSU works below and to the east of Charing Cross Road produced substantial movements but the impact within the GS5 area was limited to about 5mm settlement. The contour is based on monitoring data from TCRSU provided by CRL and on the results of joint surveys undertaken by BFK and the TCRSU contractor in April and May 2013. The contour represents the best estimate of movements at 24/04/13 at the completion of BFK shaft sinking and TaM drilling.

The observed settlements at the end of Period A (adjusted to include movements arising from TCRSU works prior to the start of BFK monitoring) are shown on Figure 3.2.2. In general, minor settlement is indicated with more than 5mm in a local area adjacent to the shaft.

The distribution of grout injected during pre-treatment is illustrated on Figure 3.2.3: the highest intensity is around the shaft with up to 20mm thickness. The intensity was varied to reflect the observed settlements.

Figure 3.2.1 Contours of settlement from TCRSU works (at 24/04/13)

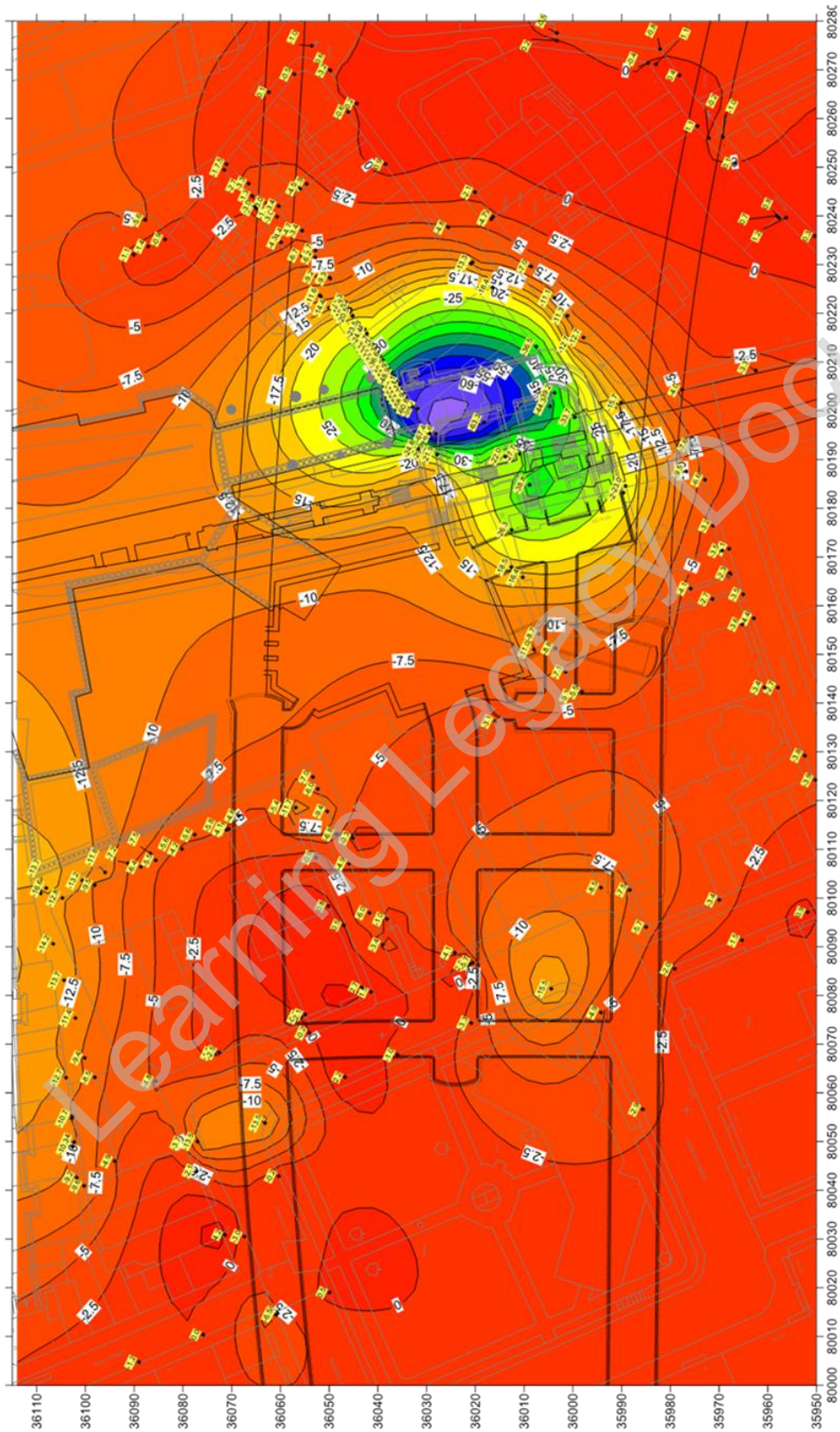


Figure 3.2.2 Period A: Total measured settlement

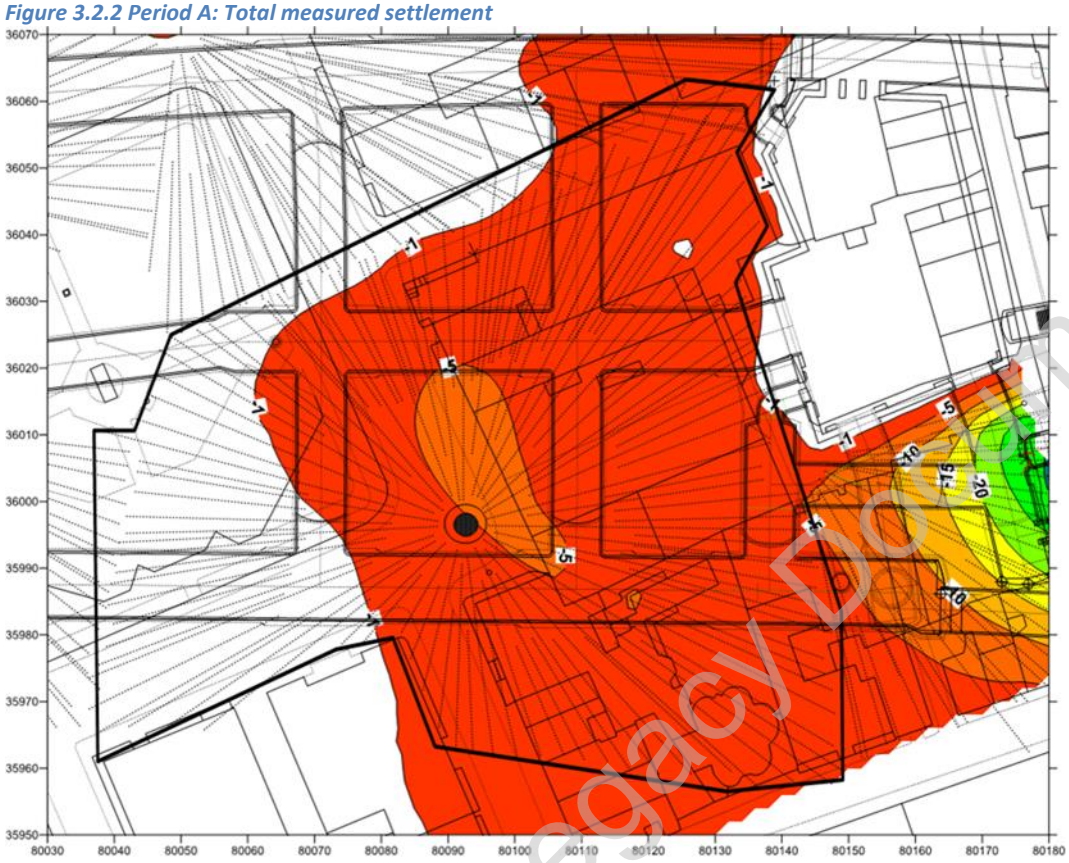
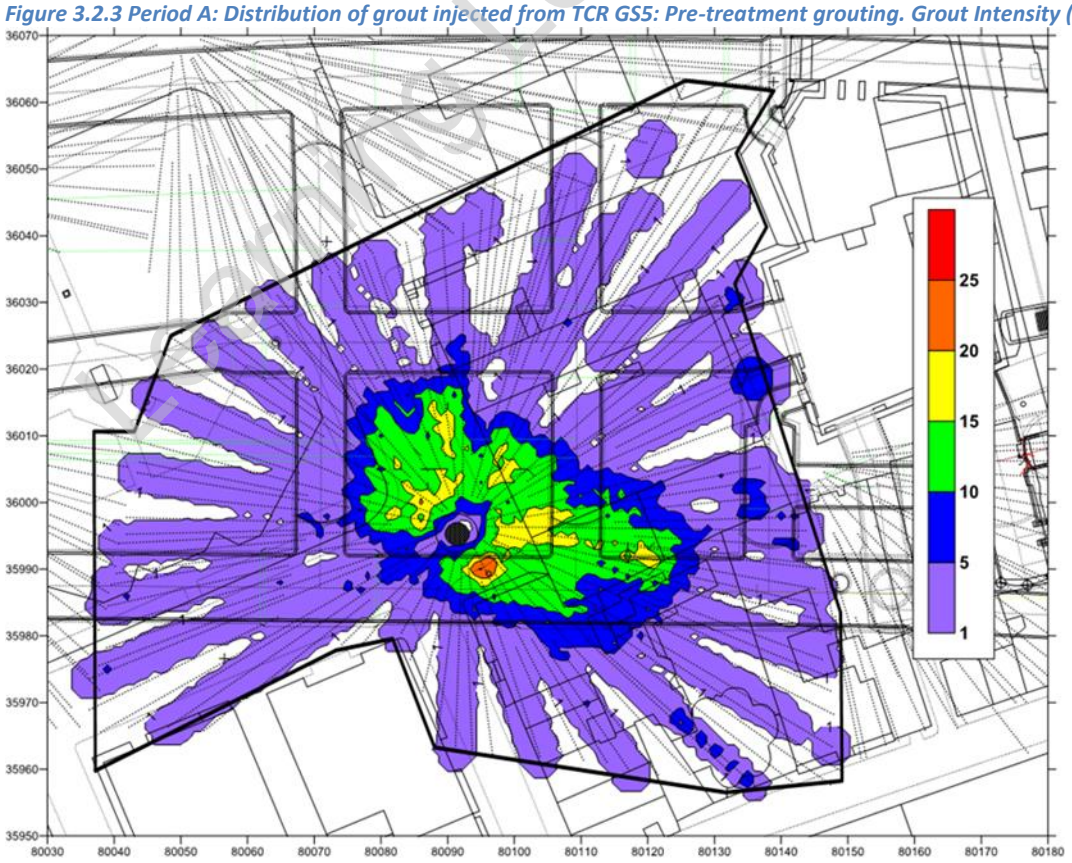
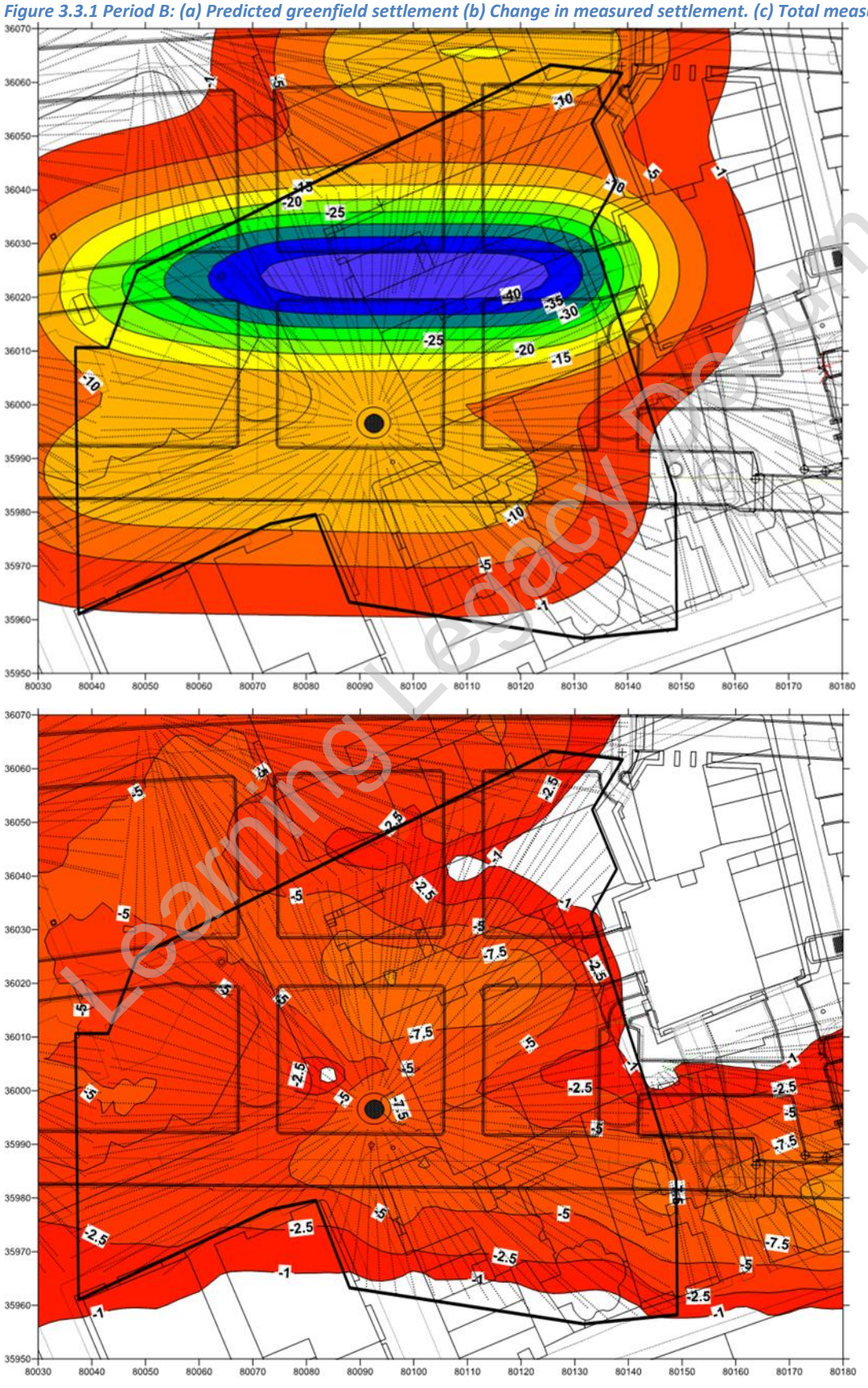


Figure 3.2.3 Period A: Distribution of grout injected from TCR GS5: Pre-treatment grouting. Grout Intensity (mm).



3.3. Period B: 02/06/13 – 08/09/13 WBRT, CH3P/E, EBRT, TCRSU_GYB, Concurrent, Jacking

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



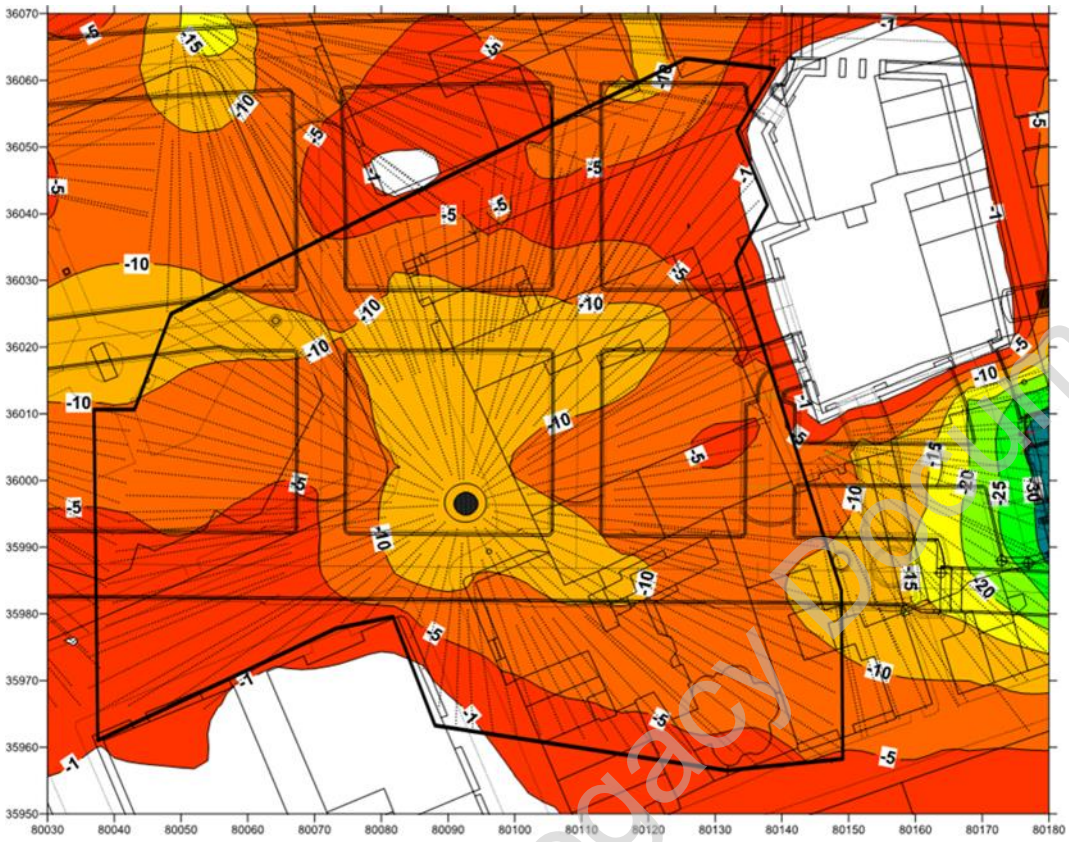


Figure 3.3.2 Period B: Distribution of grout injected from TCR GS5: Concurrent Grouting. Grout Intensity (mm).

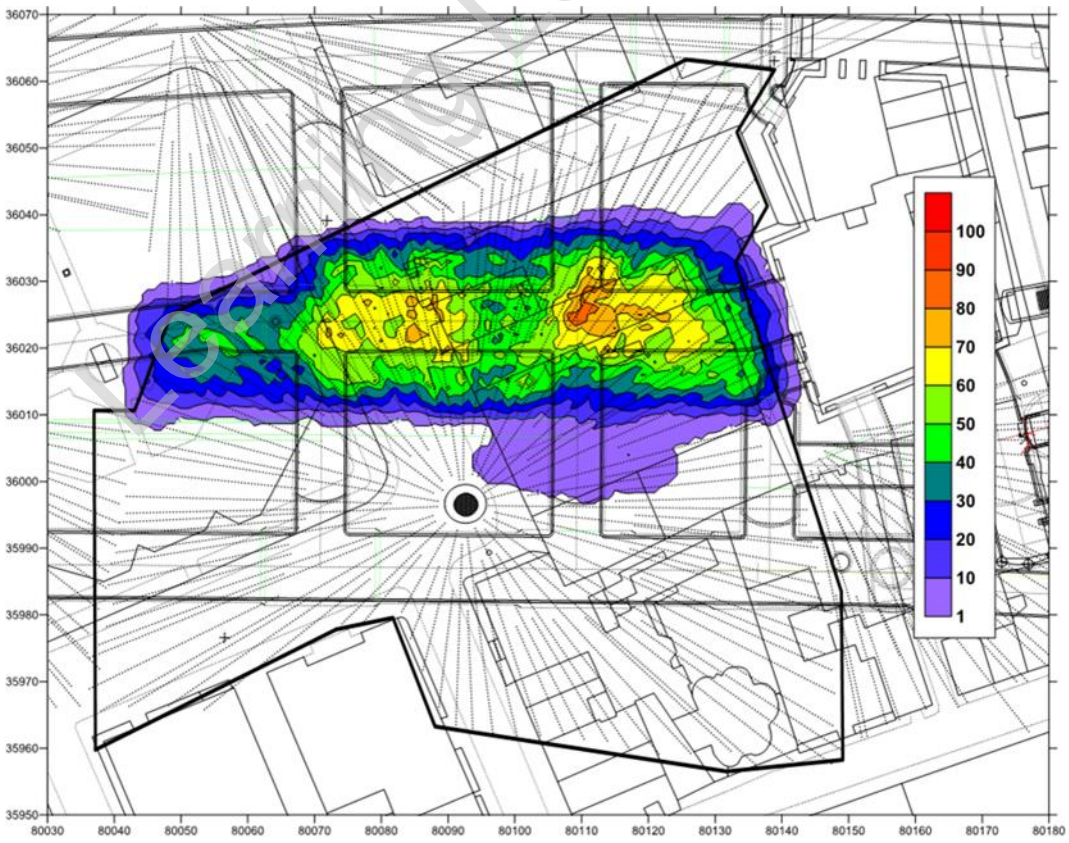


Figure 3.3.3 Period B: Distribution of grout injected from TCR GS5: Grout jacking. Grout Intensity (mm).

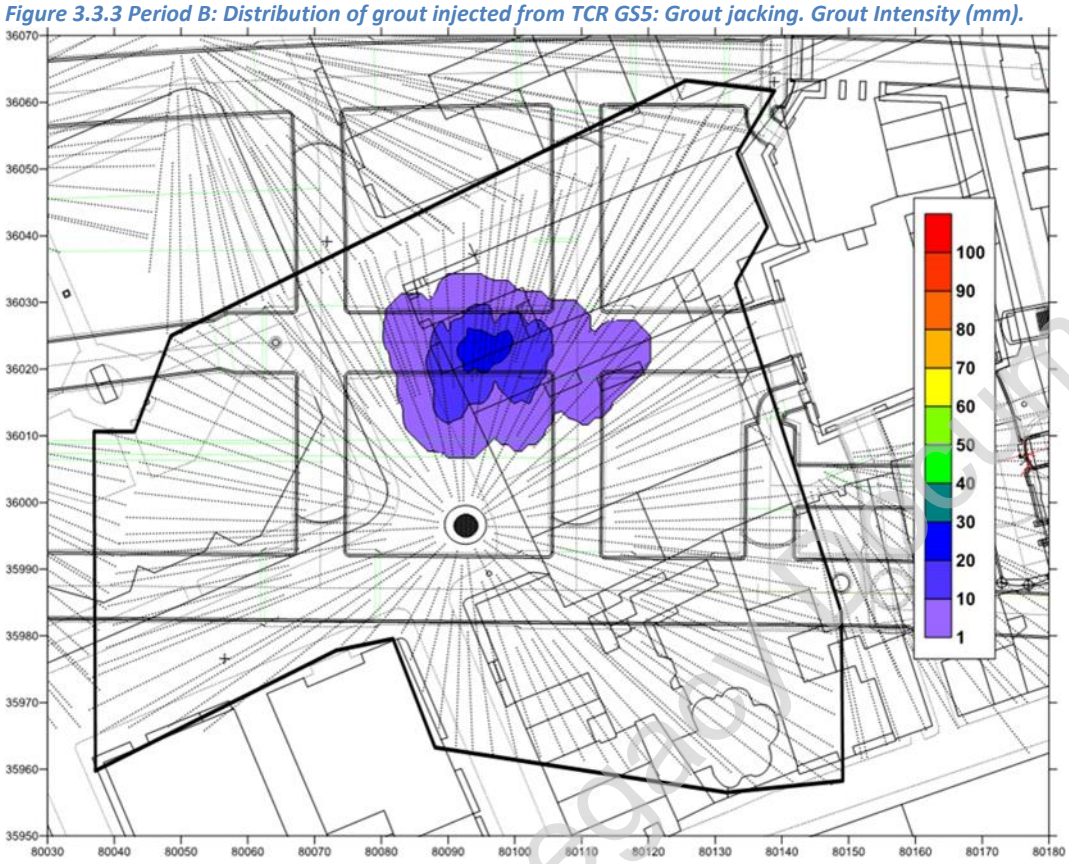
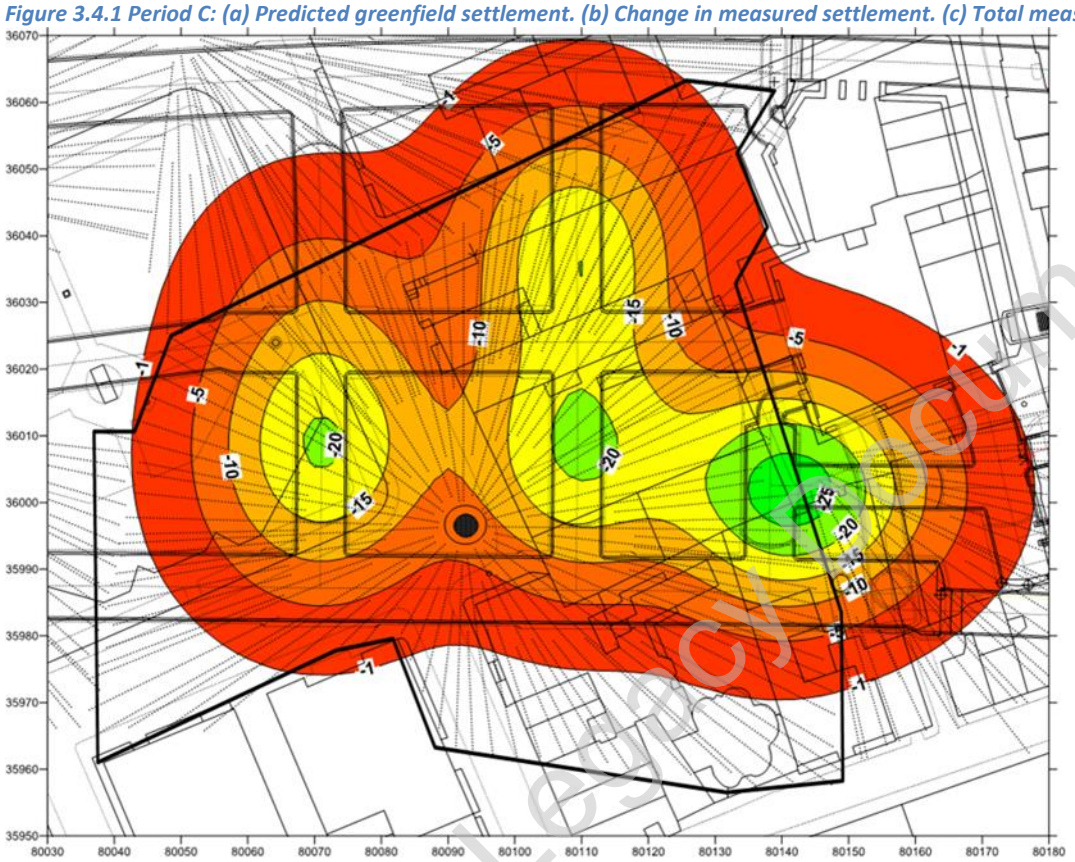


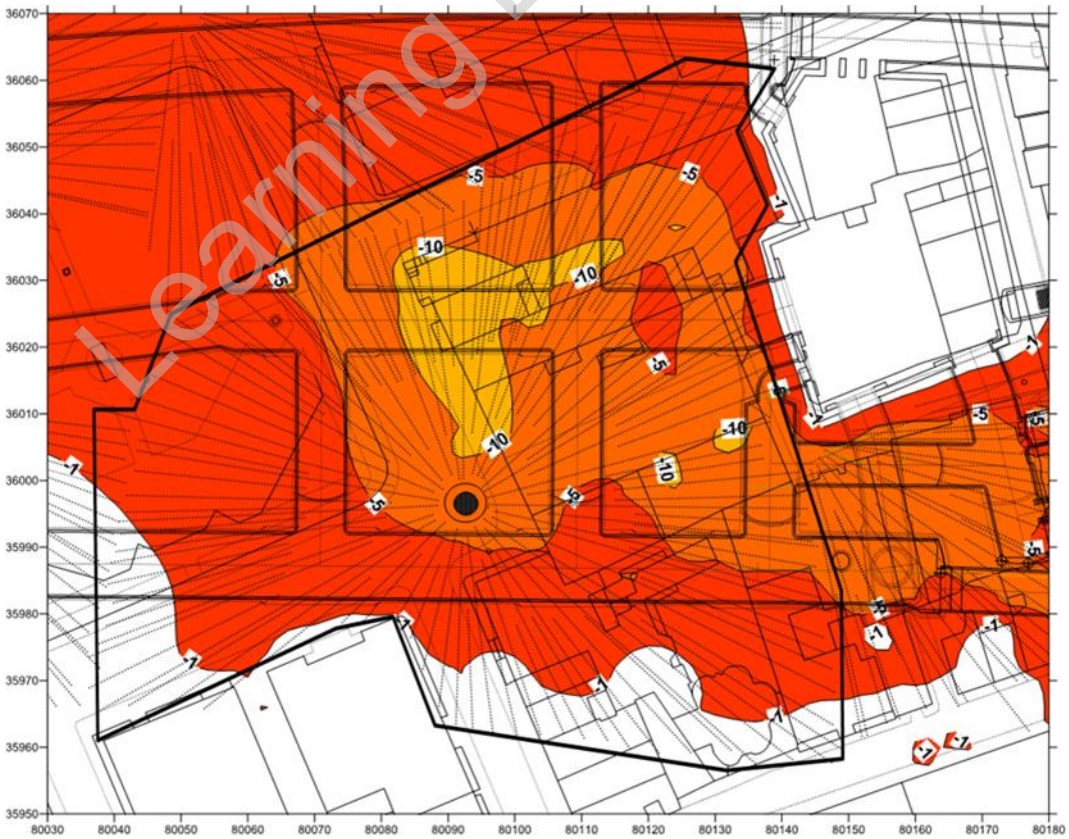
Figure 3.3.1(a) shows the calculated volume loss greenfield settlements for CH3 (pilot and enlargement) and the relevant sections of the WBRT and EBRT. The maximum calculated greenfield settlement over CH3 is over 40mm, and over the running tunnels 10 to 15mm. Figure 3.3.1(b) shows that the greatest observed settlement was 10mm above CH3 and 7.5mm over the WBRT. A contour of the intensity of concurrent grouting injected from GS5 for CH3 is shown in Figure 3.3.2. Peak intensity over the centerline varies between 50mm and 100mm as a result of successive modification of grout volumes based on the observed response of the buildings above. A grout jacking episode with a maximum intensity of ~20mm was also undertaken in the area of maximum settlement (Figure 3.3.3).

The total settlement contour in Figure 3.3.1(c) has a significant area with movement greater than 10mm but nowhere is the settlement greater than 15mm within the GS5 TaM array.

3.4. Period C: 08/09/13 – 20/01/14 AP4W, AP3W, AP4E, AP3E, AP7A, AP7B, Concurrent Grouting

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





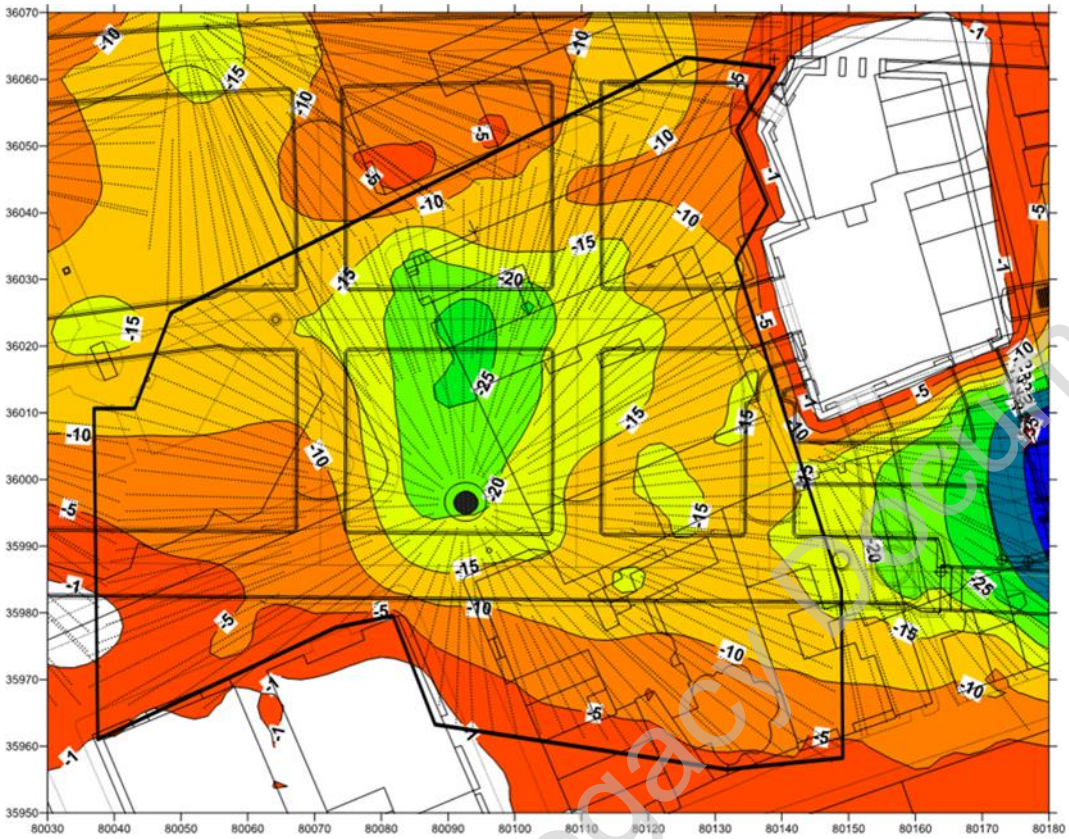


Figure 3.4.2 Period C: Distribution of grout injected from TCR GS5: Concurrent grouting. Grout Intensity (mm).

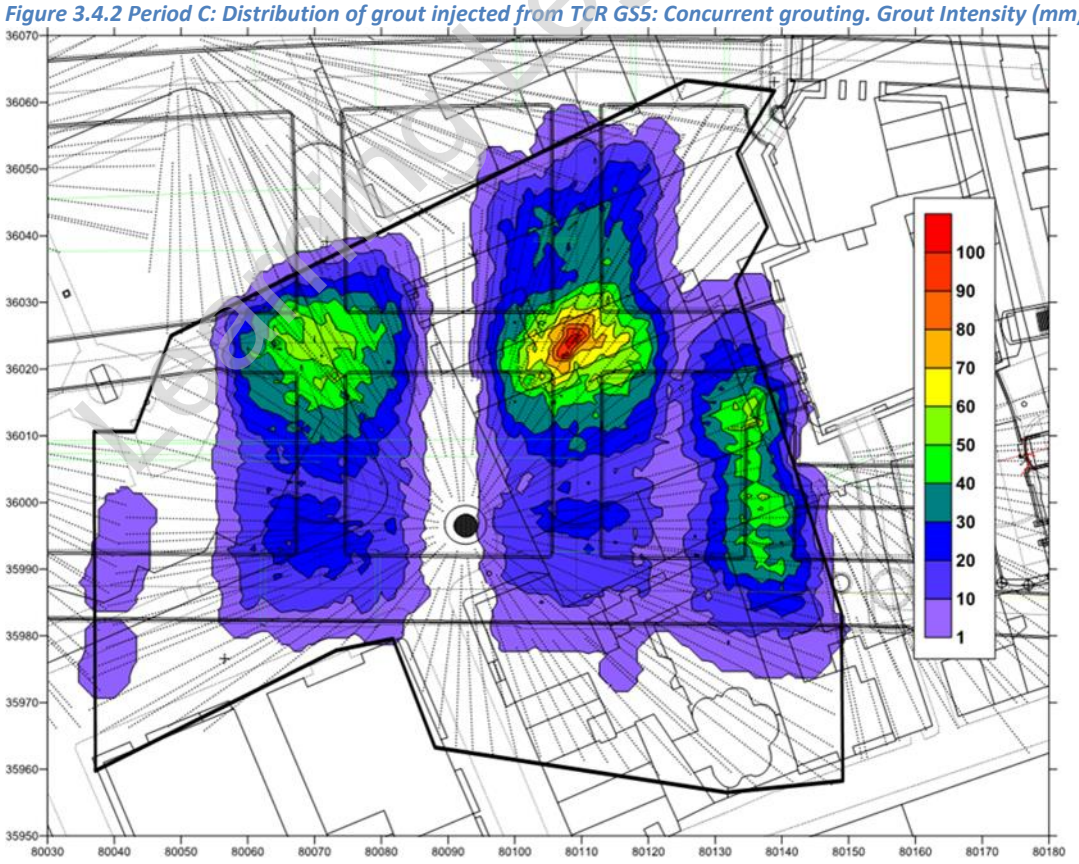


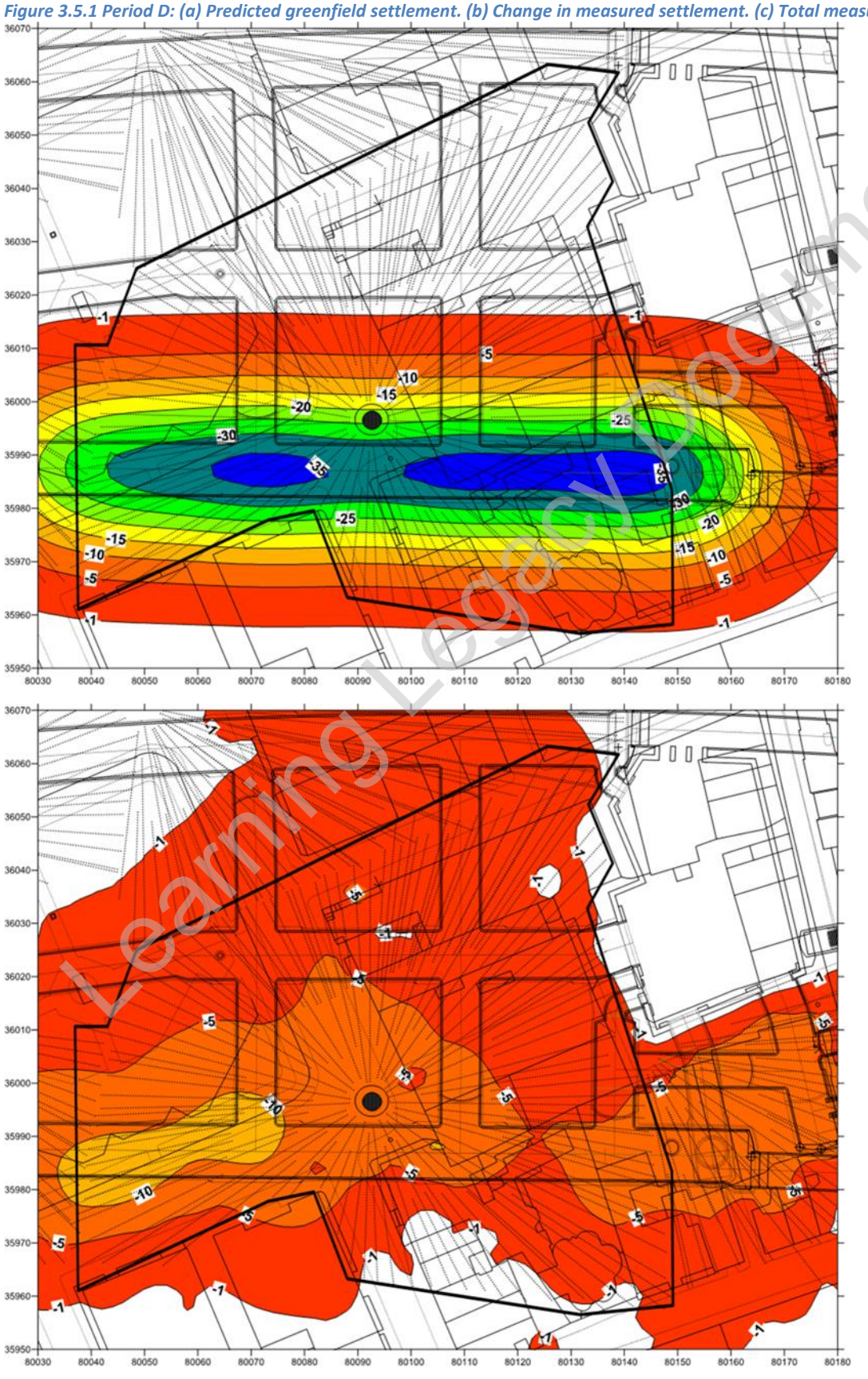
Figure 3.4.1(a) shows that between 20 and 25mm volume loss settlement was anticipated for the AP tunnels (AP3W, AP4W, AP3E, AP4E, AP7A and AP7B). Figure 3.4.1(b) shows the recorded settlement which has a maximum contour of 10mm which is greater than the predicted value in this location. Conversely, the location of the 5mm settlement contour is similar to that in the prediction.

The maximum movement within the TCR GS5 area at the end of Period C had increased to just over 25mm (Figure 3.4.1(c)) locally on the east façade of Soho Square (St. Patrick's Church). Over the majority of the area, settlement was between 10 and 20mm.

The distribution of the concurrent grouting undertaken in Period C is shown in Figure 3.4.2 with much greater volumes injected over CH3 where the injections for the east and west APs overlap.

3.5. Period D: 20/01/14 – 08/06/14 PTW, AP3W, AP4W, AP7A junctions, Concurrent & Grout Jacking

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



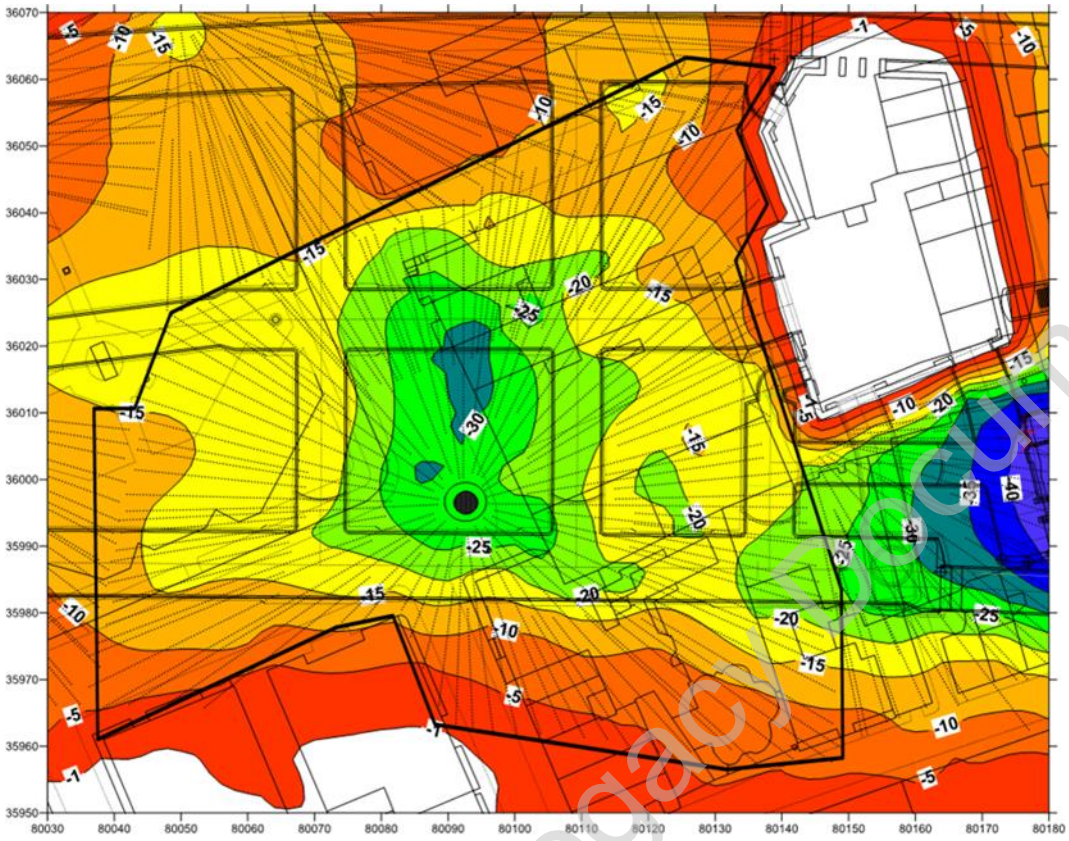


Figure 3.5.2 Period D: Distribution of grout injected from TCR GS5: Concurrent grouting. Grout Intensity (mm).

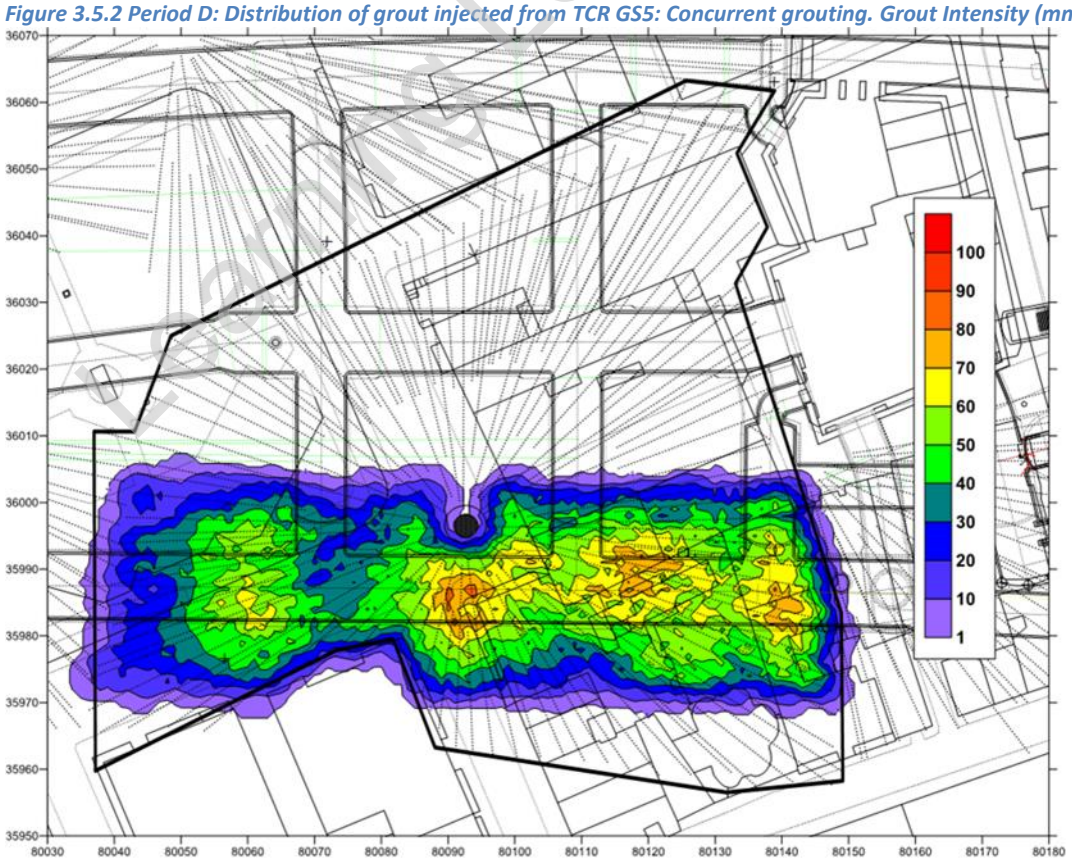
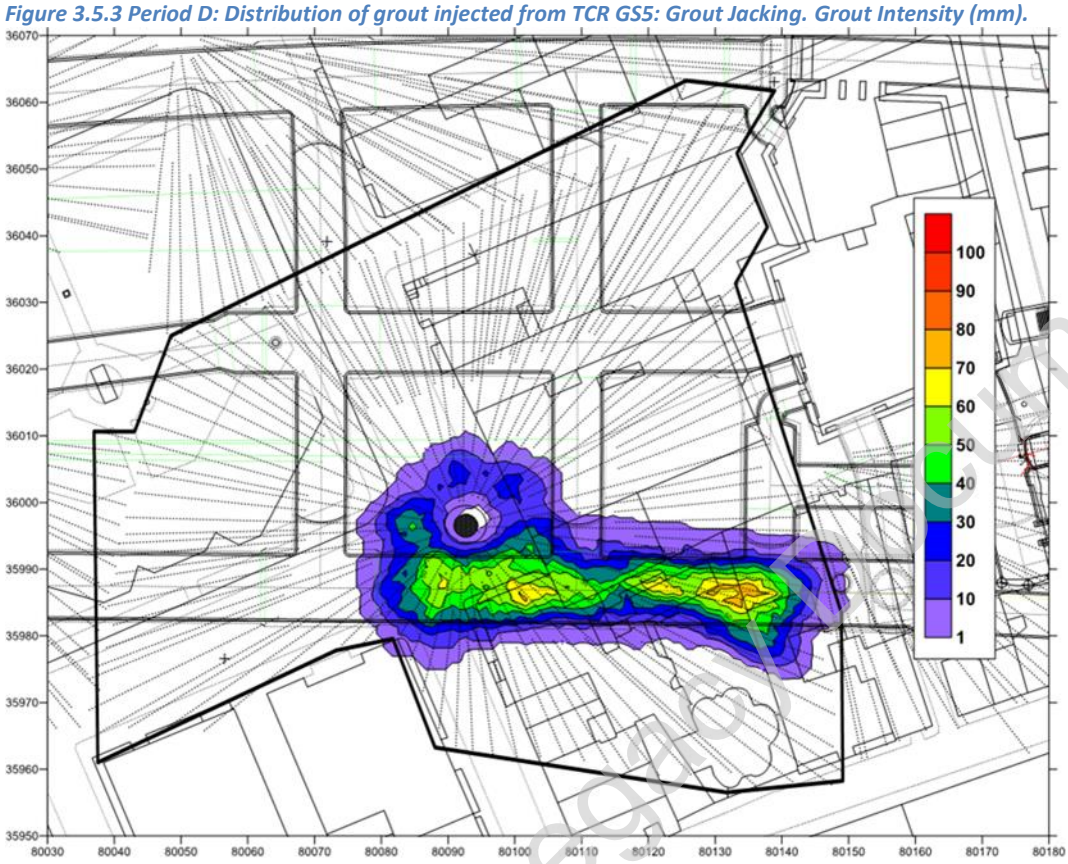


Figure 3.5.3 Period D: Distribution of grout injected from TCR GS5: Grout Jacking. Grout Intensity (mm).

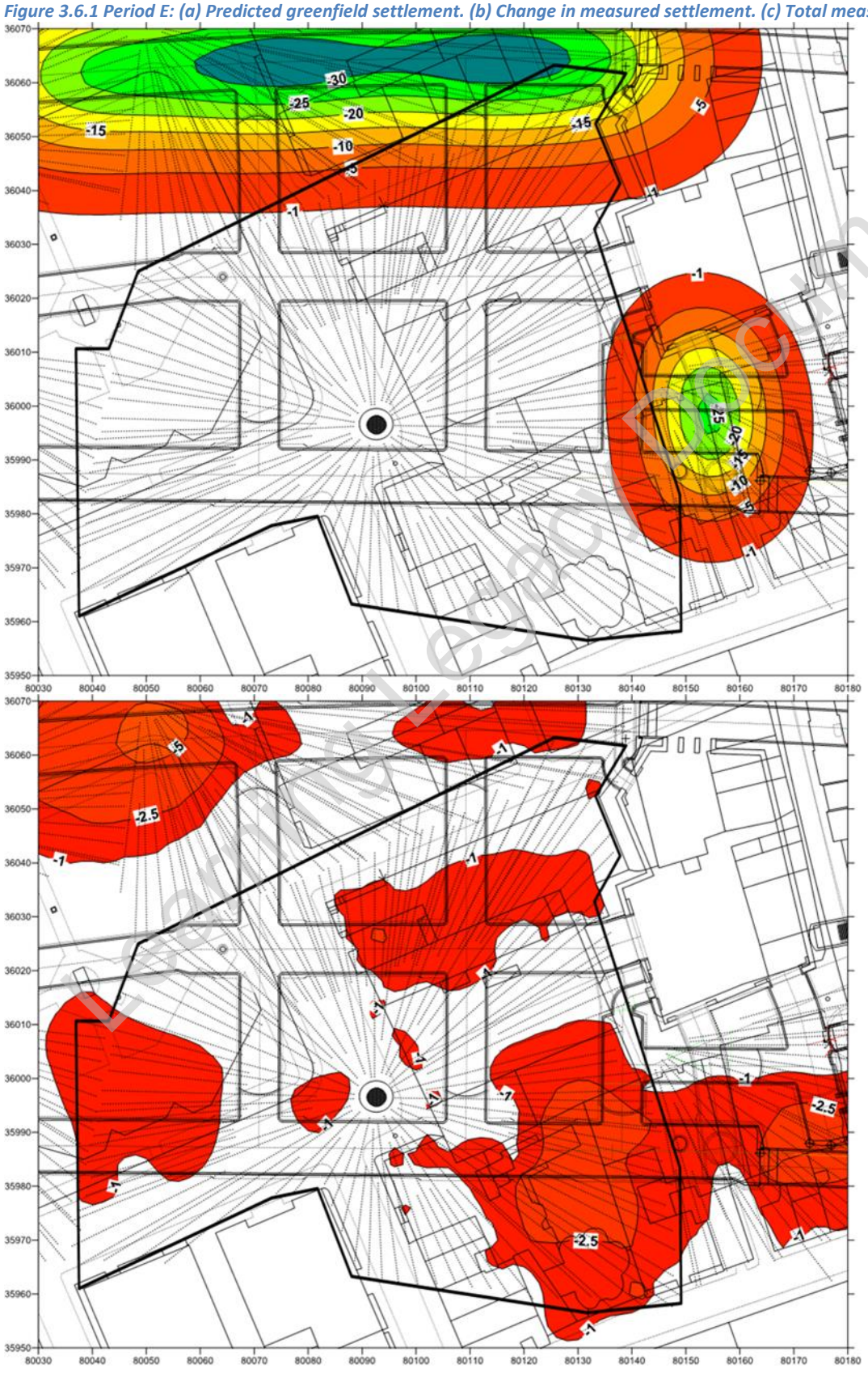


The volume loss settlement from construction of PTW and junctions with the adjacent AP tunnels is shown in Figure 3.5.1(a) and indicates a maximum combined effect of greater than 35mm within the area of TCR GS5. The maximum observed increase in settlement in Period D was 10mm locally on the inner kerb line on the south of Soho Square (Figure 3.5.1(b)): volume loss settlements were controlled within the remainder of the area to less than 5mm by a combination of concurrent grouting (Figure 3.5.2) and grout jacking (Figure 3.5.3).

The maximum total settlement increased to just over 30mm with a similar pattern to that at the end of Period C as shown in Figure 3.5.1(c).

3.6. Period E: 08/06/14 – 25/07/14 PTE, (VEW), Concurrent & Grout Jacking

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



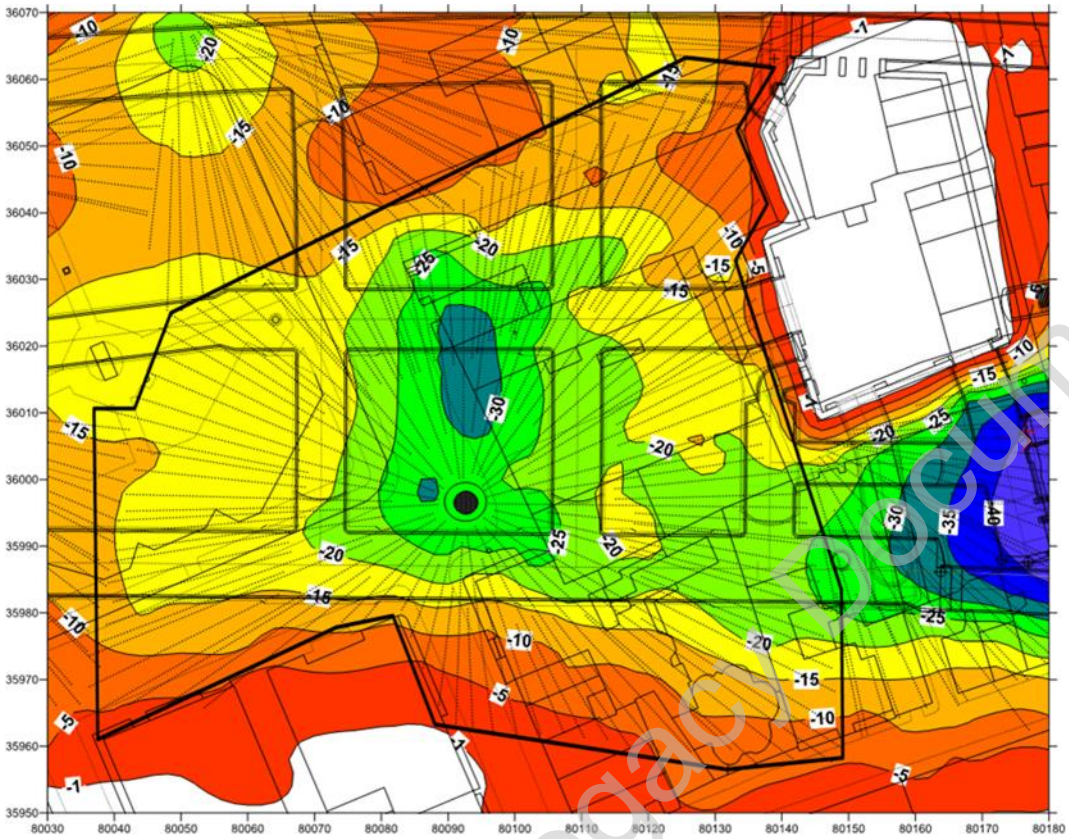


Figure 3.6.2 Period E: Distribution of grout injected from TCR GS5: Concurrent grouting. Grout Intensity (mm)

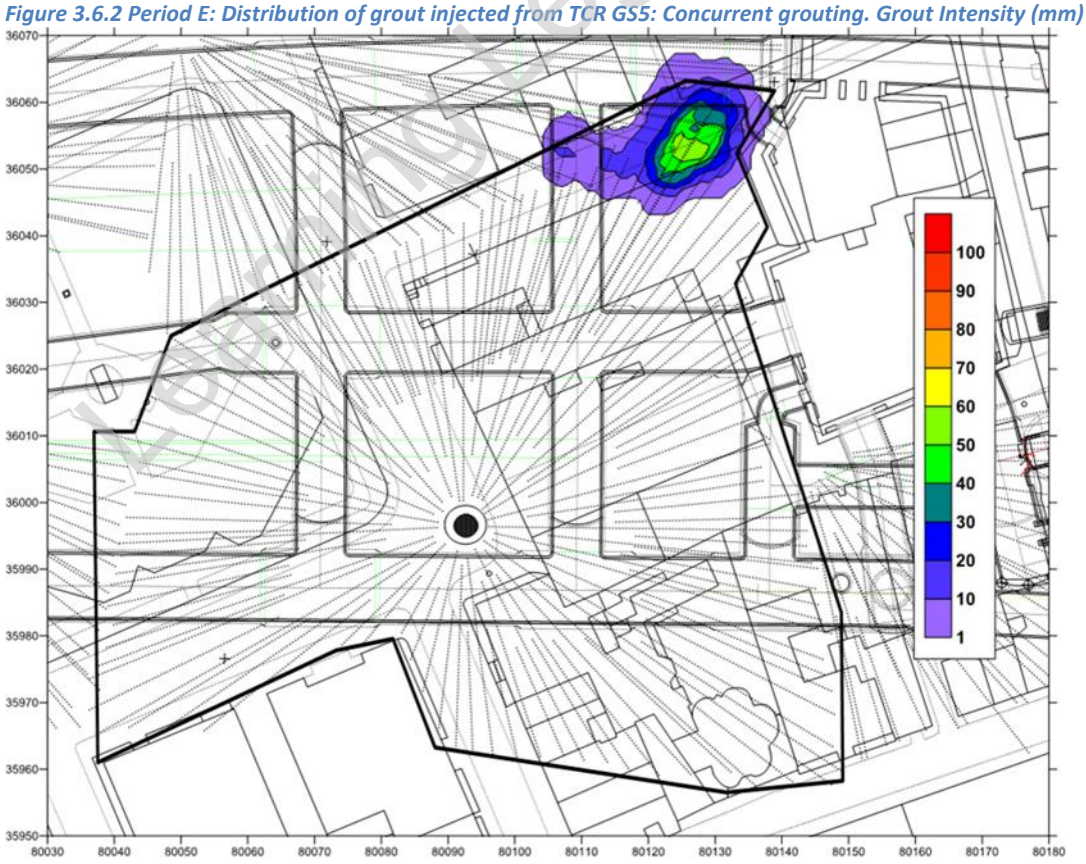
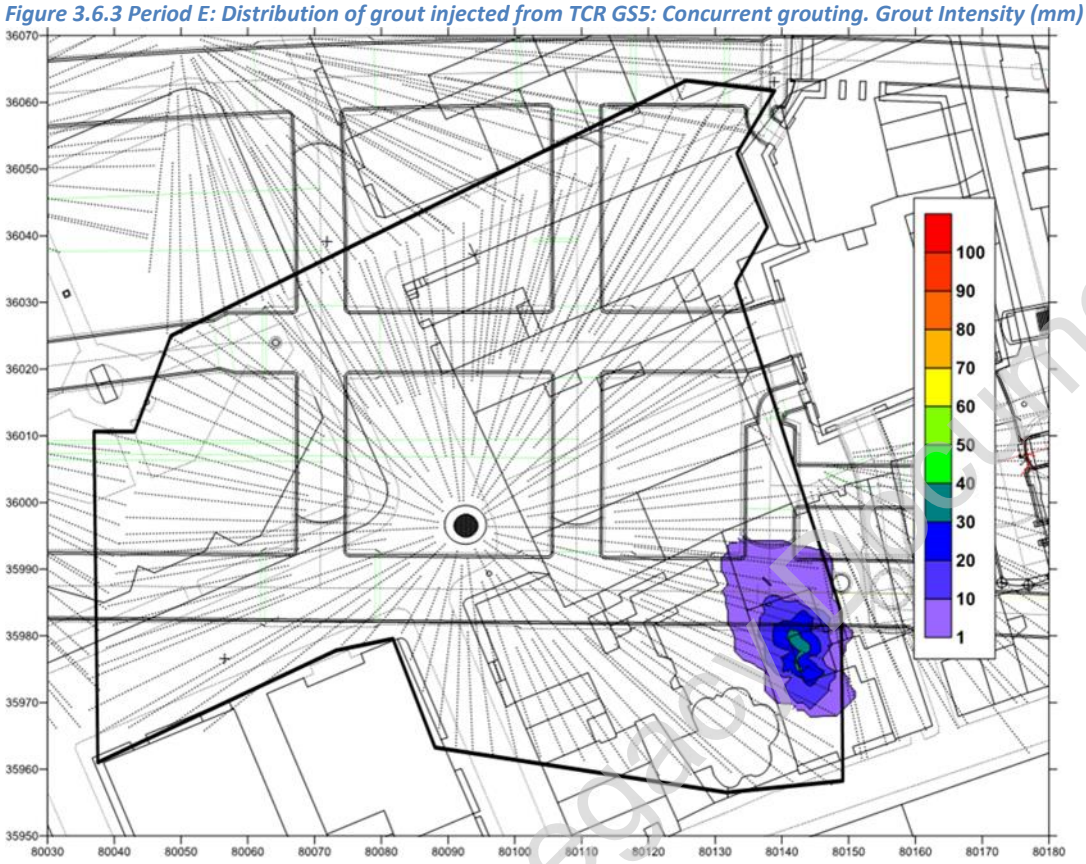


Figure 3.6.3 Period E: Distribution of grout injected from TCR GS5: Concurrent grouting. Grout Intensity (mm)

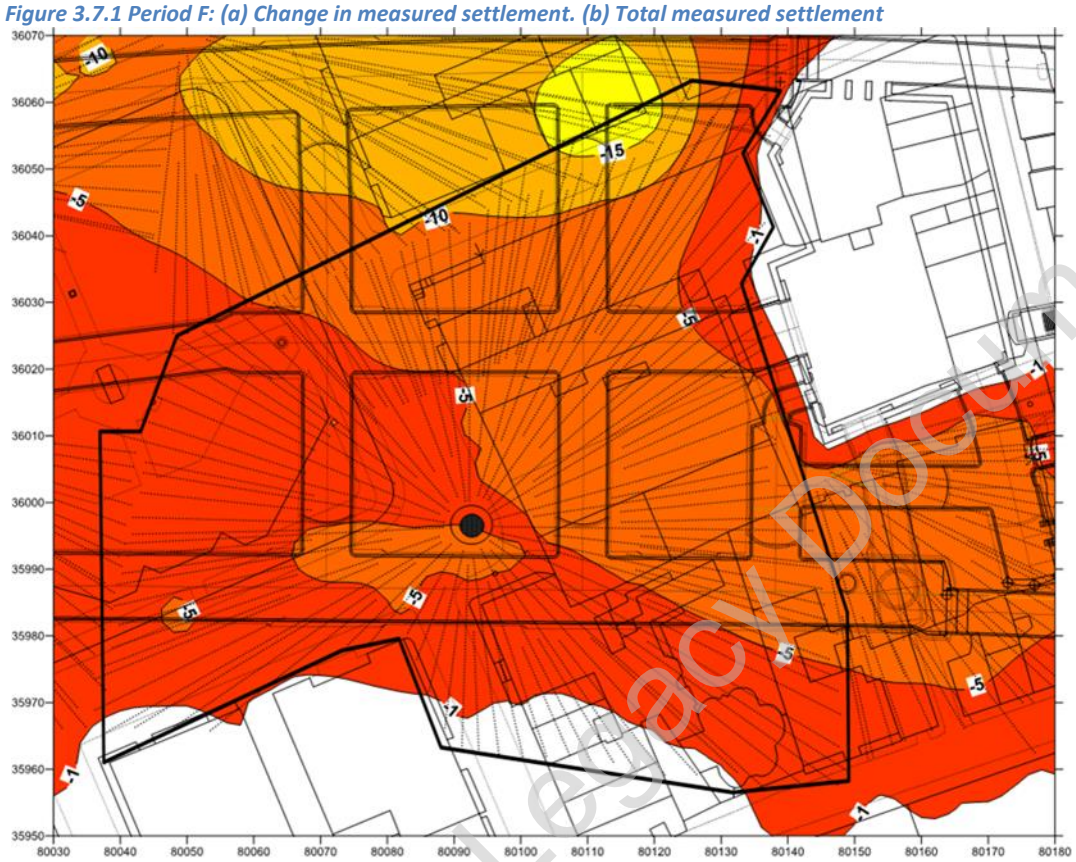


The volume loss greenfield settlement contours associated with PTE and VEW are shown on Figure 3.6.1(a). Only a small section of PTE is within the GS5 area and VEW is wholly within the plan extent of GS6 arrays. Nevertheless, volume loss settlement is shown within the GS5 area with up to 30mm at the northern boundary associated with PTE and 10mm at the eastern boundary associated with VEW. Figure 3.6.1(b) shows that settlements were controlled to less than 5mm by a combination of concurrent grouting and grout jacking. Figures 3.6.2 and 3.6.3 show that only small volumes were injected from GS5 with the majority from GS4 for PTE and GS6 for VEW (see C300-BFK-C4-RGN-CRT00_ST005-51228 and C300-BFK-C4-RGN-CRT00_ST005-51230).

The changes in settlement in Period E were minor and hence the maximum total settlement and the distribution of settlement remain similar to that at the end of Period D (see Figure 3.6.1(c)).

3.7. Period F: 25/07/14 – 25/09/15 General Post Construction Monitoring

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



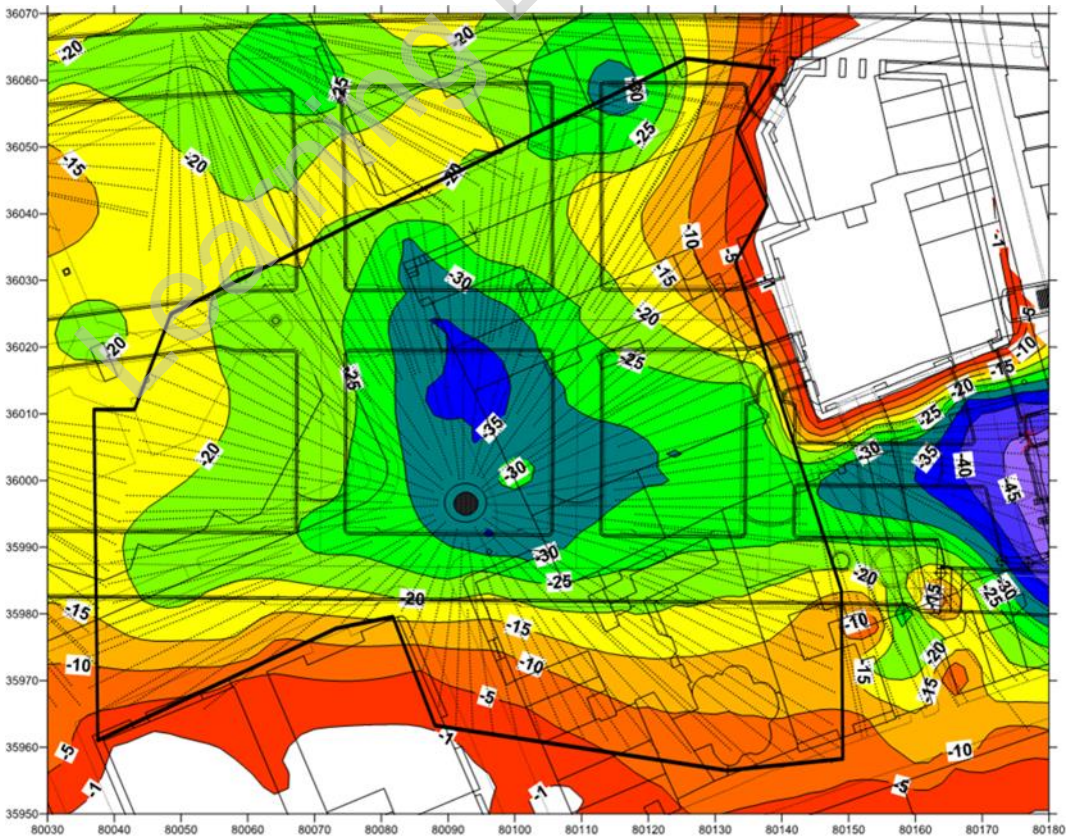


Figure 3.7.1 shows that post-construction settlement increased by up to 15mm over the 14 month period to September 2015. The maximum is located above PTE, the last major excavation to be completed. Over the majority of the area of the GS5 arrays the increase in settlement was between 5mm and 10mm.

3.8. Period G: 25/09/15 – 08/11/16 Long term monitoring

Monitoring was continued after September 2015 on selected BRE and PLP as shown on Figure 3.8.1. The average rate of post-construction settlement in mm / year has been calculated by selecting readings which appear representative of the overall trends described in Sections 4 and 5. The calculated annualized rate of settlement is illustrated by colour coding. Between October 2015 and November 2016 (~12 months), the rate of settlement to the south of the grout shaft is ~2mm/year or less whereas to the north of the grout shaft it is generally between 3mm/year and 5mm/year. Given a survey accuracy of ±1mm, these data will have a tolerance of ~±1.0mm/year. Figure 3.8.2 shows data calculated in a similar manner but using the surveys in January and November 2016 (~8 months). The rate of settlement is substantially reduced with only one point showing a rate of settlement in excess of 2mm/year. Given a survey accuracy of ±1mm, these data will have a tolerance of ~±1.5mm/year.

Figure 3.8.1 Annualised rate of settlement over 12 months to November 2016

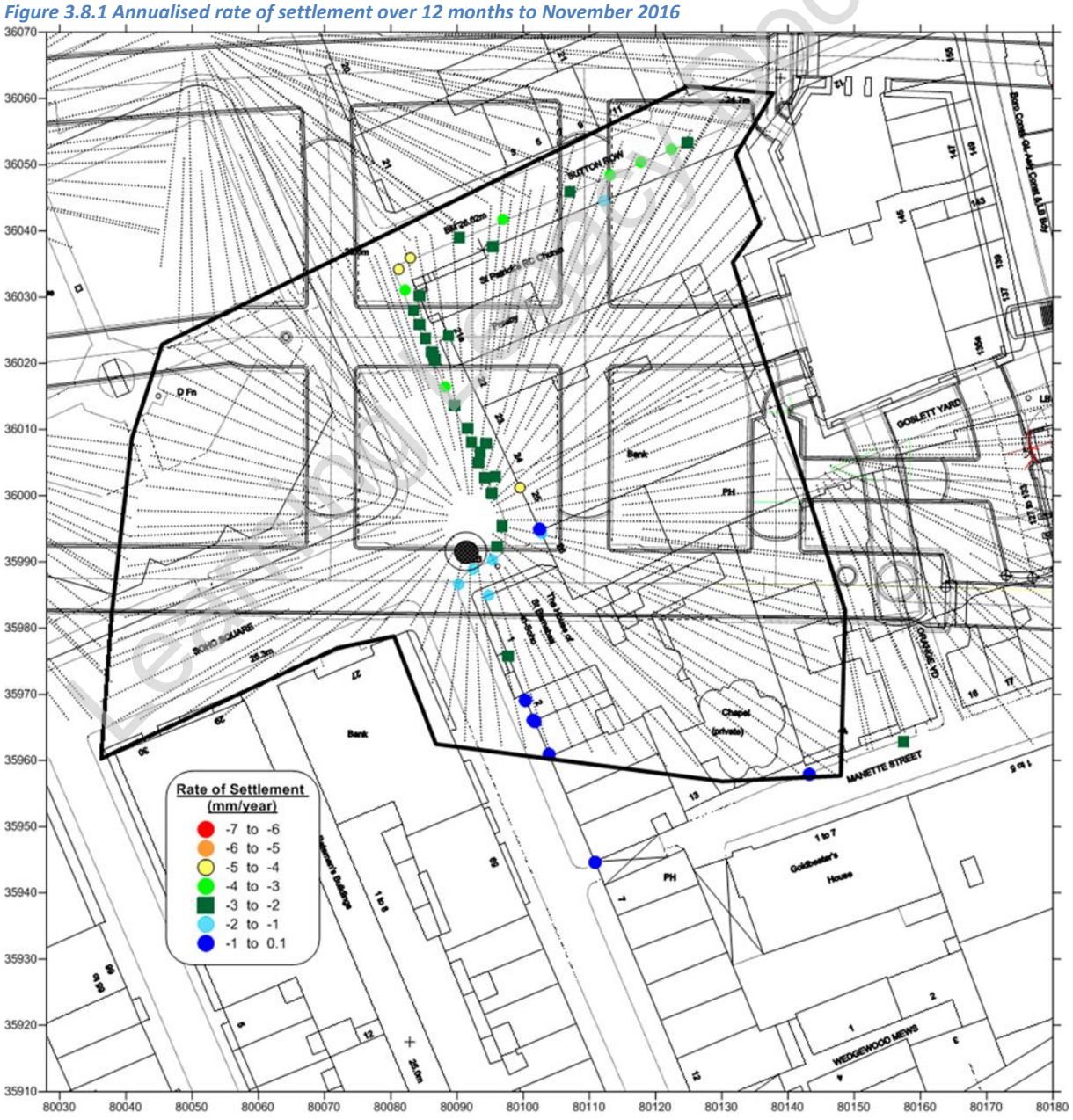
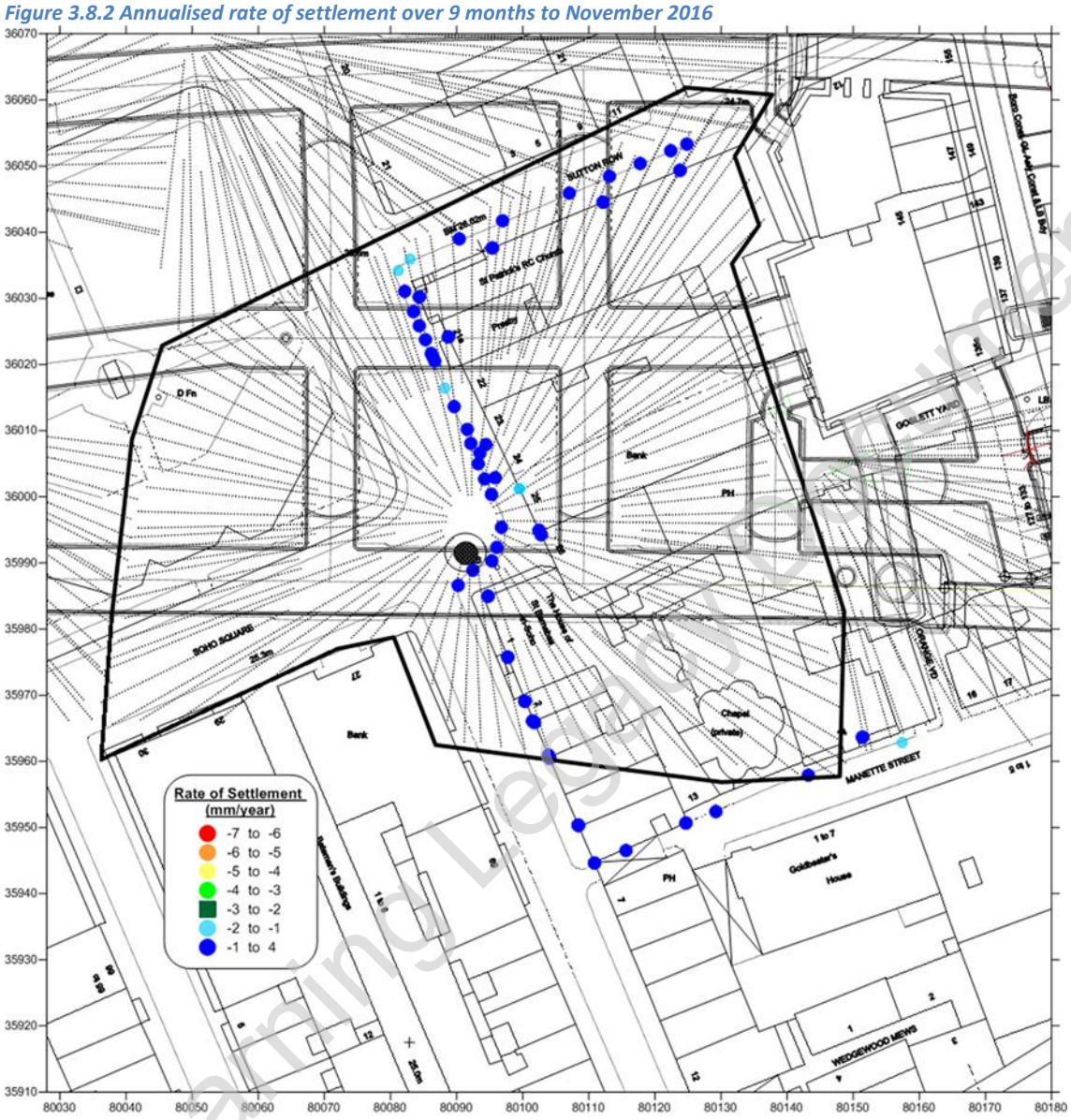


Figure 3.8.2 Annualised rate of settlement over 9 months to November 2016



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. A larger version of Figure 4.1 is included in Appendix B. Details are given in Table 4.1. By inspection, no Deflection Ratio triggers have been breached.

Slope triggers are as follows:

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

BRE monitoring data from the facades within the footprint of GS5 are presented in the following sections, namely:

- Frith Street - east
- Bateman's Buildings – west and east
- Soho Square - south and east
- Greek Street – west and east
- Manette Street – north and south
- Sutton Row - south

The plots presented for each comprise, as appropriate:

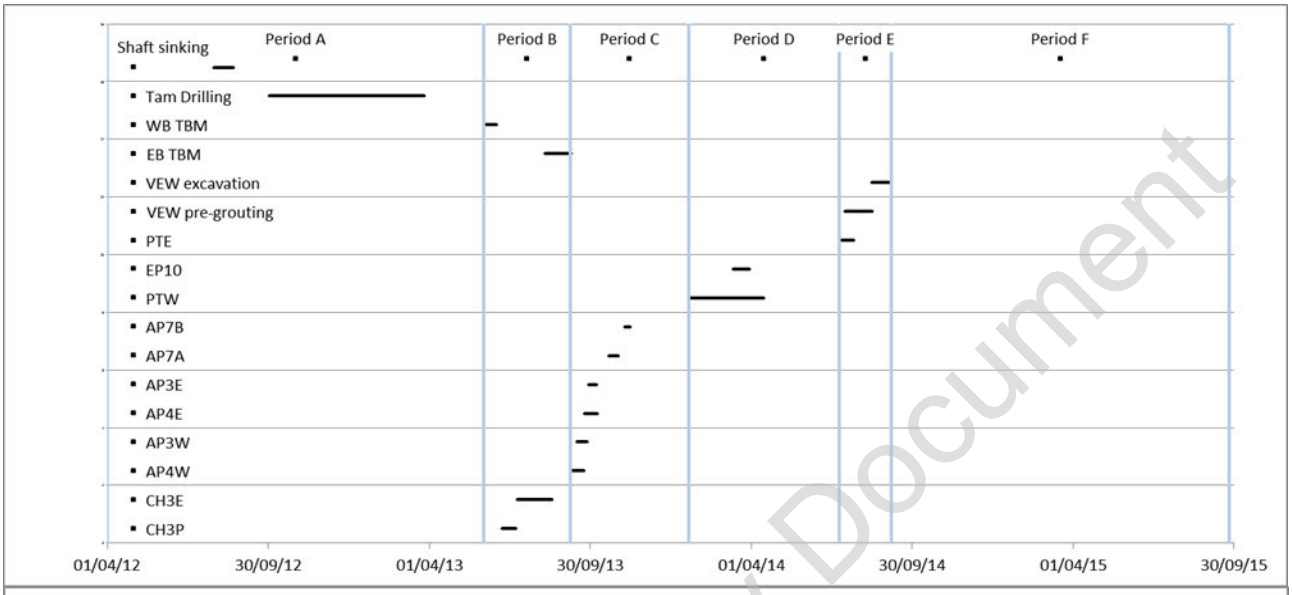
1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres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

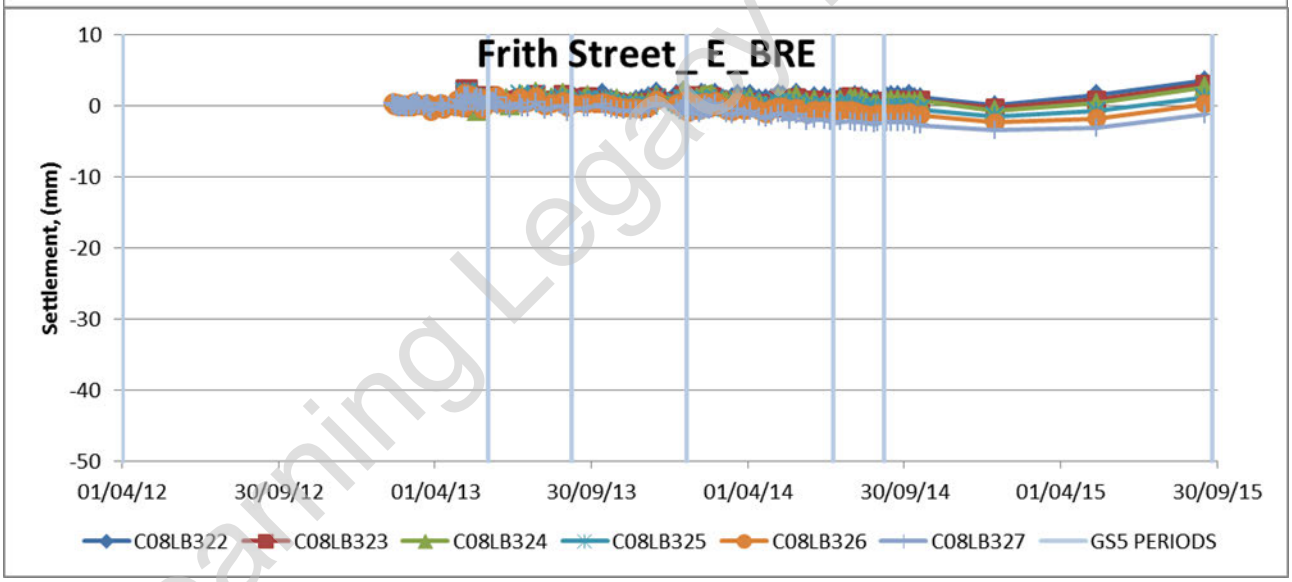
Table 4.1 Details of Amber trigger breaches on BRE & HLC

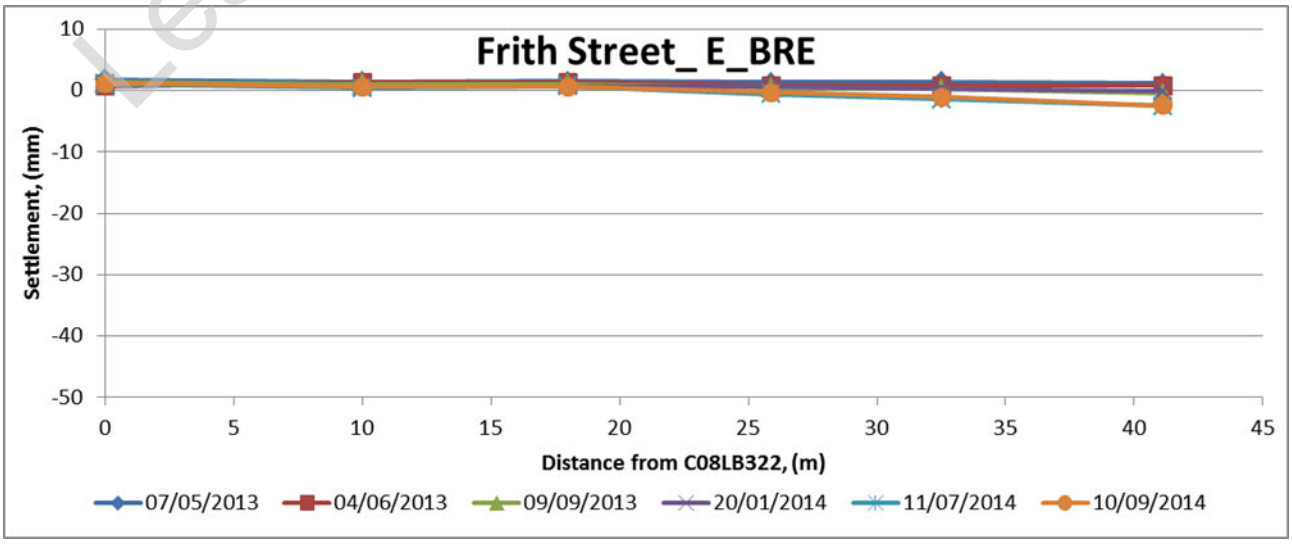
BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Frith Street - East: NONE					
Bateman's Buildings - West: NONE					
Bateman's Buildings – East: NONE					
Soho Square – South:					
D08LB106-DO8LB105	Amber	POST CONTRUCTION: 1 reading only in excess of 1mm/m in Period F, no significant change in Period G. Marginal trigger.	24/07/15	1.05	1.02
Greek Street – West: NONE					
Greek Street – East:					
D08LB108-DO8LB107	Amber	PTW: Maximum slope transitory during construction of PTW. Exceeded again due to post construction settlement in Period D. More scatter as points 3.4m apart.	21/02/14	1.35	1.26
D08LB107-DO8LB106	Amber	PTW: Maximum slope transitory during construction of PTW. Exceeded again due to post construction settlement in Period D. Stable in Periods F & G 1.0±0.1mm/m.	18/02/14	1.28	1.05
Manette Street – North (west): NONE					
Manette Street – South (west): NONE					
Soho Square – East (south): NONE					
Sutton Row – South: NONE					

Figure 4.1. Locations of BRE and building slope Amber trigger breaches.

4.2. Frith Street – East



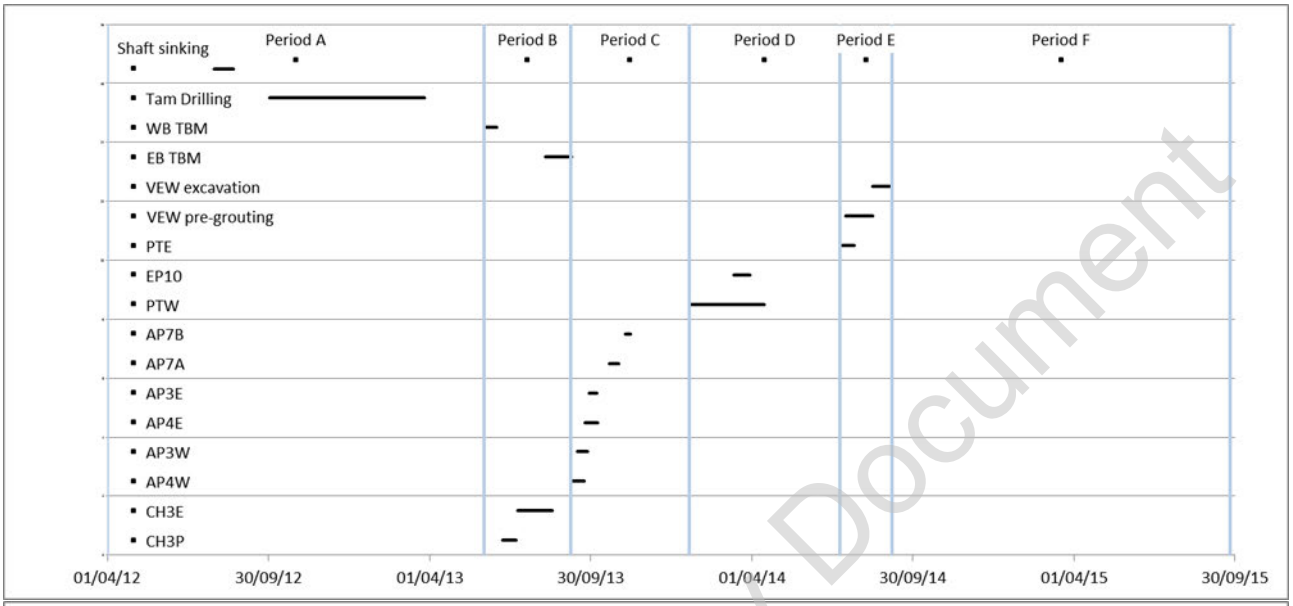


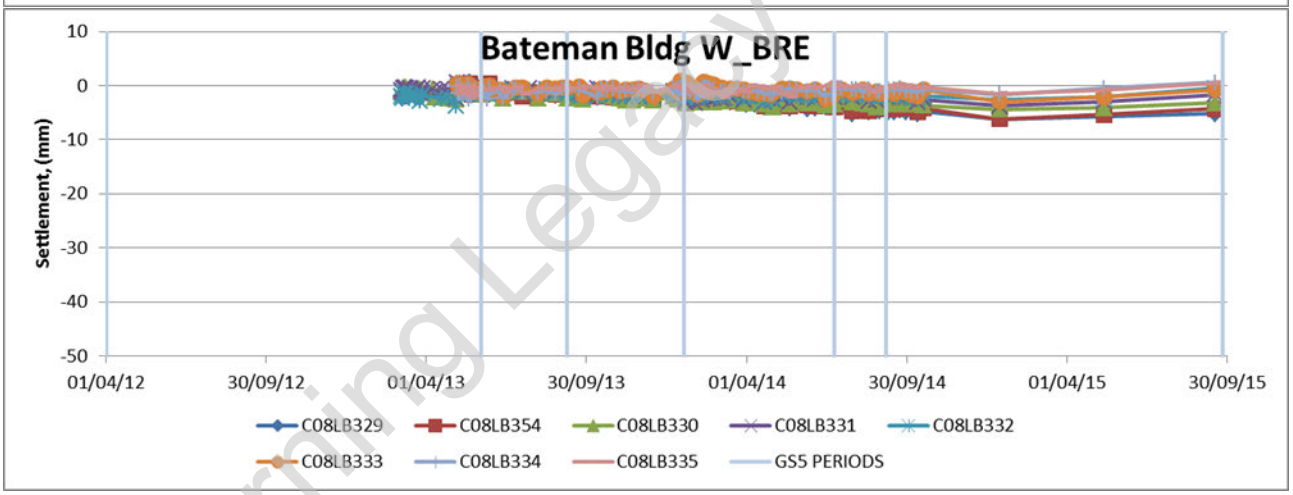


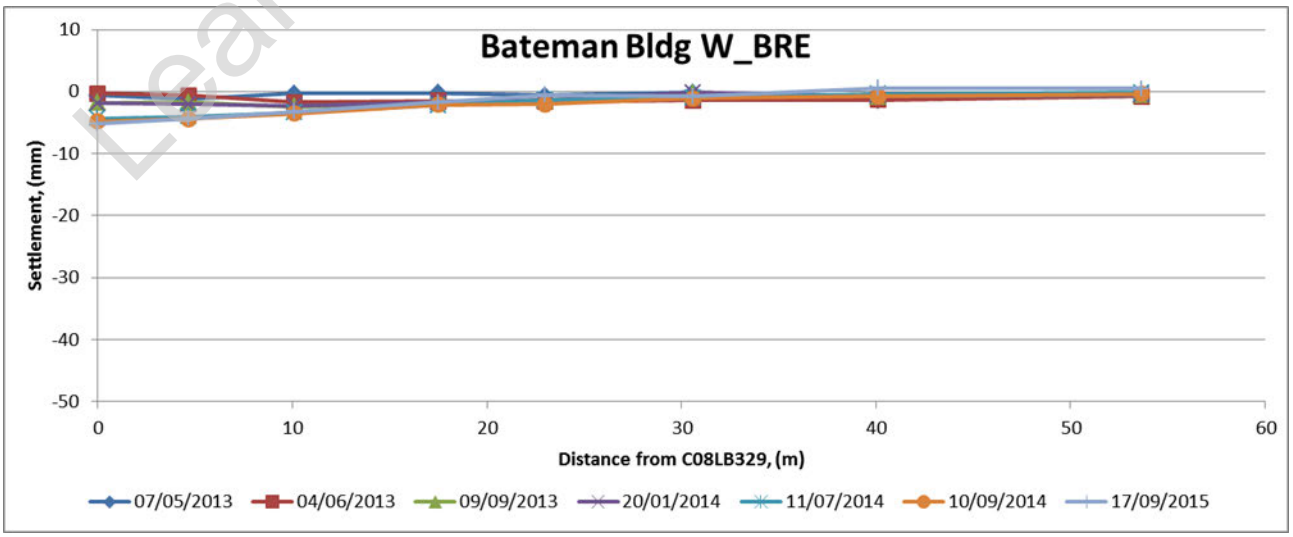
The following points are noted:

- Data are presented for the BRE located on the east facade of Frith Street. All points are located outside the plan extent of the GS5 arrays.
- Overall settlement was ~5mm or less throughout construction and subsequently.
- No significant increase in settlement is evident as a result of any particular tunnel.
- There is negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

4.3. Bateman's Buildings – west



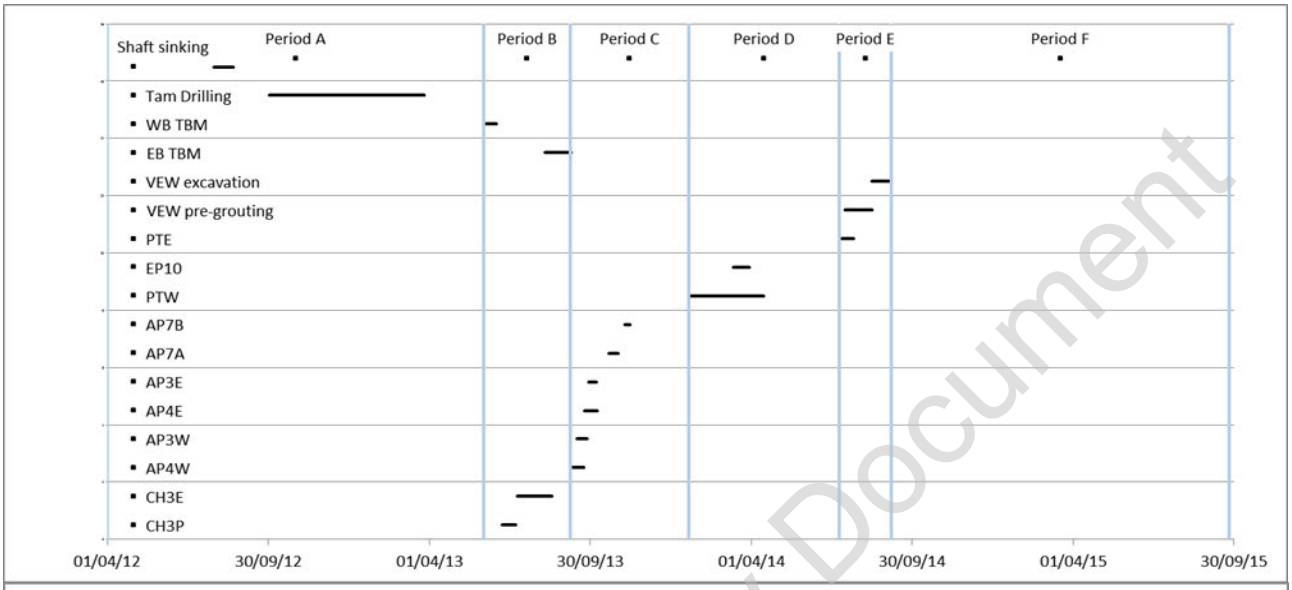


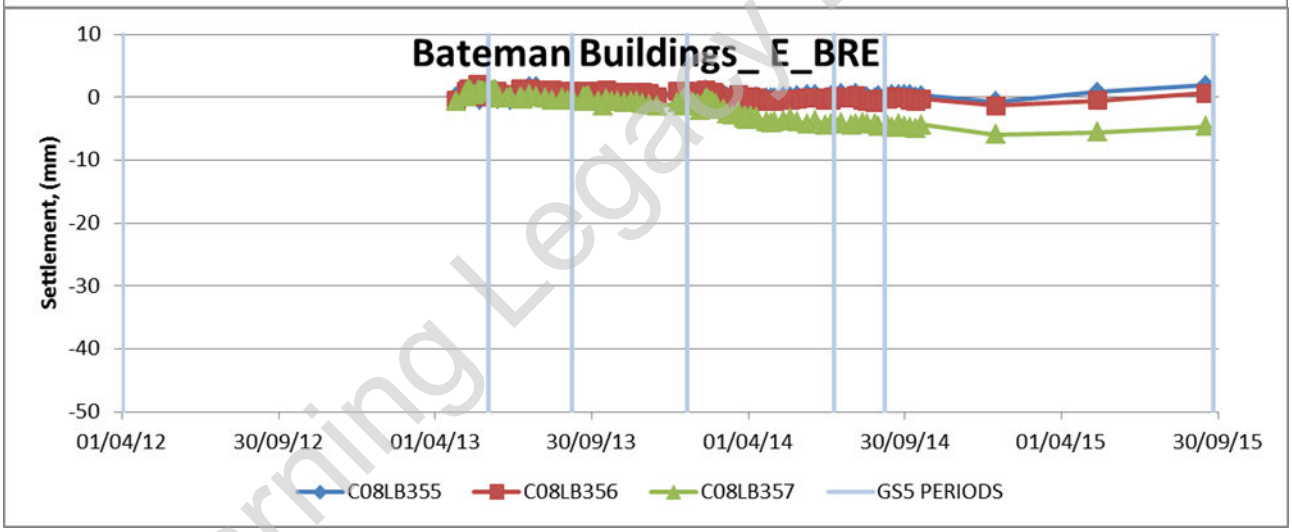


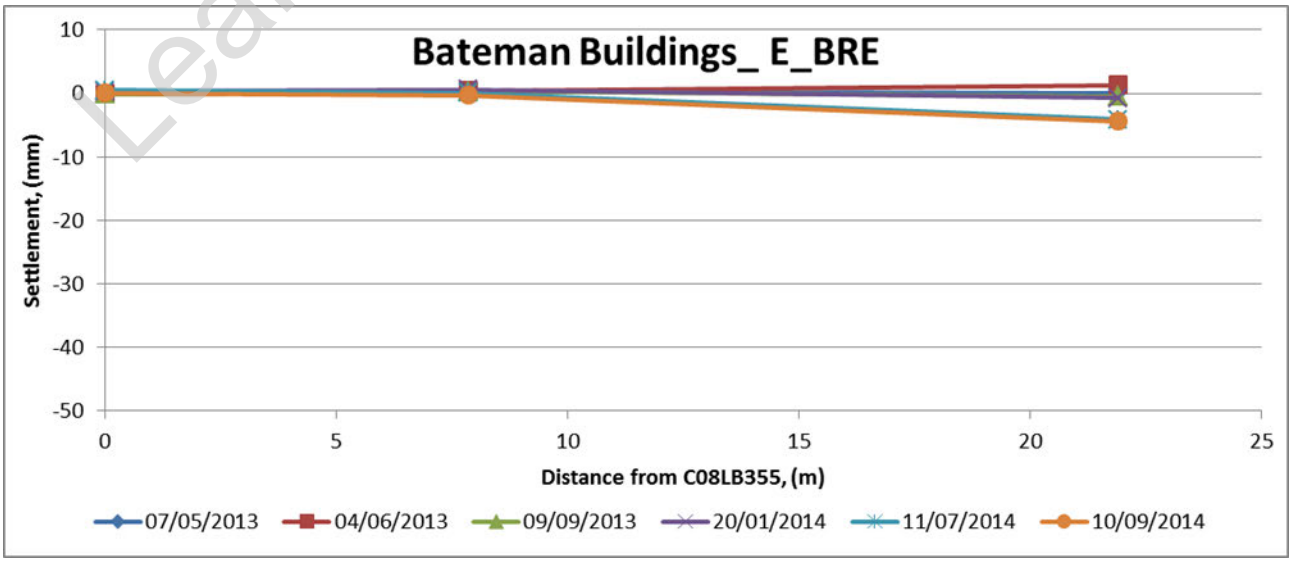
The following points are noted:

- Data are presented for the BRE located on the west façade of Bateman's Buildings. Only two points (to distance 5m) are within the plan extent of the GS5 arrays.
- Overall settlement was ~5mm or less throughout construction and subsequently.
- No significant increase in settlement is evident as a result of any particular tunnel.
- There is negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

4.4. Bateman's Buildings – east



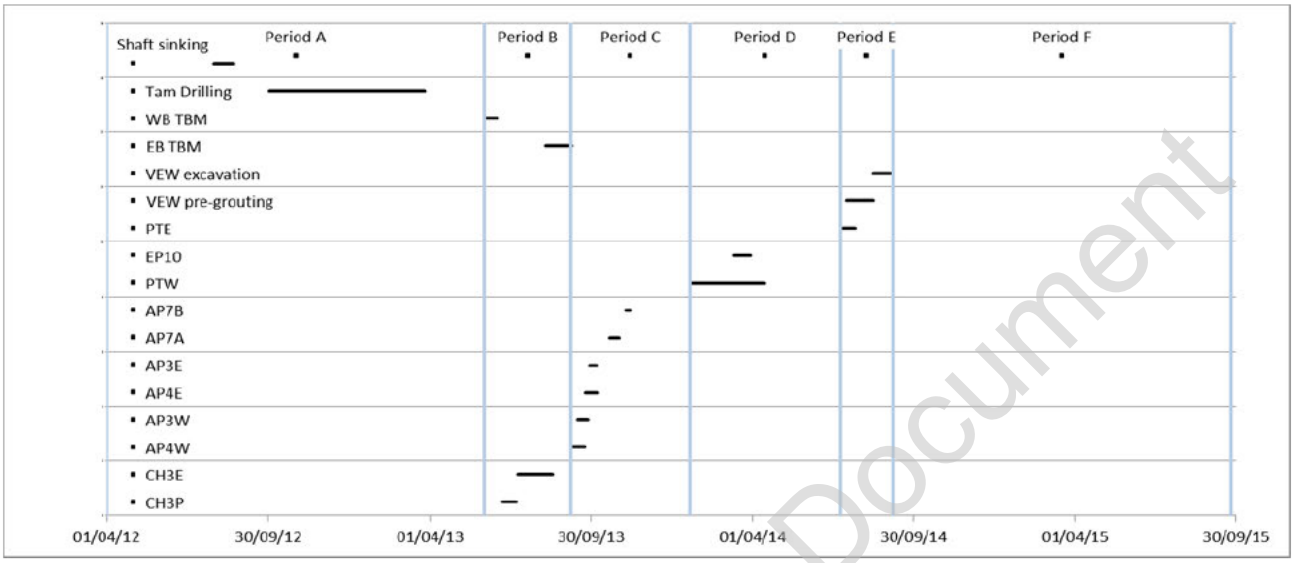


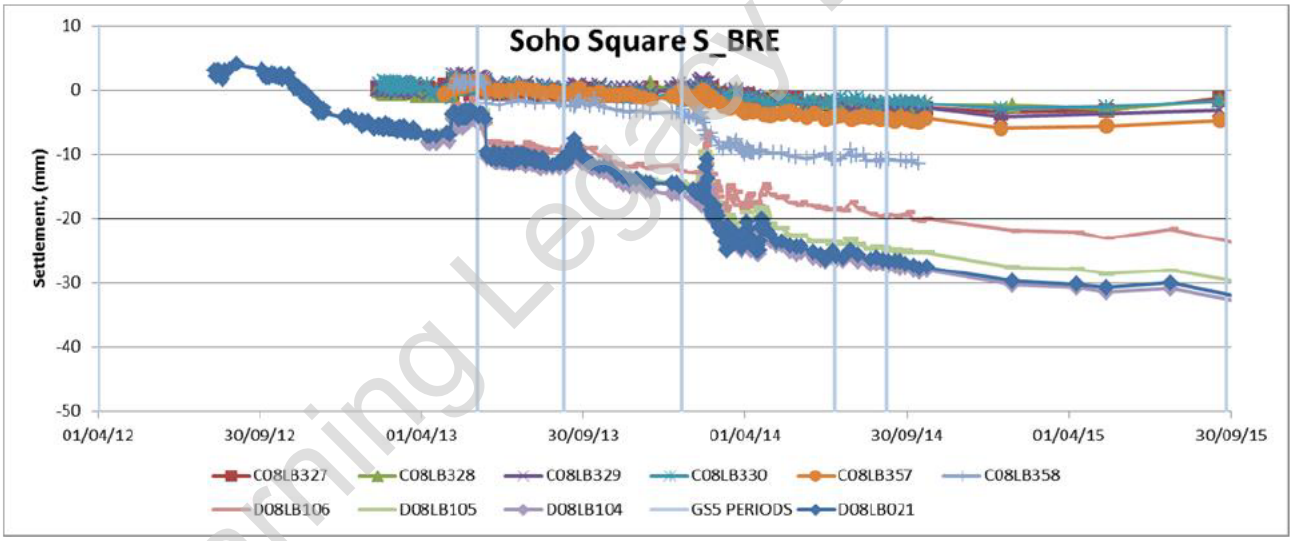


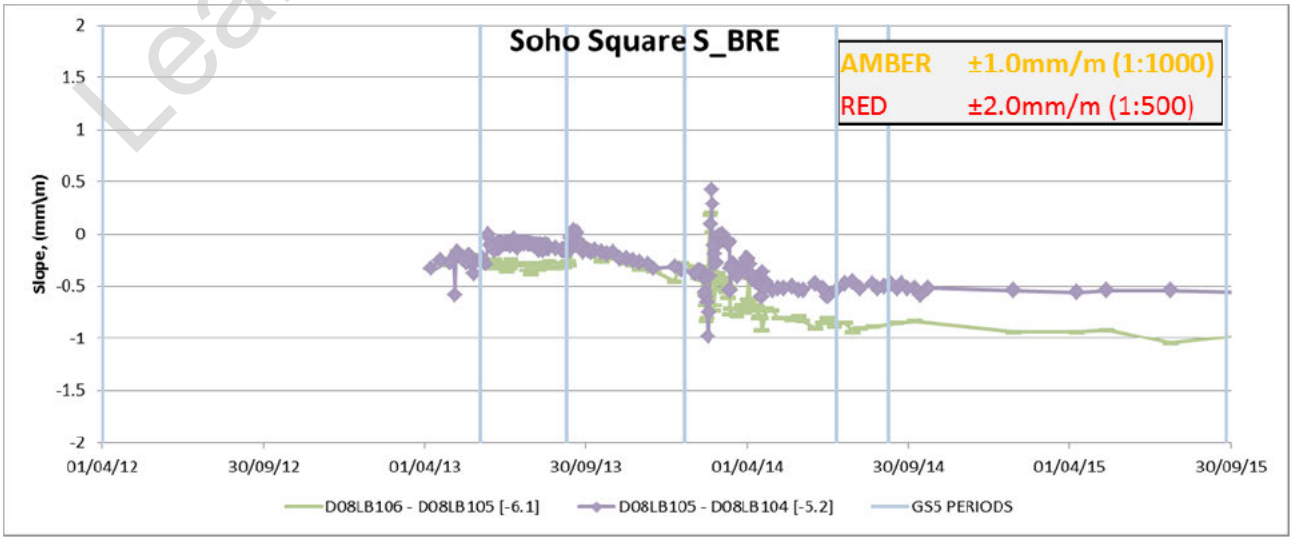
The following points are noted:

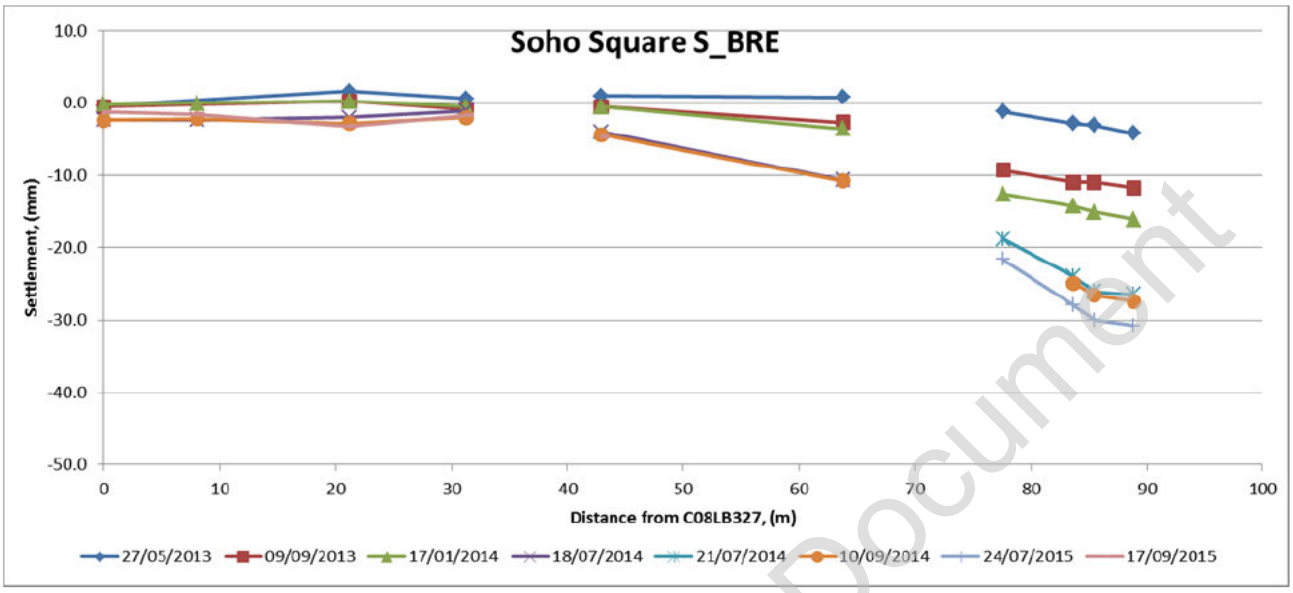
- Data are presented for the BRE located on the east façade of Bateman's Buildings. The building (27 Soho Square) is piled and is outside the plan extent of the GS5 arrays.
- Overall settlement was ~5mm or less throughout construction and subsequently.
- The only notable increase in settlement evident was as a result of PTW construction in Period D, which generated about 3mm settlement at the northern end of the facade.
- There was negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

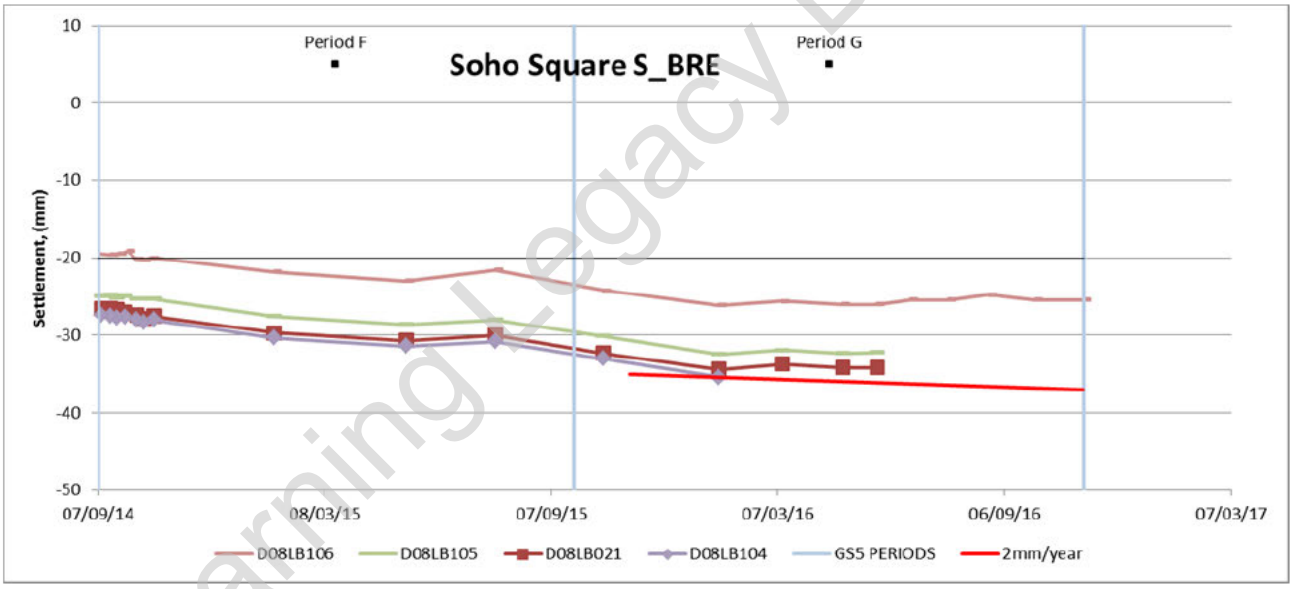
4.5. Soho Square south

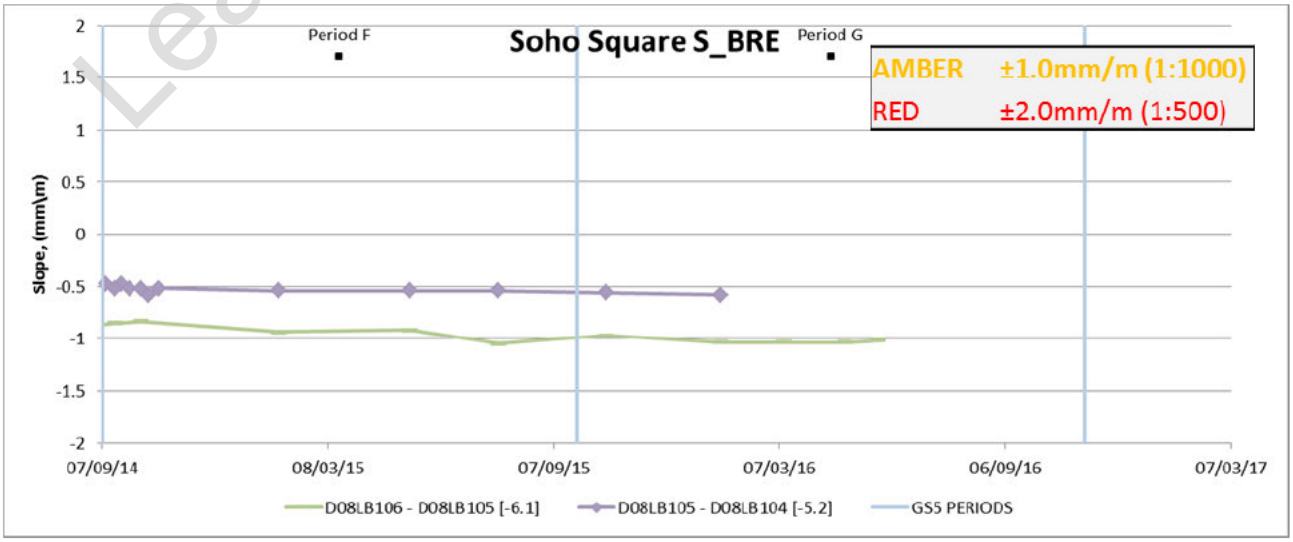








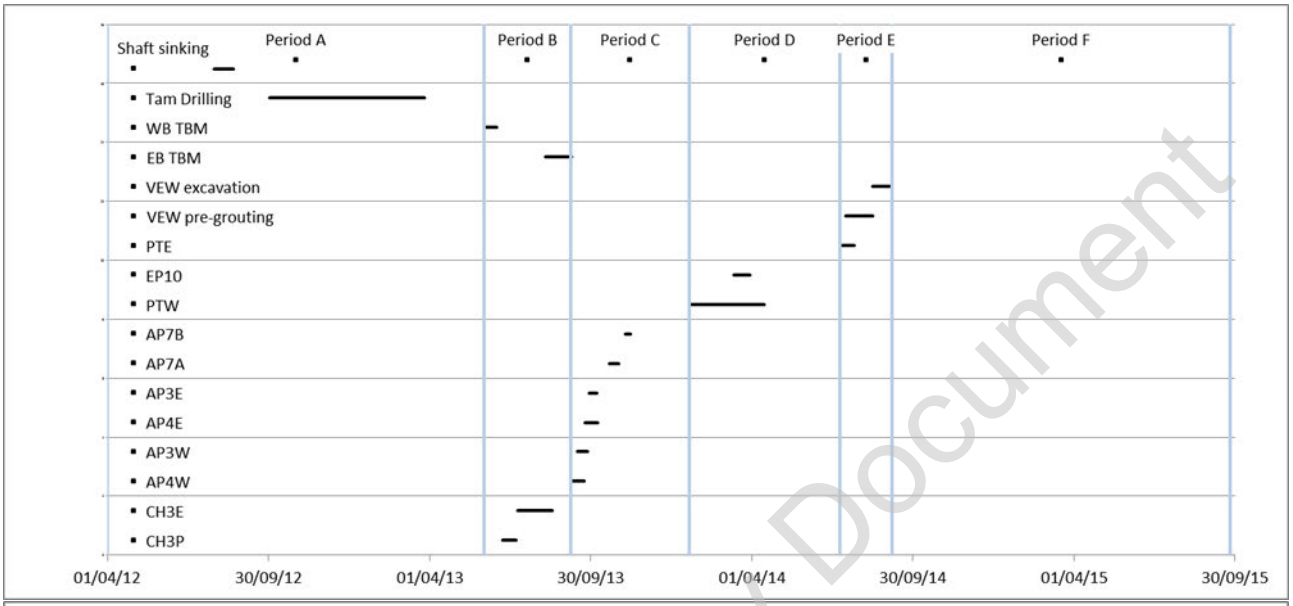


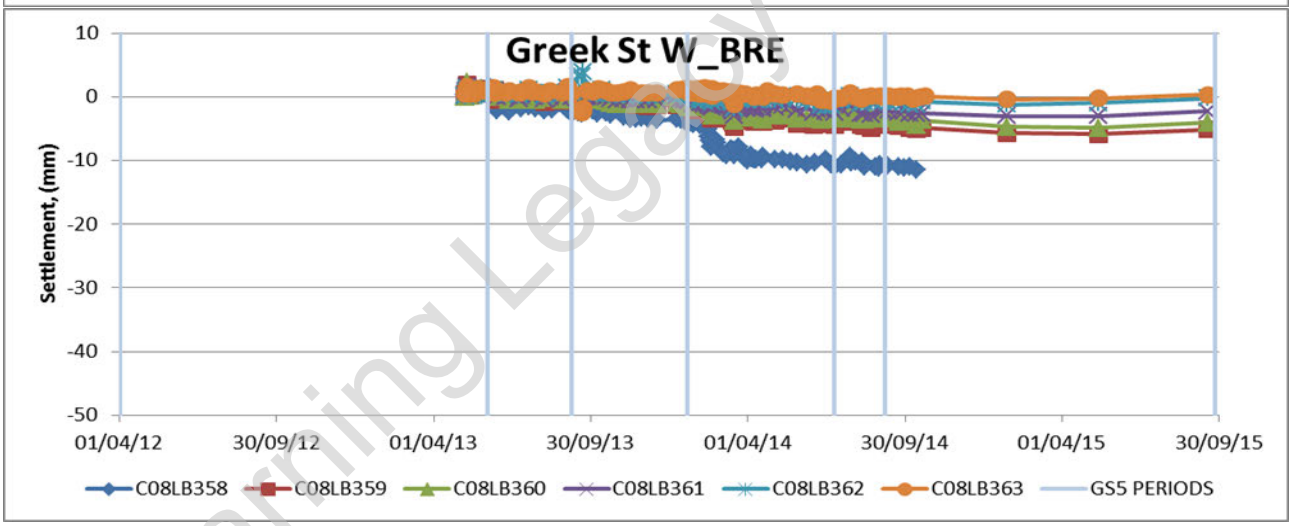


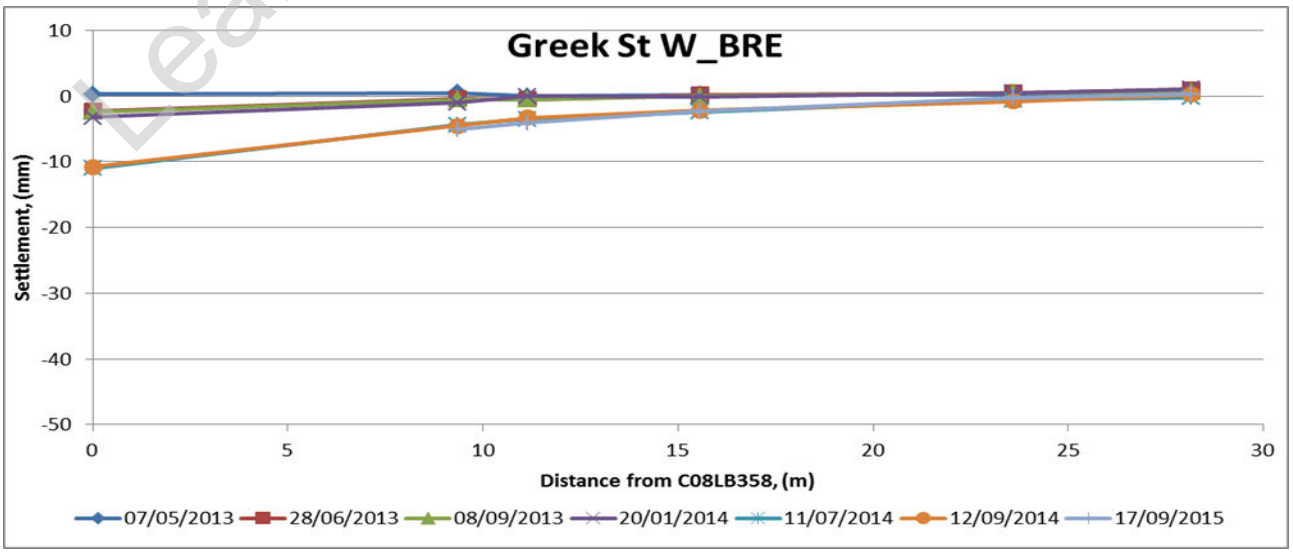
The following points are noted:

- Data are presented for the BRE located on the south facade of Soho Square. The façade is split into 3 sections: west of Bateman's Buildings, between Bateman's Buildings and Greek Street and east of Greek Street. The western section (29-30 Soho Square) is partly within the GS5 grouting arrays. The central section (27 Soho Square) is a piled building and is excluded from the grouting zone. The eastern section (the north façade of 1 Greek Street) is wholly within the GS5 arrays.
- For the western section (C08LB353, C08LB327 – 329):
    - Overall settlement was ~5mm or less throughout construction and subsequently.
    - The only notable increase in settlement evident was as a result of PTW construction in Period D, which generated about 3mm settlement.
    - There was negligible change in settlement post-construction.
    - By inspection of the profile plot, no slope triggers have been exceeded
- For the central section (C08LB357 – 358):
    - Overall settlement was ~12mm or less throughout construction and subsequently.
    - The only notable increase in settlement evident was as a result of PTW construction in Period D, which generated about 5mm settlement.
    - There was negligible change in settlement post-construction.
    - By inspection of the profile plot, no slope triggers have been exceeded.
- For the eastern section (D08LB106 – 104):
    - Settlement was ~10mm at the commencement of BFK monitoring in Period A but was reduced to about 5mm at the end of Period A by pre-treatment grouting.
    - At the start of Period B, the construction of the WBRT without concurrent grouting increased the maximum settlement to ~10mm short term and to ~12mm by the end of Period B.
    - At the start of Period C, construction of AP3W and AP4W resulted in a net reduction in movement due to concurrent grouting, however, post construction settlement increased to a maximum of 17mm at the end of Period C.
    - The most significant impact was associated with PTW in Period D. Concurrent grouting and subsequent grout jacking limited the increase in settlement to ~7mm.
    - Since the completion of PTW, during the remainder of Period D through Periods E and F, the rate of post construction settlement has gradually decreased.
    - Significant differential settlement is evident and the associated slopes are presented. The slope did not exceed the Amber trigger value during construction but it has continued to increase gradually during Period F and at the end of Period F was at the limit of 1:1000 (1mm/m).
- Long term monitoring – Period G
    - Monitoring continues on the eastern section and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring. The slope time history over the same periods is also presented.
    - The rate of settlement is gradually decreasing: over a 12 months period it is slightly greater than 2mm/year, but over the latest 6 months the rate is less than 2mm/year.
    - The available data show that the maximum slope has stabilised at ~1mm/m

4.6. Greek Street – west



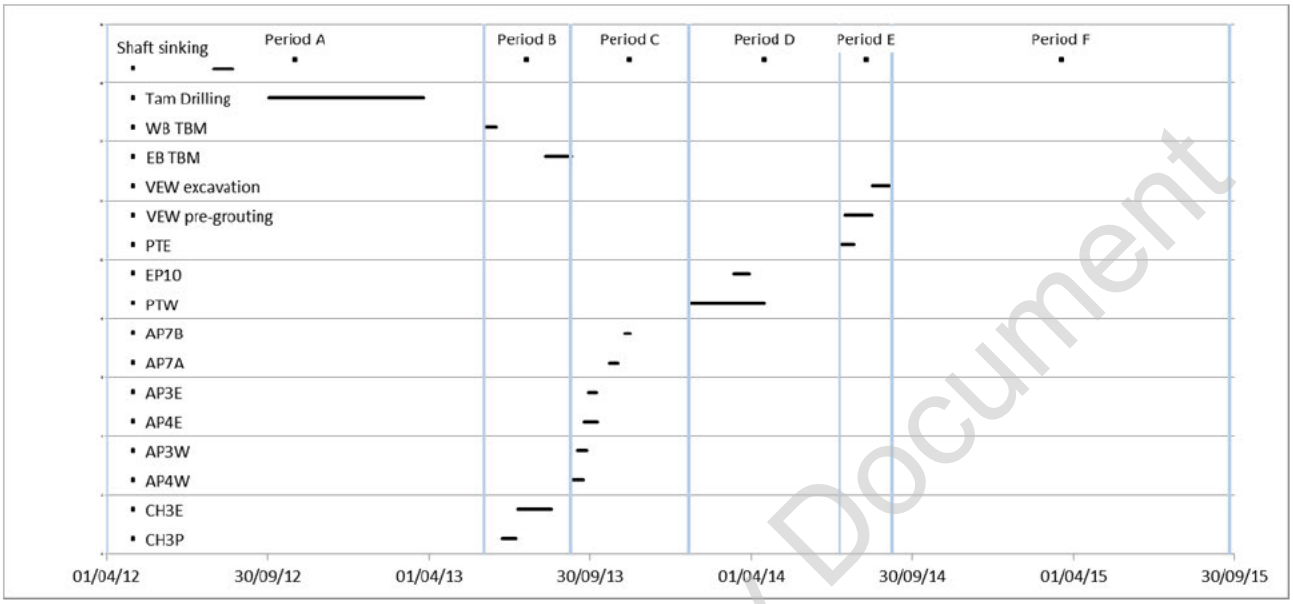


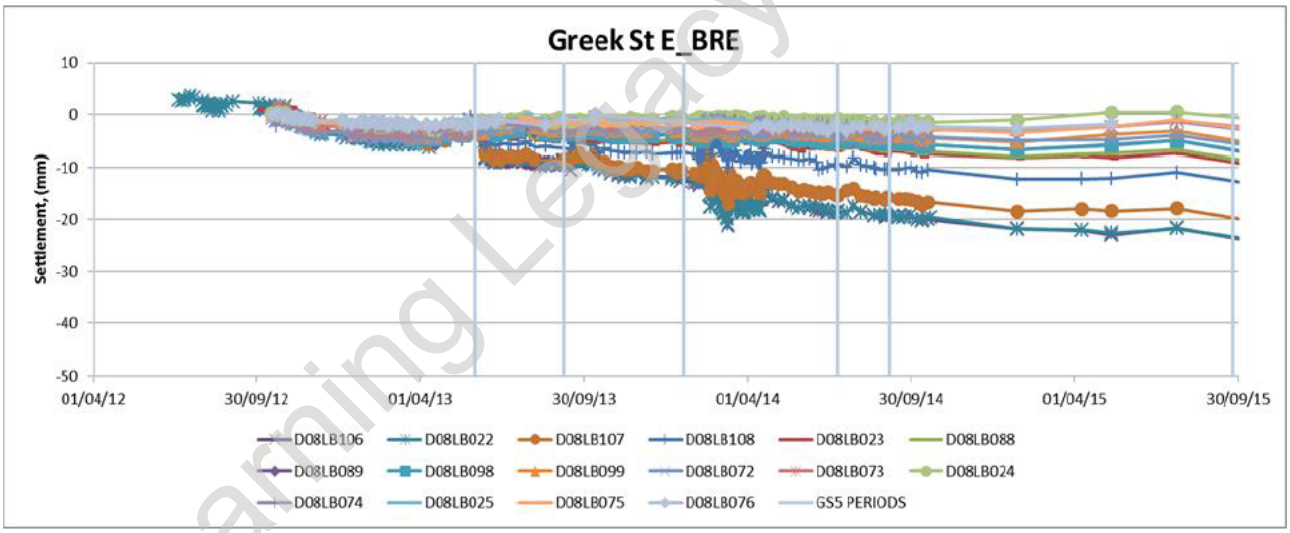


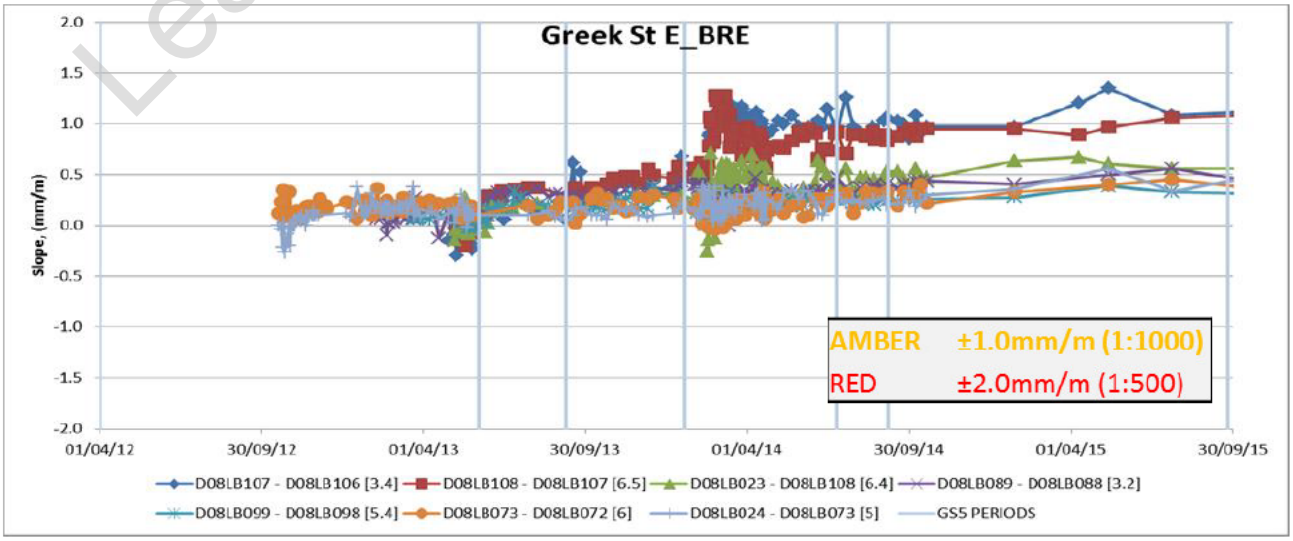
The following points are noted:

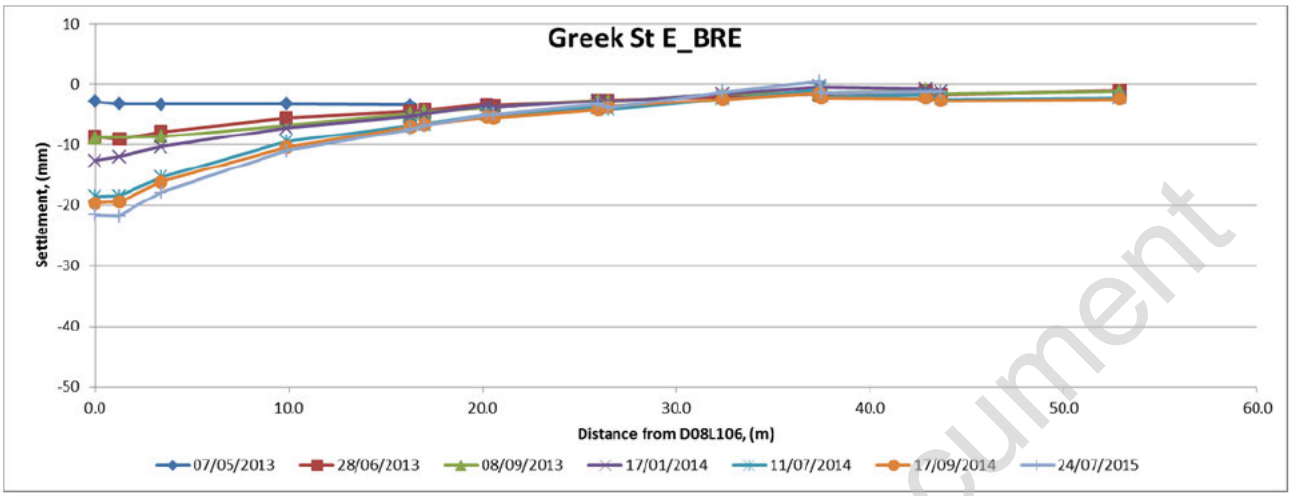
- The west façade of Greek Street is part of 27 Soho Square (a piled building) which is excluded from the specified grouting zone.
- Overall settlement was ~10mm or less throughout construction and subsequently.
- The only notable increase in settlement evident was as a result of PTW construction in Period D, which generated about 5mm settlement.
- There was negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

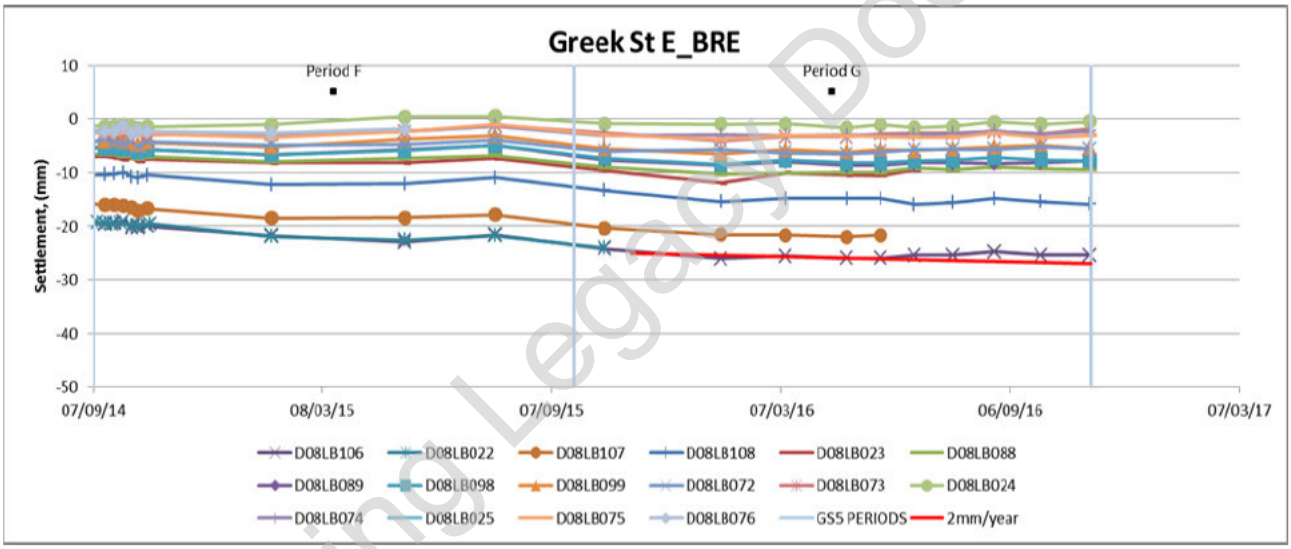
4.7. Greek Street – east

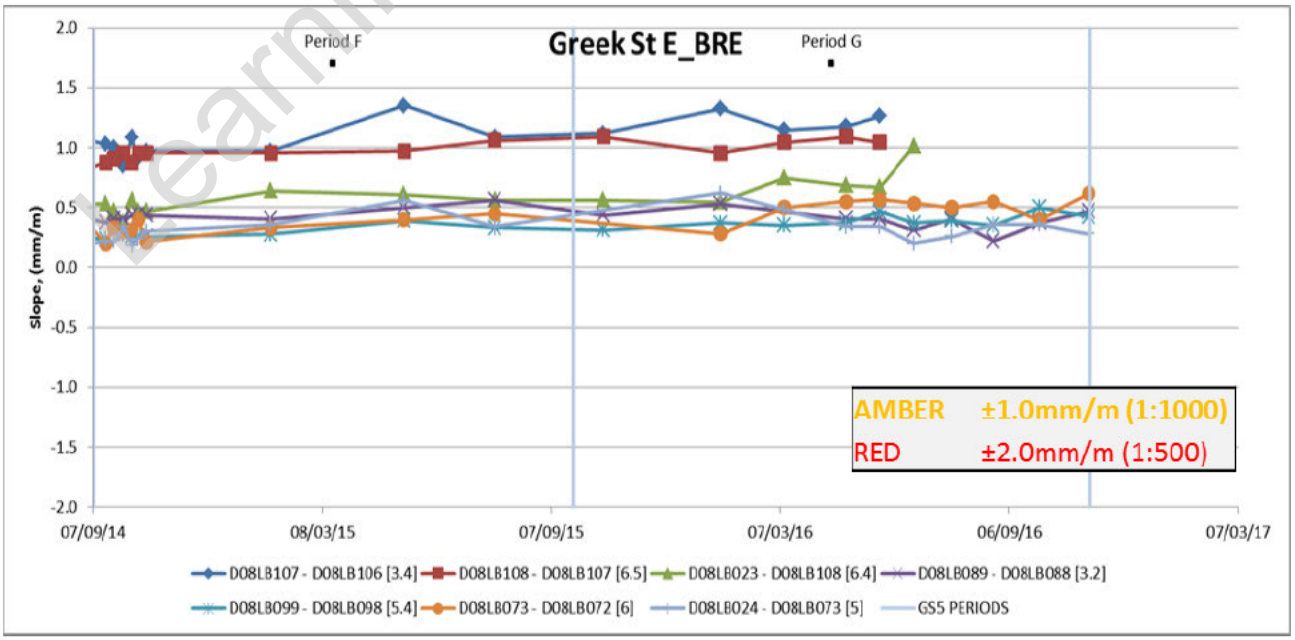








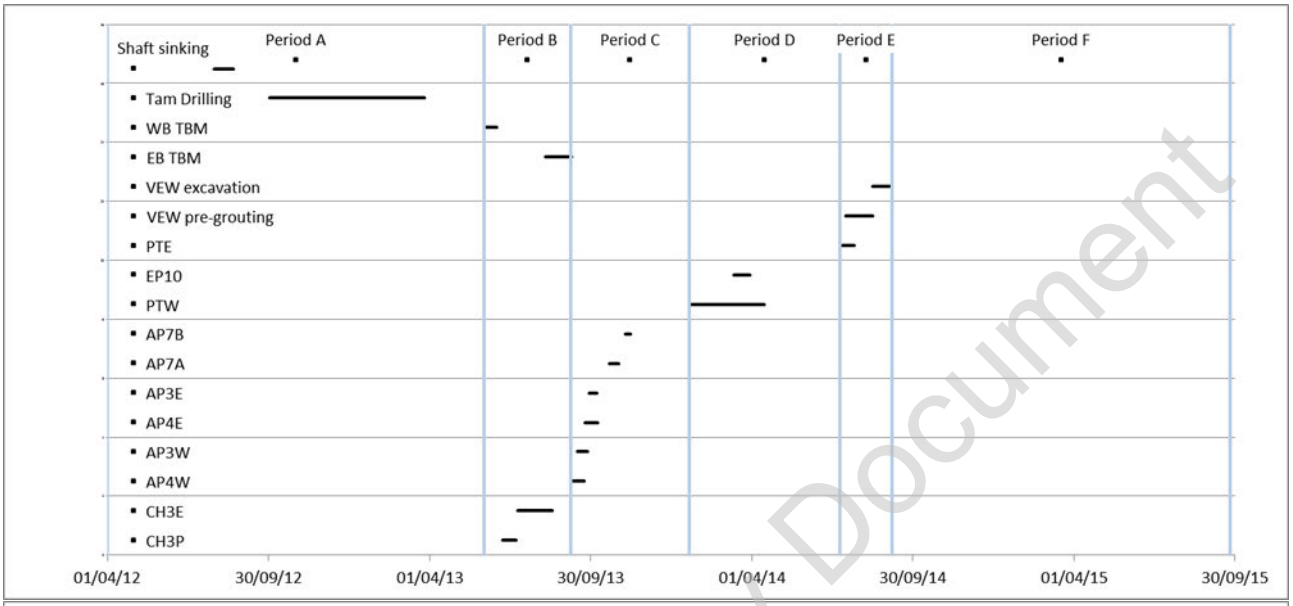


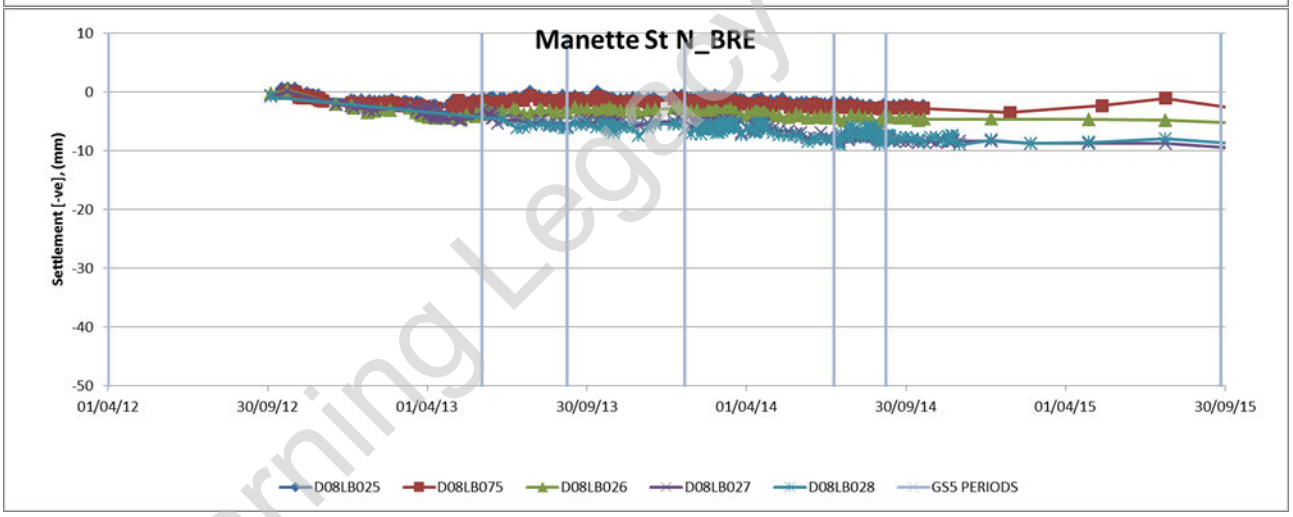


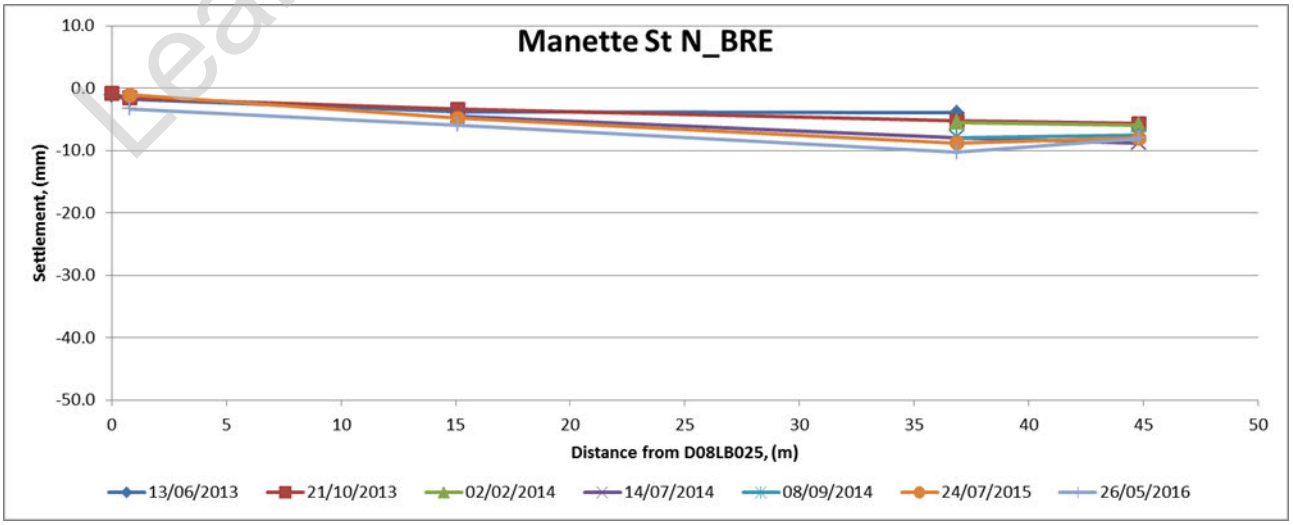
The following points are noted:

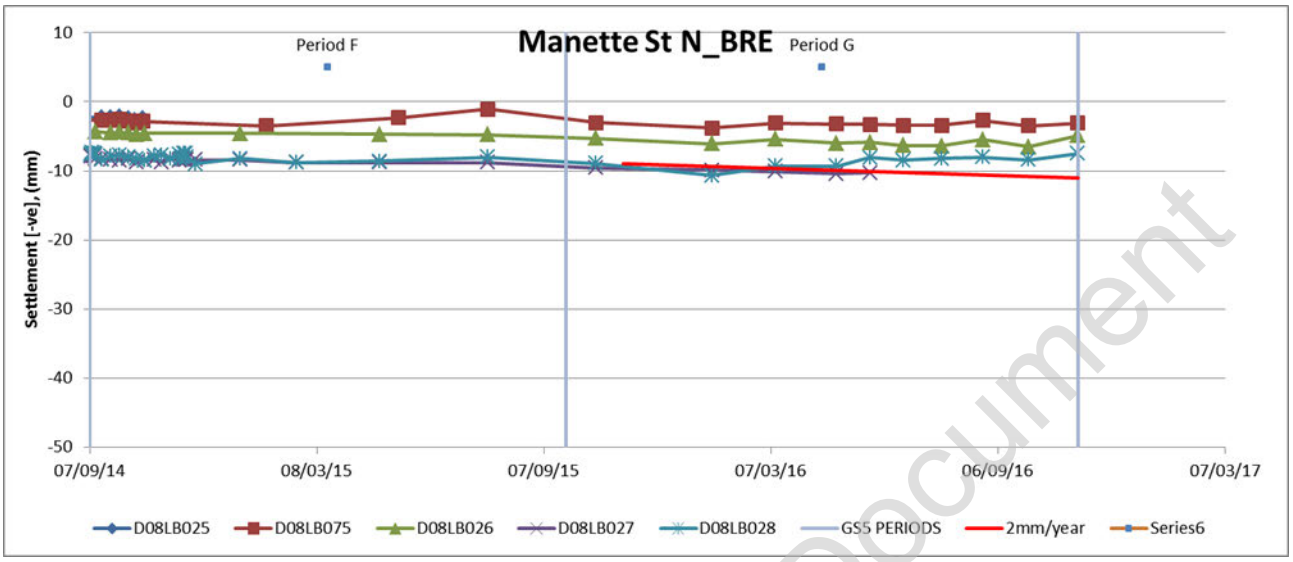
- Data are presented for the BRE located on the east facade of Greek Street. The northern part of the façade (up to distance ~25m) is within the extent of the GS5 array.
- Settlement increased to ~5mm during in Period A but was reduced to about 2mm by the end of Period A by pre-treatment grouting.
- At the end of Period B, the construction of the WBRT without concurrent grouting and subsequent post construction movements had increased the maximum settlement to ~10mm.
- At the start of Period C, construction of AP3W and AP4W resulted in a net reduction in movement due to concurrent grouting, however, post construction settlement increased to a maximum of 12mm at the end of Period C.
- The most significant impact was associated with PTW in Period D. Concurrent grouting and subsequent grout jacking limited the increase in settlement to ~7mm.
- Since the completion of PTW, during the remainder of Period D through Periods E and F, the rate of post construction settlement has gradually decreased.
- Significant differential settlement is evident and the associated slopes are presented. The slopes between the three BRE at the north end of the profile did exceed the Amber trigger value during construction associated with the movements generated by PTW, but were subsequently reduced by grout jacking.
- At the end of construction, the slopes between D08LB108 – D08LB 107 and D08LB107 – D08LB 106 were close to or at the Amber trigger value. The slopes continued to increase gradually during Period F and, at the end of Period F, there were two slopes slightly in excess of 1:1000 (1mm/m).
- Long term monitoring – Period G
    - Monitoring continues on this façade and the data are presented from the end of construction (start of Period F) to June 2016. The data are compared to the specified rate of settlement (2mm/year) for the termination of monitoring. The slope time history over the same Periods is also presented.
    - The rate of settlement is gradually decreasing: over a 12 months period it is slightly greater than 2mm/year, but over the latest 6 months the rate is less than 2mm/year.
    - The available data show that the maximum slope has stabilised at ~1.2mm/m.

4.8. Manette Street – north (west)





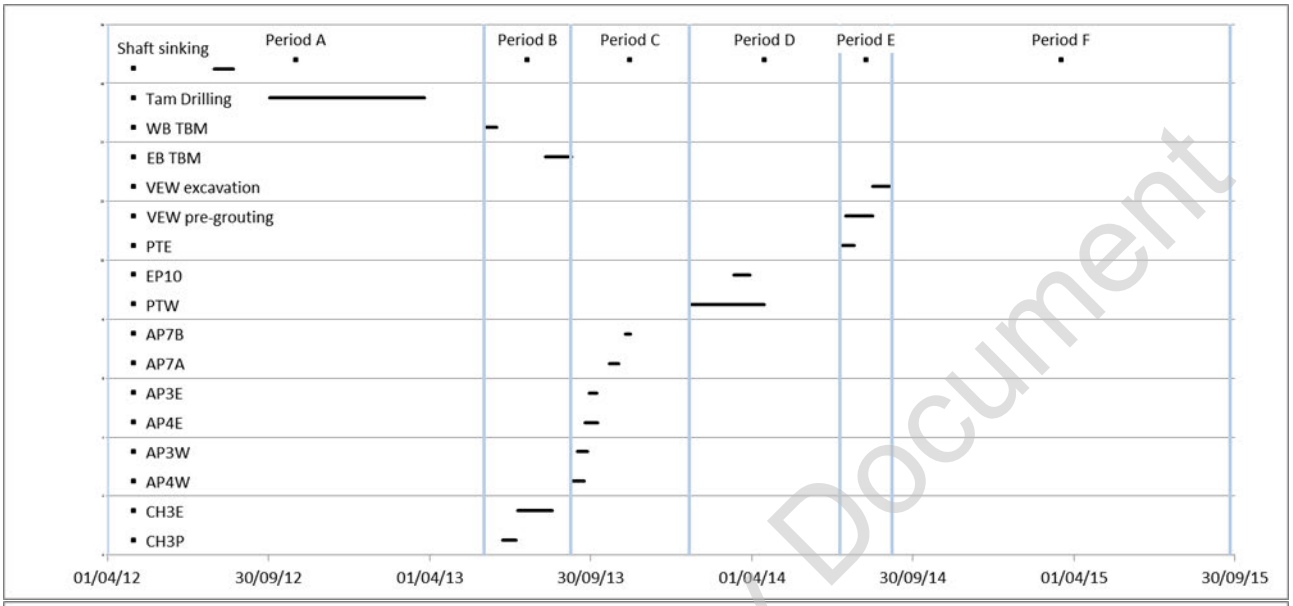


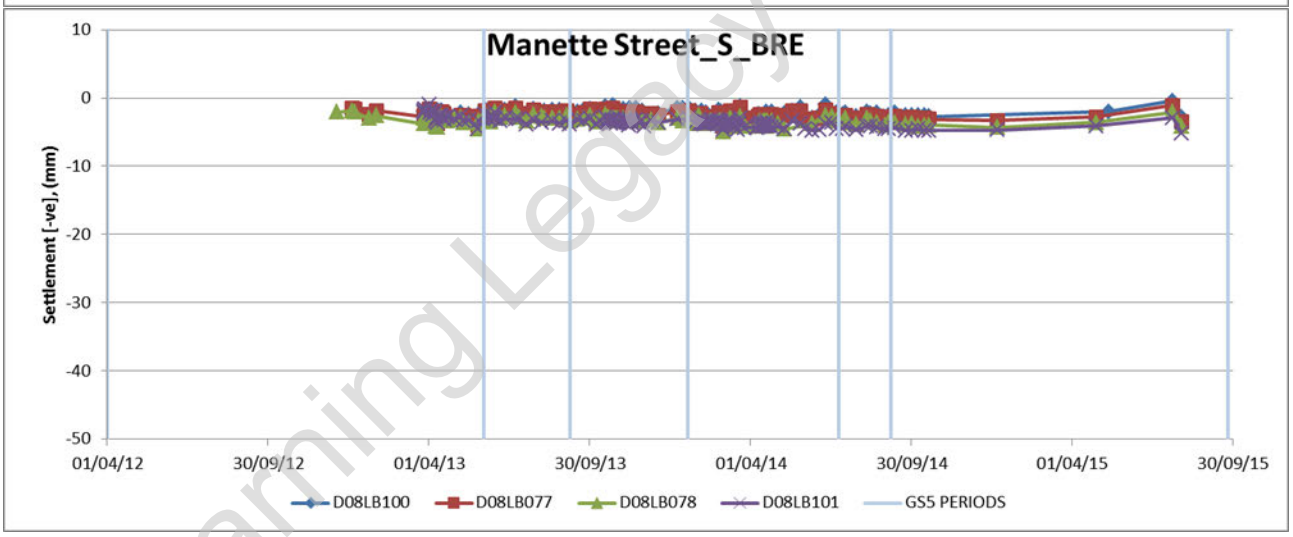


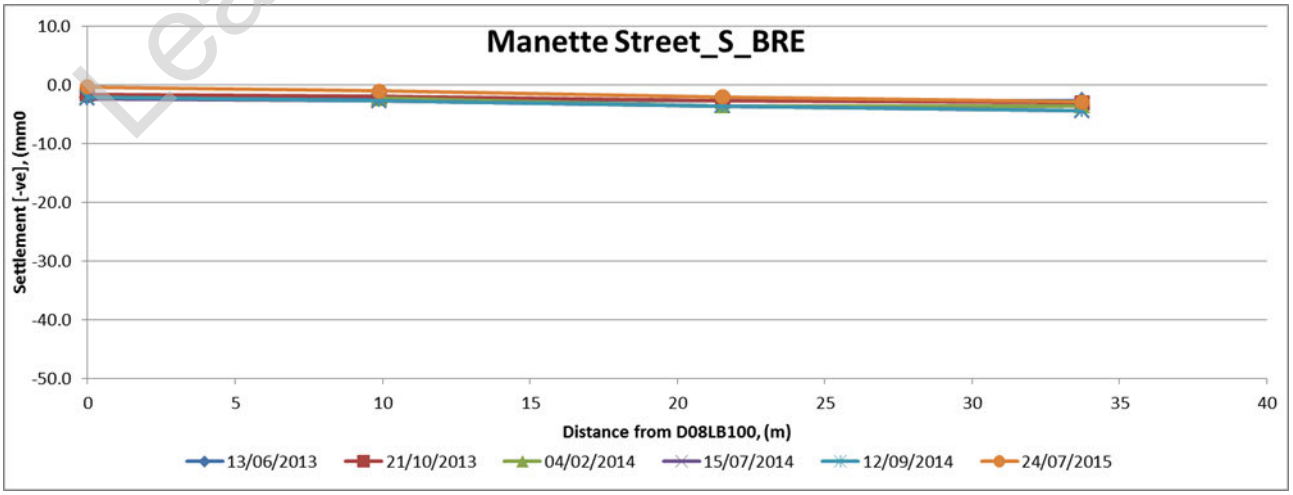
The following points are noted:

- Data are presented for the BRE located at the western end of the north facade of Manette Street. The points are on or outside the southern extremity of the GS5 arrays.
- Maximum settlement was less than 10mm throughout construction and subsequently.
- There was negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.
- Long term monitoring – Period G
    - Monitoring continues on this façade and the data are presented from the end of construction (start of Period F) to June 2016. Data are compared to the specified rate of settlement (2mm/year) for the termination of monitoring.
    - The rate of settlement is approximately constant over a 12 month period at 2mm/year.

4.9. Manette Street – south (west)



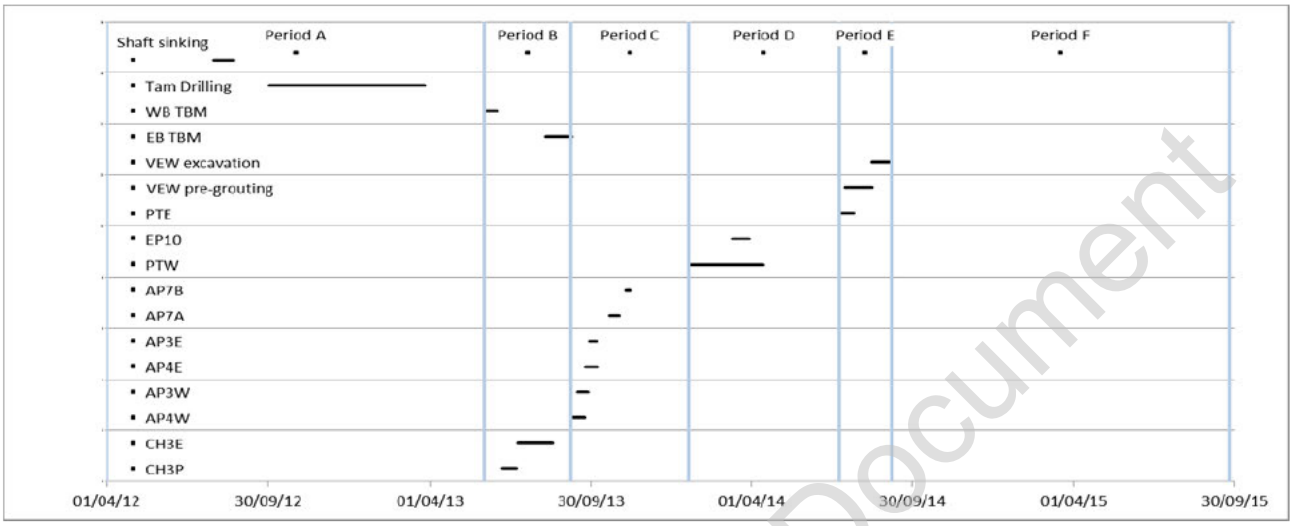


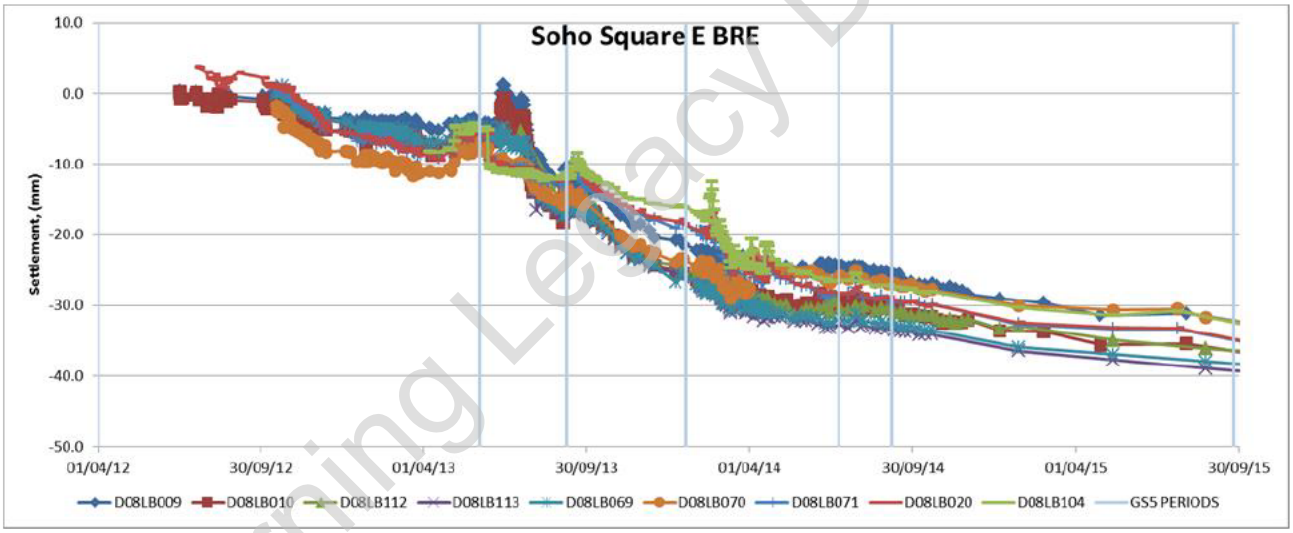


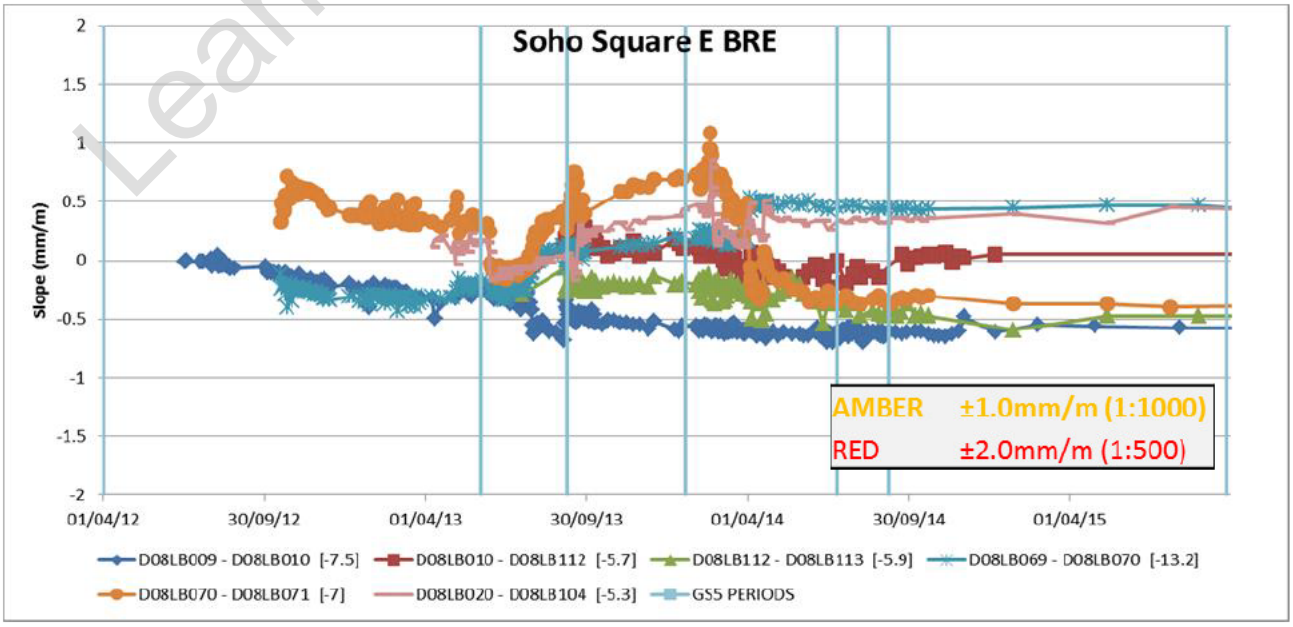
The following points are noted:

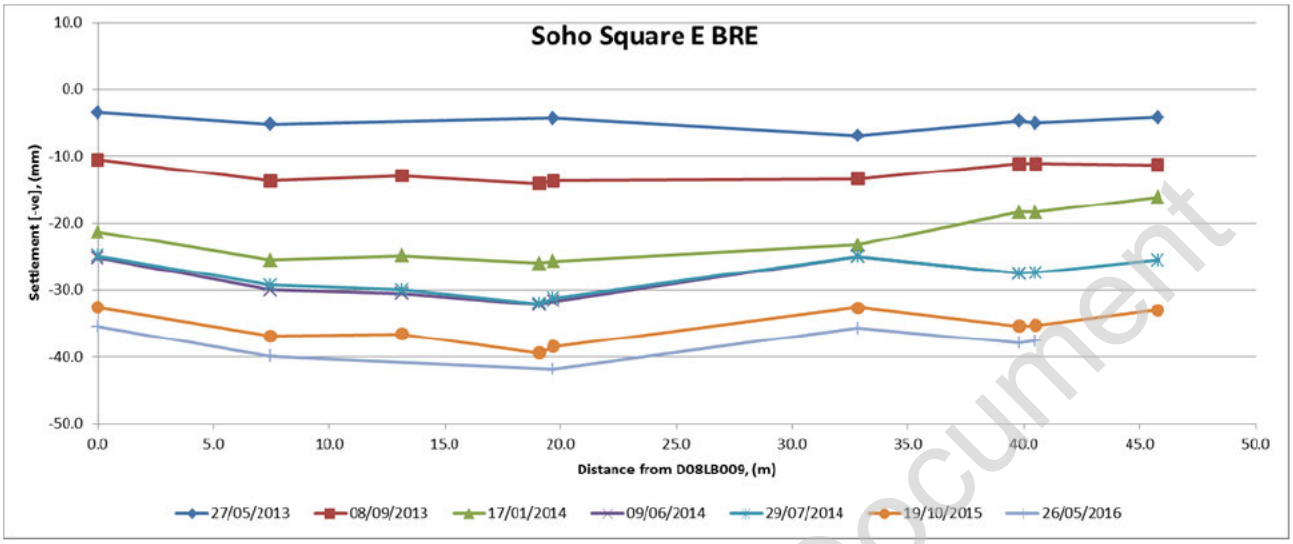
- Data are presented for the BRE located at the western end of the south facade of Manette Street. The points are outside the southern extremity of the GS5 arrays.
- Maximum settlement was less than 5mm throughout construction and subsequently.
- There was negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

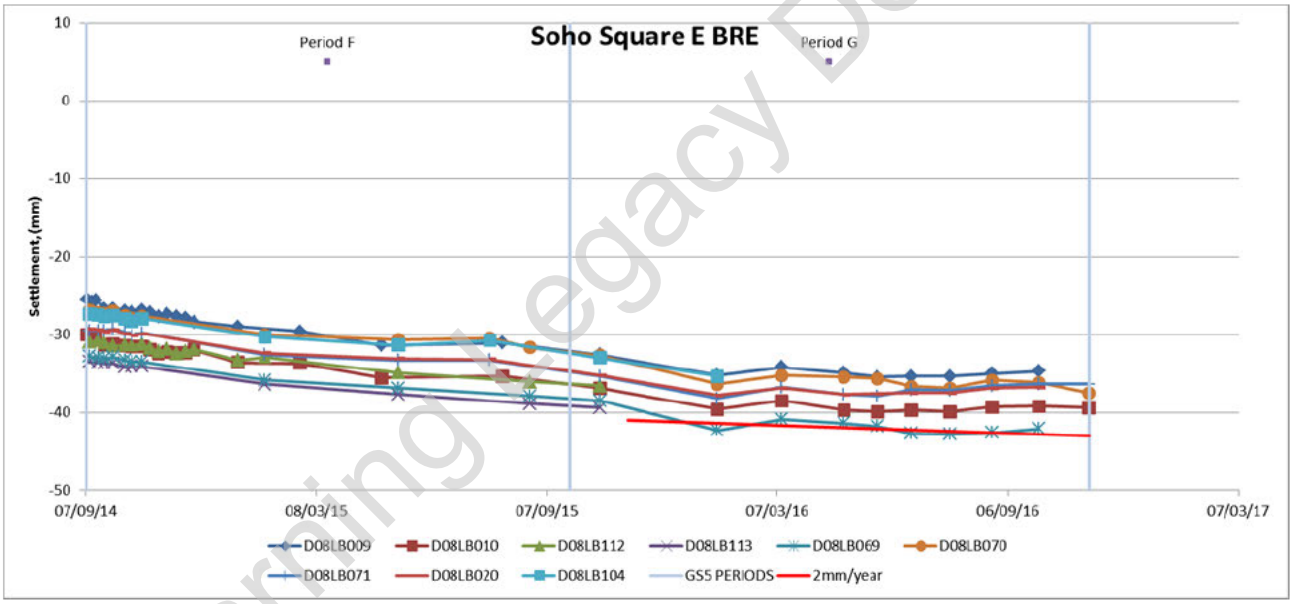
4.10. Soho Square east – south

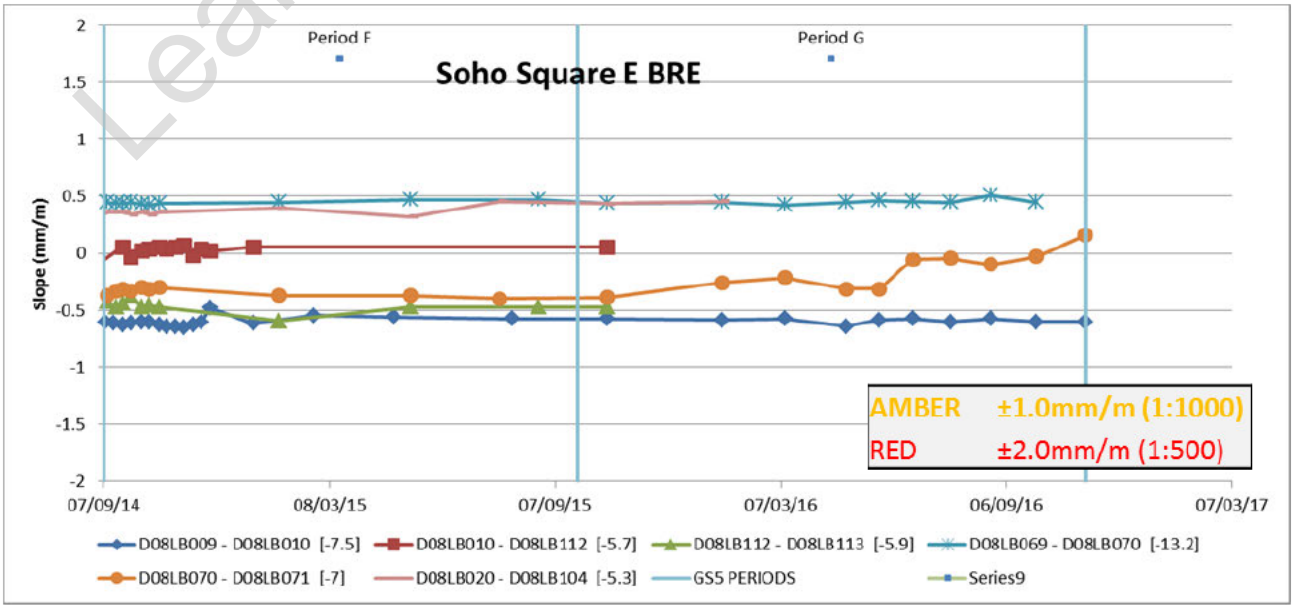








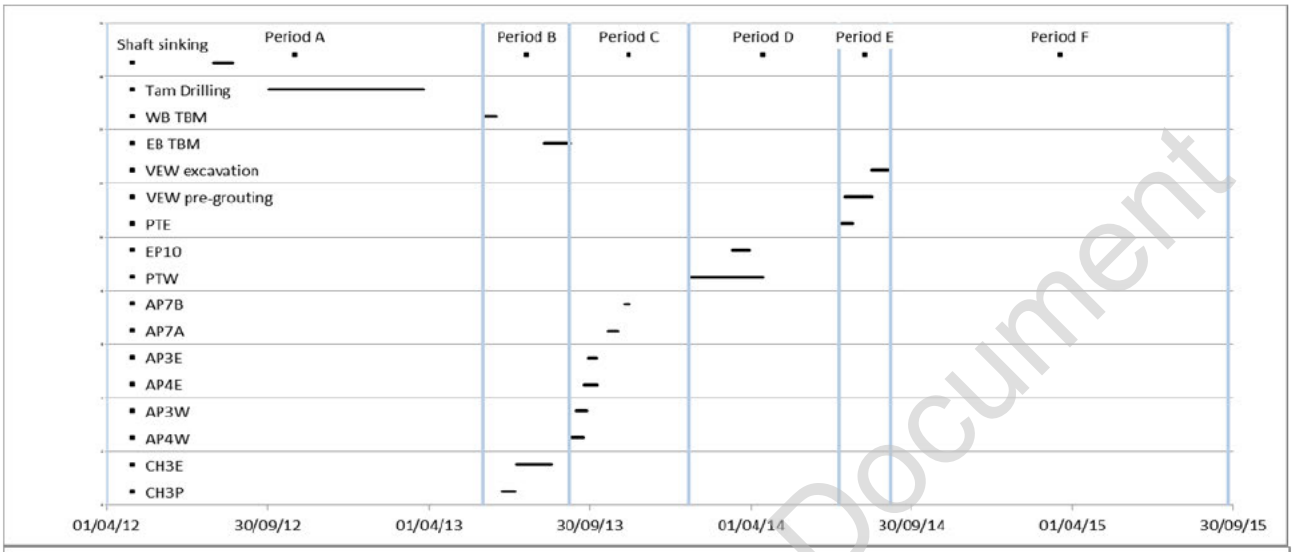


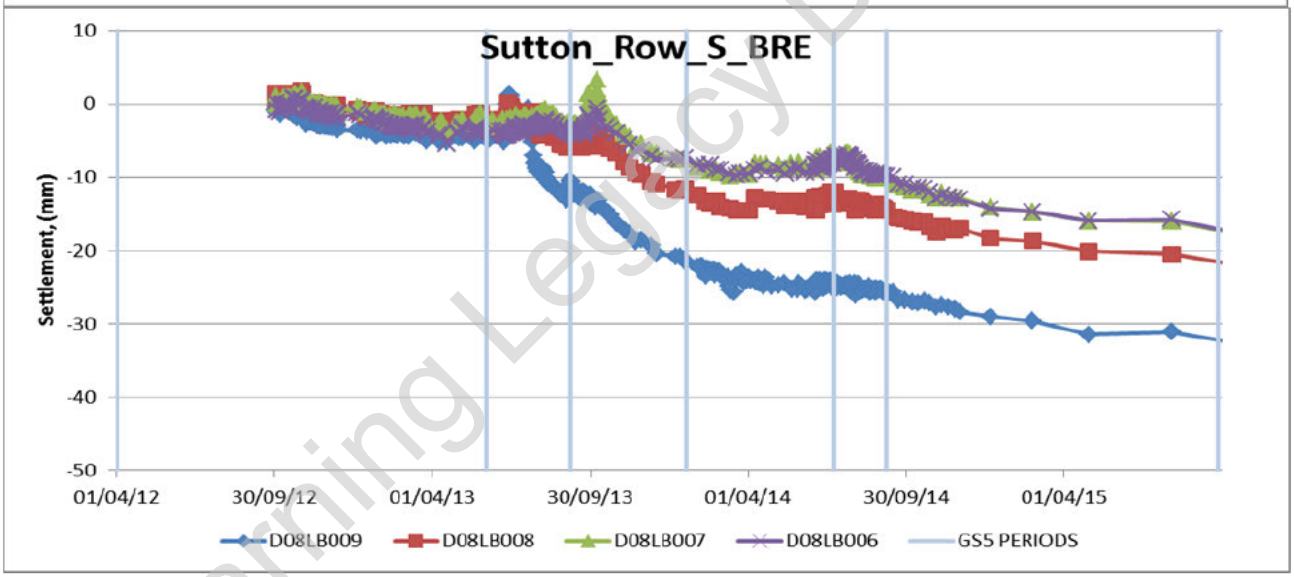


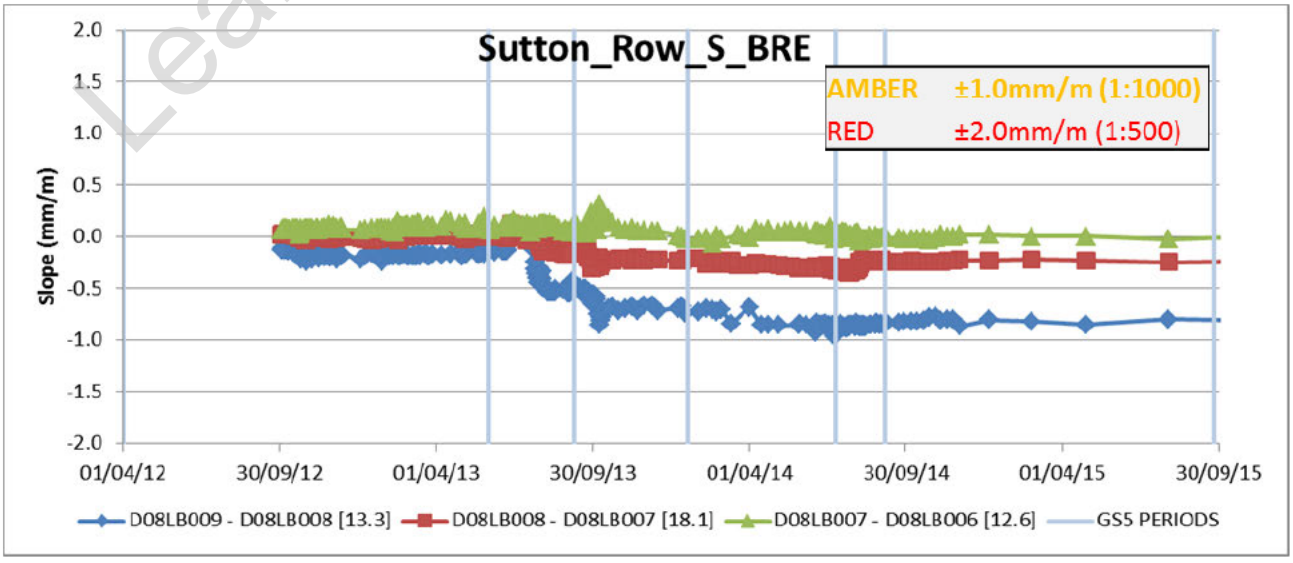
The following points are noted:

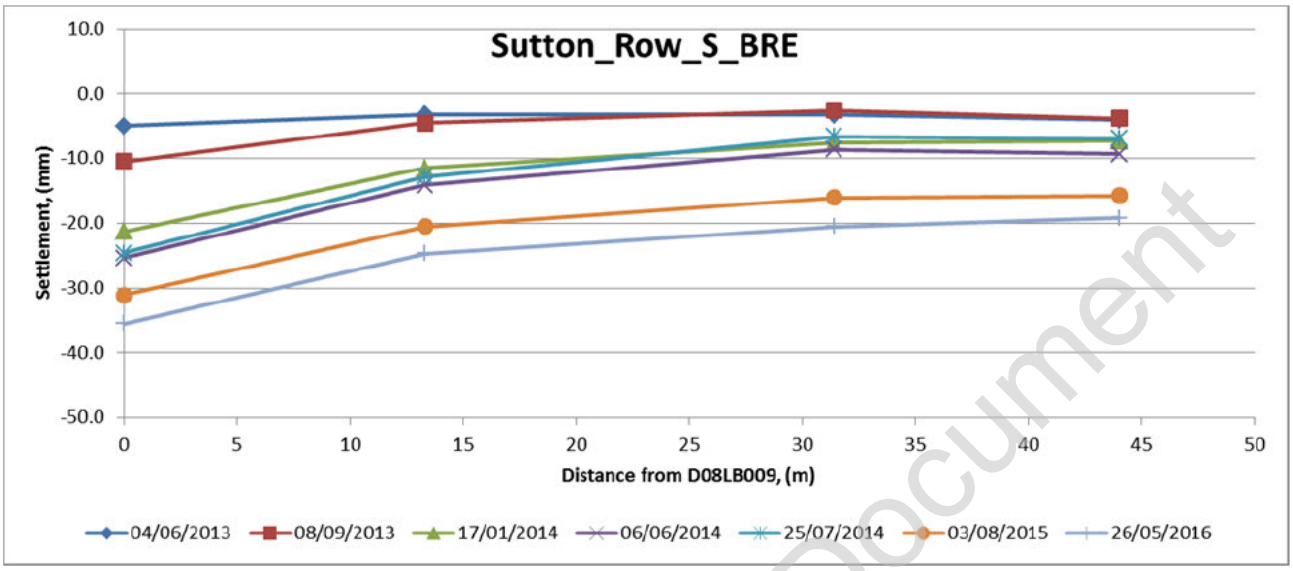
- Data are presented for the BRE located on the east facade of Soho Square, south of Sutton Row. The whole facade is within the extent of the GS5 array.
- Settlement increased to ~10mm during in Period A but was reduced to about 5mm by the end of Period A by pre-treatment grouting.
- At the end of Period B, the construction of CH3P, CH3E and the WBRT (without concurrent grouting) had increased the maximum settlement to ~15mm.
- In the first half of Period C, construction of AP3W, AP4W, AP3E and AP4E show no evidence of significant volume loss settlement; however, settlement increased steadily throughout the Period and reached a maximum of ~25mm at the end of Period C.
- The impact associated with PTW in Period D is evident with pre-heave followed by settlement followed by heave giving a small net movement. There was only a minor effect on the points at the north end of the profile (D08LB009 to D08LB113) and consequently PTW did not significantly increase the maximum value of settlement on the profile, albeit the maximum settlement increased from ~25mm to ~34mm during Period D.
- Since the completion of PTW, during the remainder of Period D through Period E and F, the rate of post construction settlement gradually decreased. An increased rate is eveident at the start of Period F, presumed to be associated with post-construction consolidation associated with VEW, followed by a gradual decrease in rate throughout the remainder of Period F.
- Significant differential settlement is evident and the associated slopes are presented. The slope between D08LB070 and D08LB071 almost reached the Amber trigger value on one reading (maximum 0.96mm/m) during construction of PTW, but was subsequently reduced by grout jacking.
- At the end of construction, the slopes were significantly less than the Amber trigger and remained stable throughout the post-construction monitoring.
- Long term monitoring – Period G
    - Monitoring continues on this façade and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring. The slope time history over the same Periods is also presented.
    - The rate of settlement is gradually decreasing: over a 12 months period it is slightly greater than 2mm/year, but over the latest 6 months the rate is about 2mm/year.
    - The data show that the slopes are stable and are significantly less than 1.0mm/m.

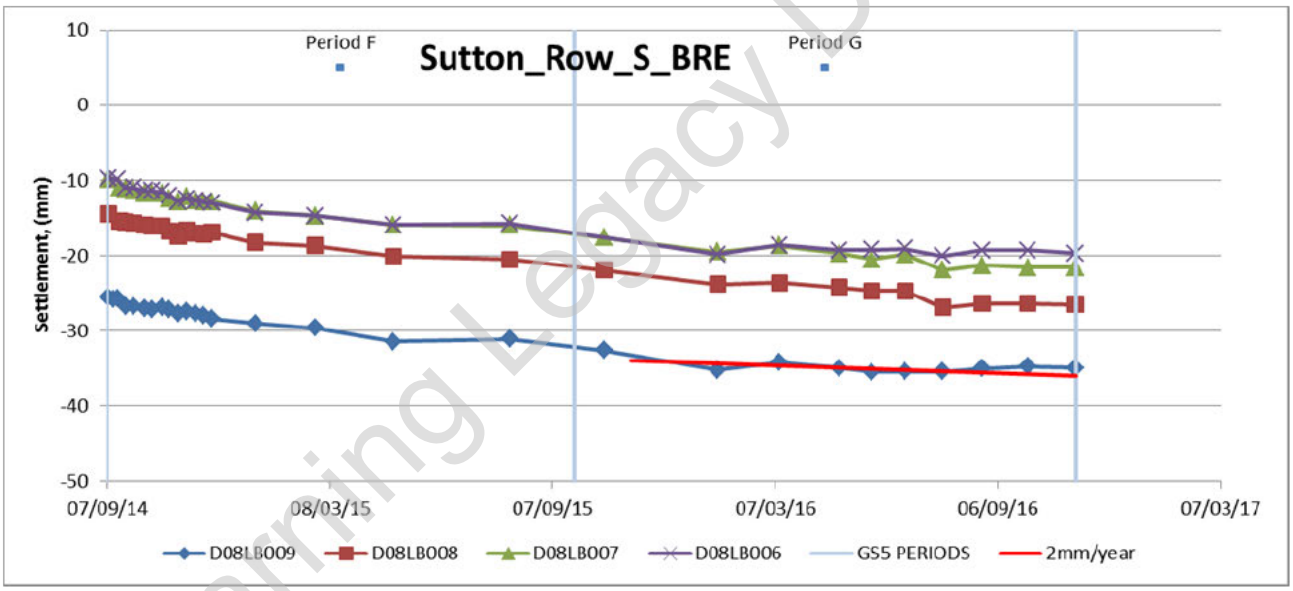
4.11. Sutton Row - south

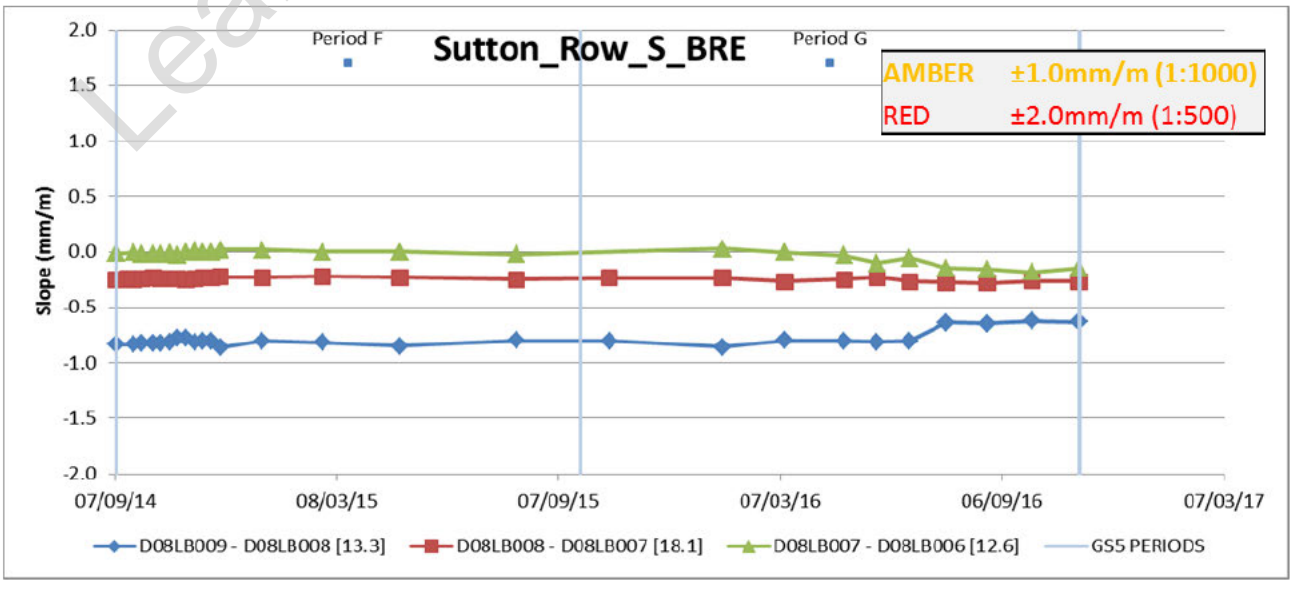












The following points are noted:

- Data are presented for the BRE located on the south facade of Sutton Row, the north façade of St. Patrick's church. The whole facade is within the extent of the GS5 array.
- Settlement was less than 5mm in Period A.
- During Period B, the construction of CH3P, CH3E increased the maximum settlement to ~13mm. Subsequent grout jacking reduced the maximum to ~10mm at the end of the Period.
- In the first half of Period C, construction of AP3W, AP4W, AP3E and AP4E show no evidence of significant volume loss settlement, however, settlement increased steadily throughout the Period and reached to a maximum of ~22mm at the end of Period C and 25mm at the end of Period D.
- The construction of PTE in Period E had little impact but post construction in Period F, settlement increased to 31mm.
- Significant differential settlement is evident and the associated slopes are presented. The slopes was less than the Amber trigger throughout construction and subsequently.
- Long term monitoring – Period G
    - Monitoring continues on this façade and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring. The slope time history over the same Periods is also presented.
    - The rate of settlement is gradually decreasing: over a 12 months period it is slightly greater than 2mm/year, but over the latest 6 months the rate is about 2mm/year.
    - The data show that the slopes are stable and less than 1.0mm/m.

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 D. Details are given in Table 5.1. By inspection, no Deflection Ratio triggers have been breached.

Slope triggers are as follows:

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

PLP monitoring data from the kerblines within the footprint of GS5 are presented in the following sections, namely:

- Soho Square South – outer
- Soho Square South – inner
- Bateman's Buildings
- Greek Street west
- Manette Street North (west)
- Manette Street South (west)
- Soho Square East – outer
- Soho Square East - inner

Note that the PLPs on the north kerbline of Sutton Row have been reported in the GS4 report (C300-BFK-C4-RGN-CRT00_ST005-51228).

The plots presented for each comprise, as appropriate:

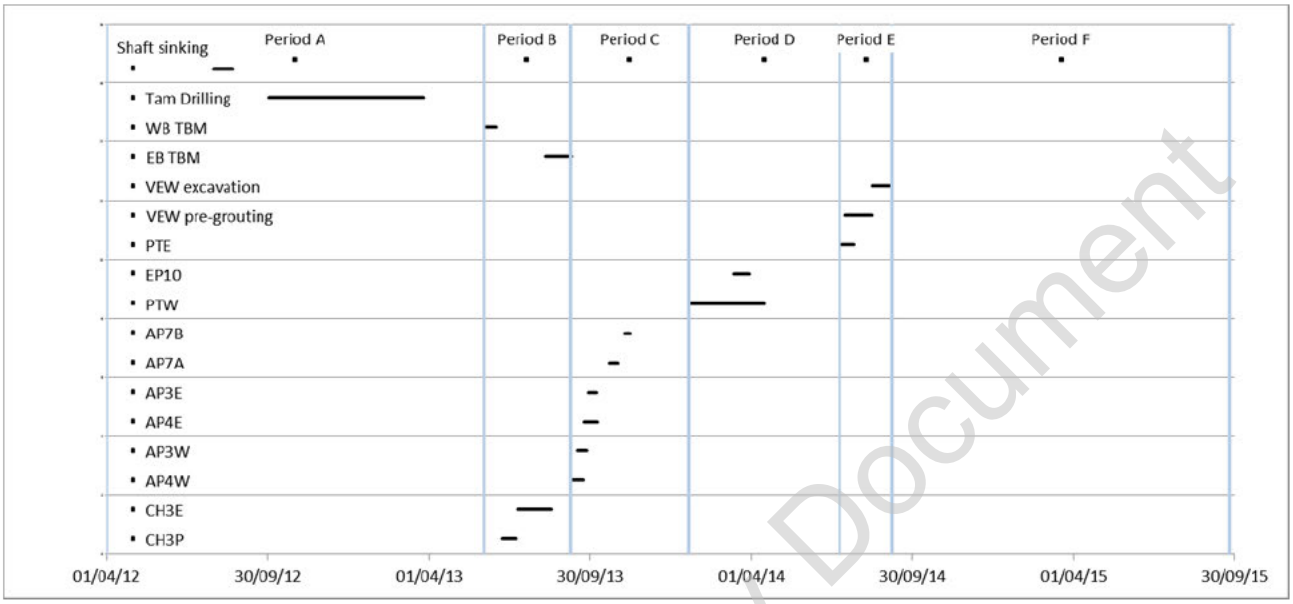
1. Summary of tunnel construction and associated construction periods
2. Time settlement history up to the end of the general monitoring in Period F
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres shown in the legend in square brackets
5. Time settlement history since the completion of tunnelling i.e. construction Periods F and G for points monitored past September 2015
6. Time slope history since the completion of tunnelling i.e. construction Periods F and G for points monitored past September 2015

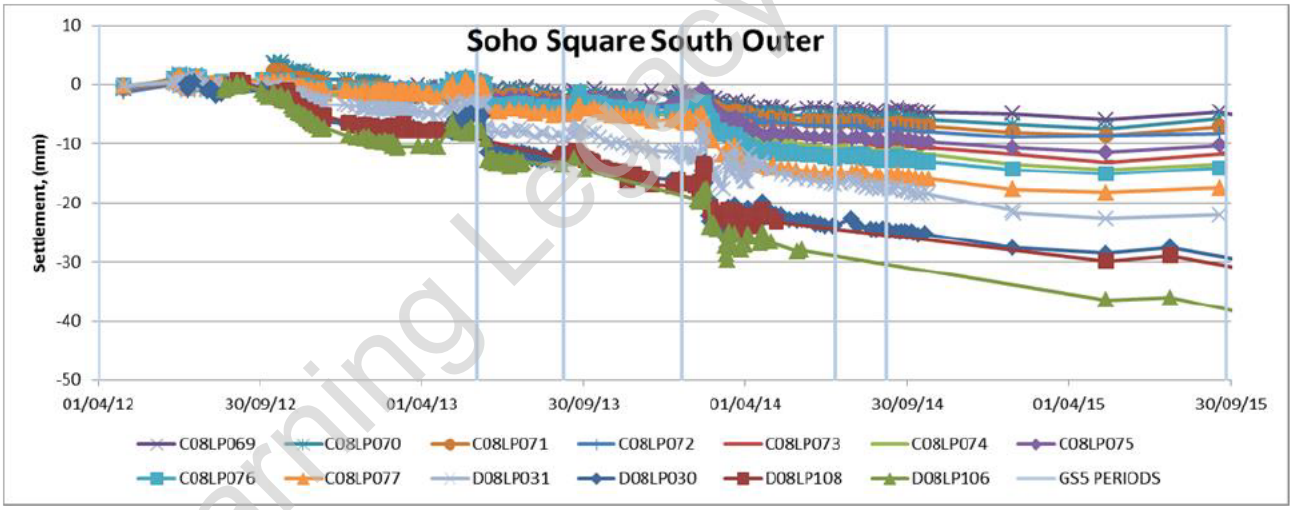
Table 5.1 Details of Amber trigger breaches on PLP

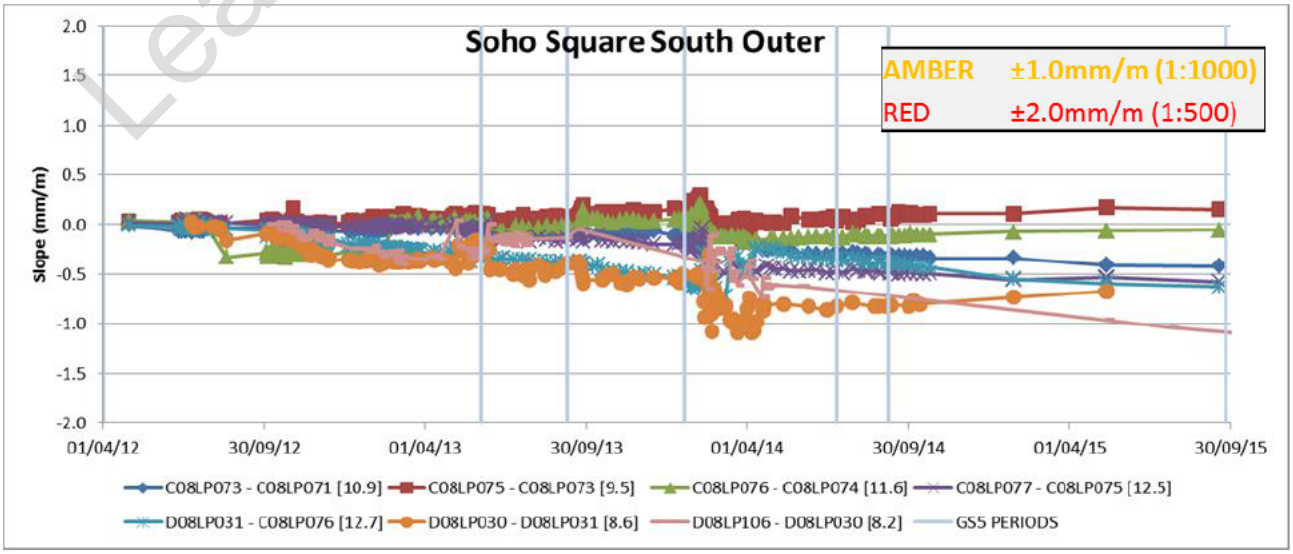
Kerb Line		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Soho Square South - outer:					
D08LP30 – D08LP031	Amber-	PTW: Transitory within exclusion zone for PTW: below trigger from 09/04/14 onwards	20/03/14	1.09	0.70
D08LP106 – D08LP030	Amber-	POST CONSTRUCTION	24/07/15	1.16	1.12
Soho Square South - inner: NONE					
Bateman's Buildings: NONE					
Greek Street -West					
D08LP031 – D08LP033	Amber	POST CONSTRUCTION	28/01/15	1.16	1.16
Manette Street – North: NONE					
Manette Street – North : NONE					
Soho Square East - outer: NONE					
Soho Square East - inner: NONE					

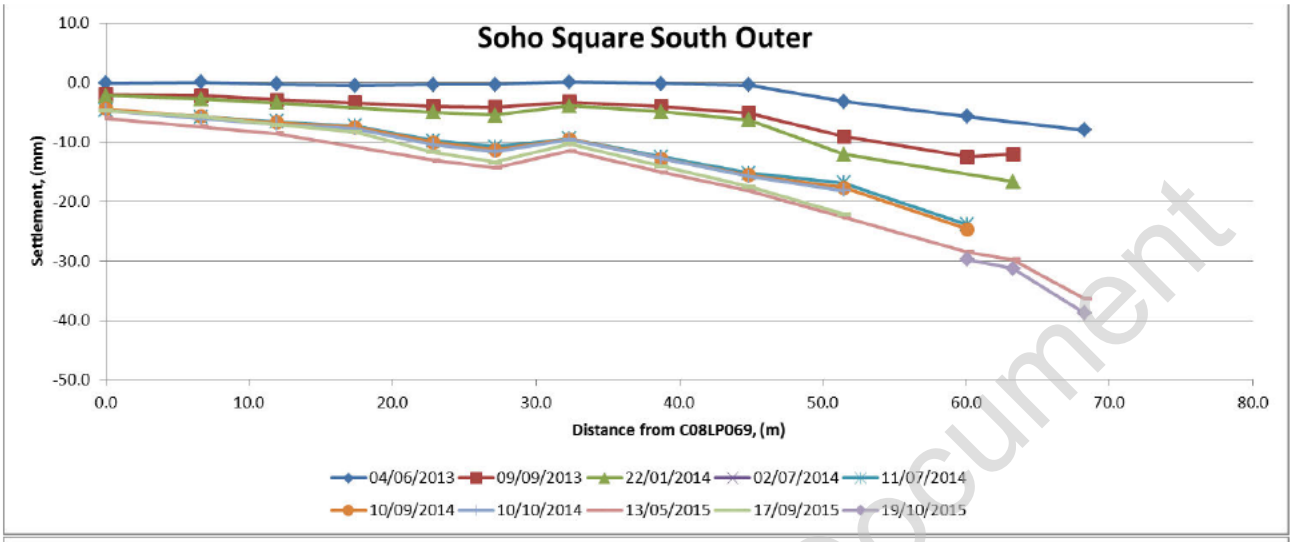
Figure 5.1 Location of PLP and Amber slope trigger breaches

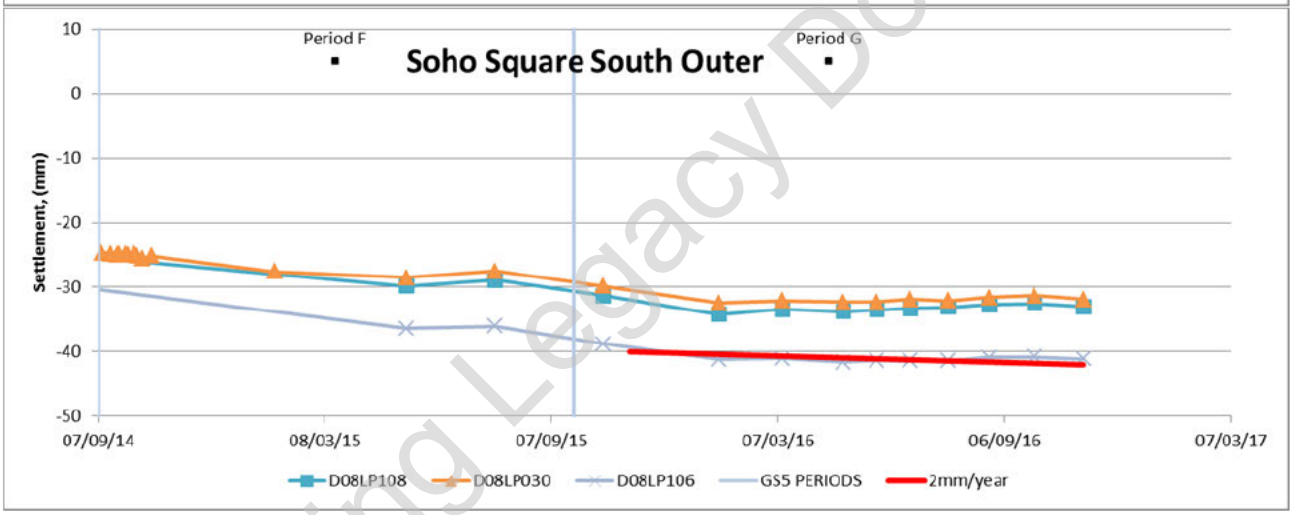
5.2. Soho Square South – outer

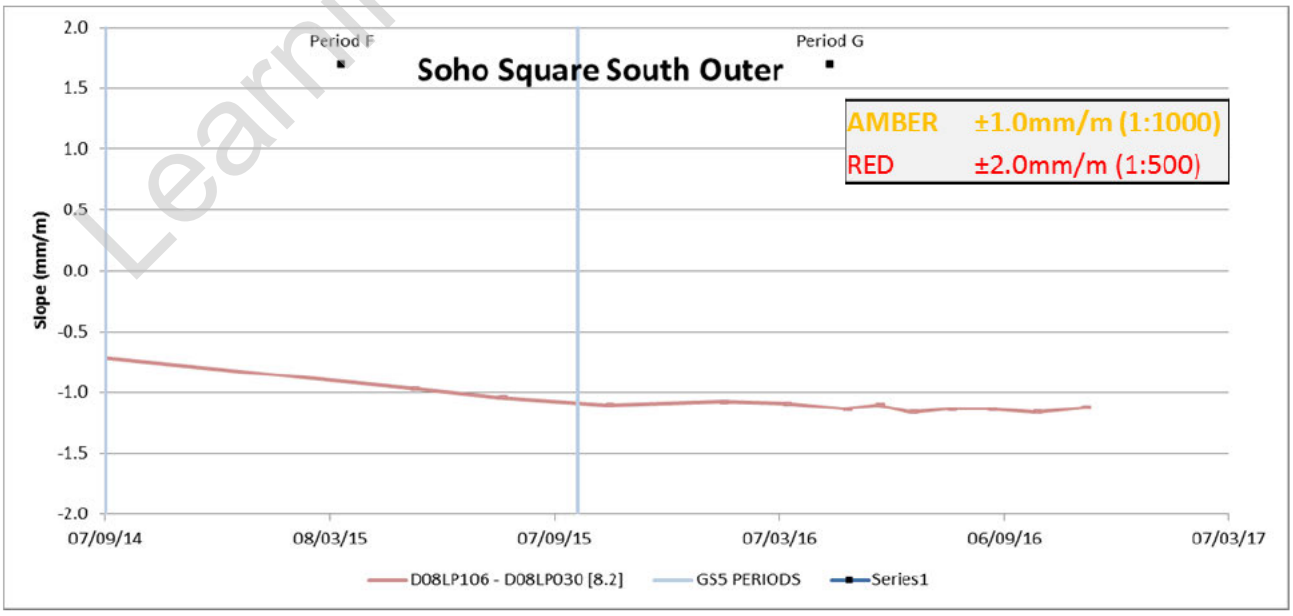








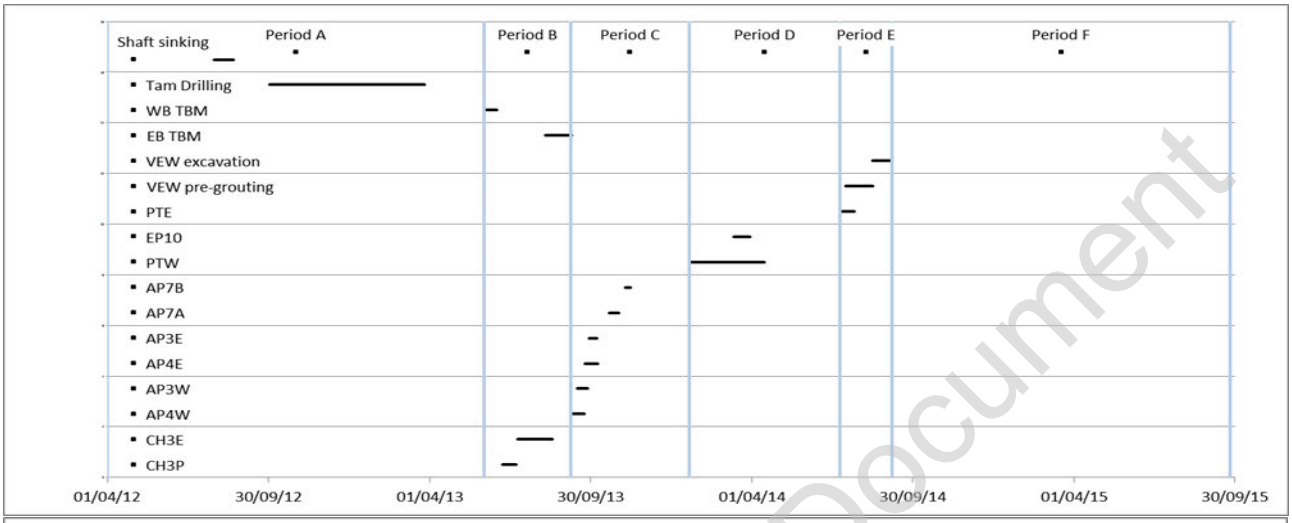


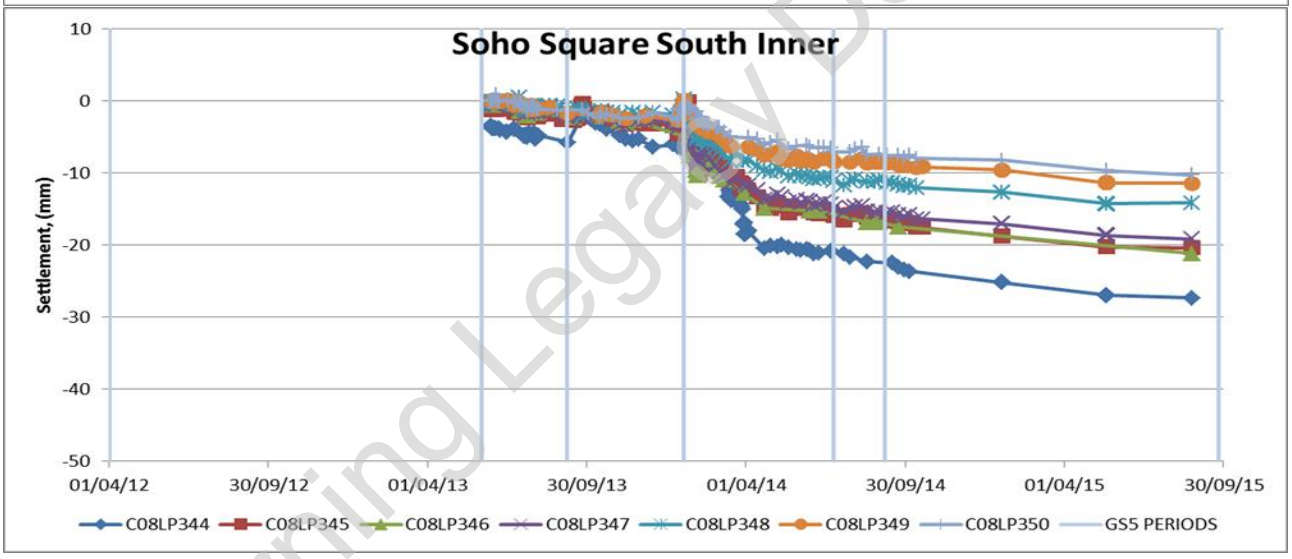


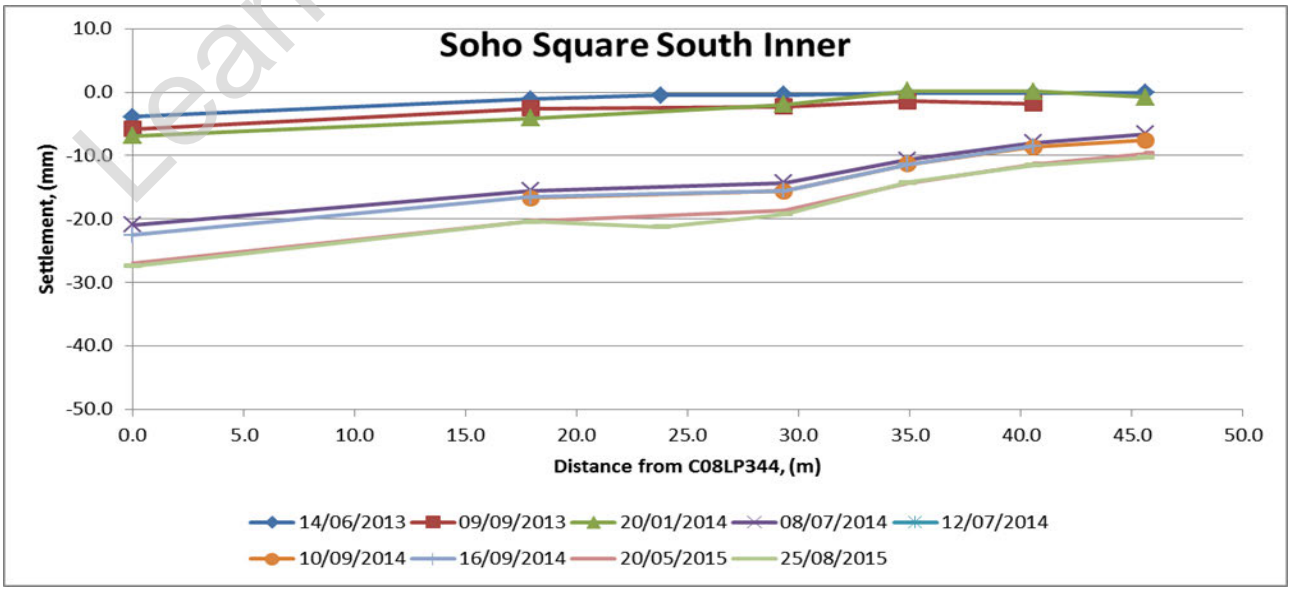
The following points are noted:

- Data are presented for the PLP located on the south outer kerb line of Soho Square to the east of Frith Street. All points above a distance of 3m on the profile plot are within the plan extent of the GS5 arrays.
- Settlement increased to ~10mm in Period A but was reduced to about 8mm at the end of Period A by pre-treatment grouting.
- At the end of Period B, the construction of the WBRT without concurrent grouting had increased the maximum settlement to ~14mm.
- At the start of Period C, construction of AP3W and AP4W resulted in a small net reduction in movement due to concurrent grouting, however, post construction settlement increased to a maximum of 17mm at the end of Period C.
- The most significant impact was associated with PTW in Period D. Concurrent grouting and subsequent grout jacking limited the increase in settlement to ~7mm.
- Since the completion of PTW, during the remainder of Period D through Periods E and F, the rate of post construction settlement has gradually decreased. A maximum settlement of ~37mm was recorded at the end of Period F.
- Significant differential settlement is evident and the associated slopes are presented. The slope between D08LP030 and D08LP 031 temporarily exceeed the Amber trigger value during construction of PTW. Details are given in Table 5.1
- Long term monitoring – Periods F and G
    - Monitoring continued during Period G on the 3 most easterly points and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring. The slope time history over the same periods is also presented.
    - The rate of post construction settlement gradually decreased and over the last 12 months of Period G the rate is about 2mm/year.
    - The available data show that the slope between points D08LP106 and D08LP030 increased significantly in Period F, exceeding 1mm/m towards the end of Period F. The slope has been effectively stable during Period G at ~1.1mm/m.

5.3. Soho Square South – inner



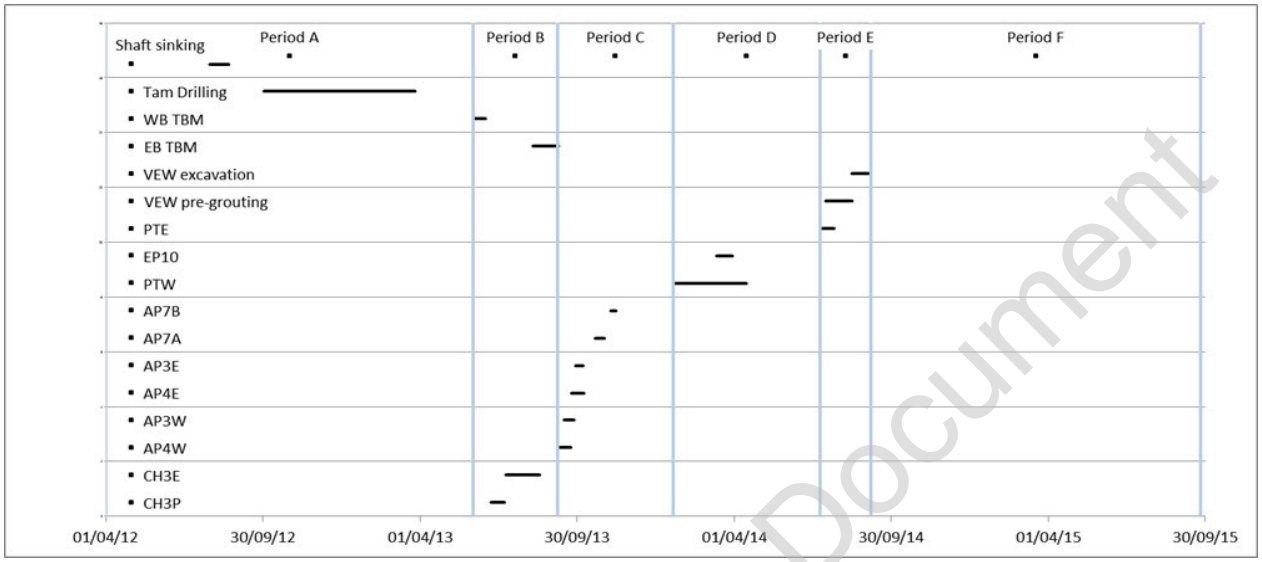


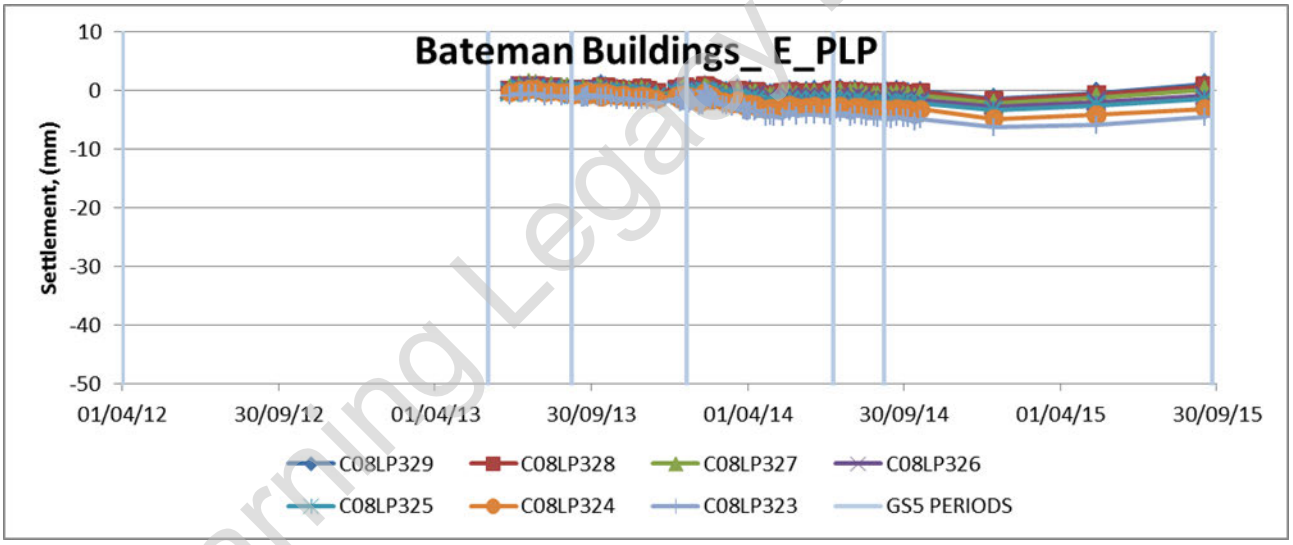


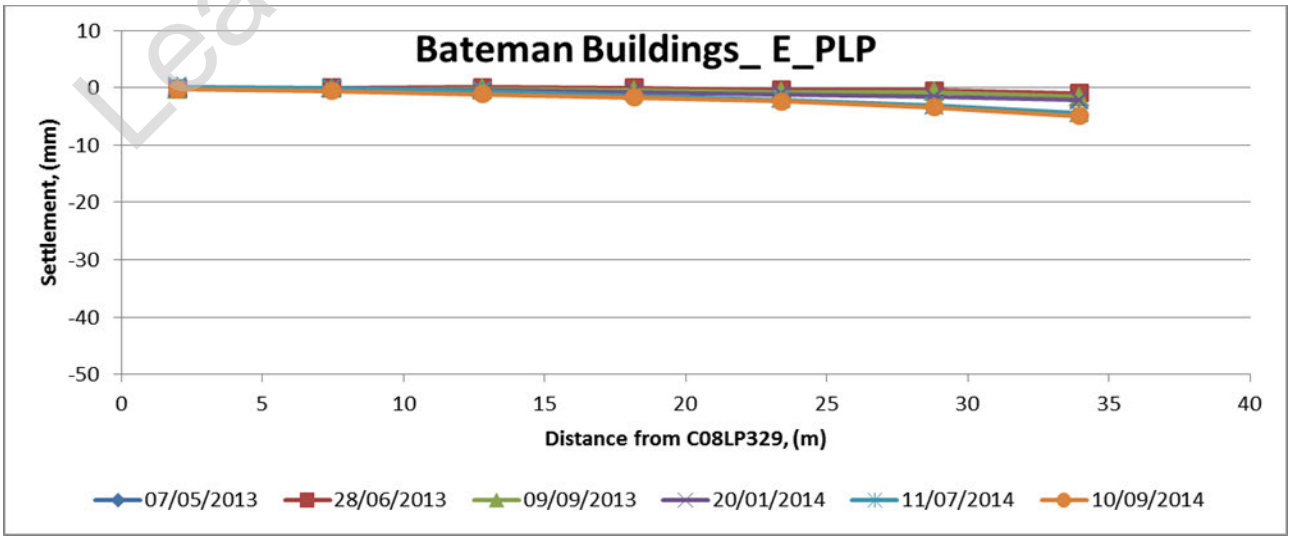
The following points are noted:

- Data are presented for the PLP located on the south inner kerb line of Soho Square to the east of Frith Street. All points up to a distance of 35m on the profile plot are within the plan extent of the GS5 arrays.
- Settlement was negligible at the end of Period A. At the end of Period B, the construction of the WBRT together with grout jacking resulted in a maximum settlement of 6mm.
- At the start of Period C, construction of AP3W and AP4W resulted in a small net reduction in movement due to concurrent grouting, however, post construction settlement increased to a maximum of 7mm at the end of Period C.
- The most significant impact was associated with PTW in Period D. Concurrent grouting and subsequent grout jacking limited the increase in settlement to ~14mm.
- Since the completion of PTW, during the remainder of Period D through Periods E and F, the rate of post construction settlement has gradually decreased. The maximum observed settlement at the end of Period F was 28mm
- By inspection of the profile plot, no slope triggers have been exceeded.

5.4. Bateman's Buildings



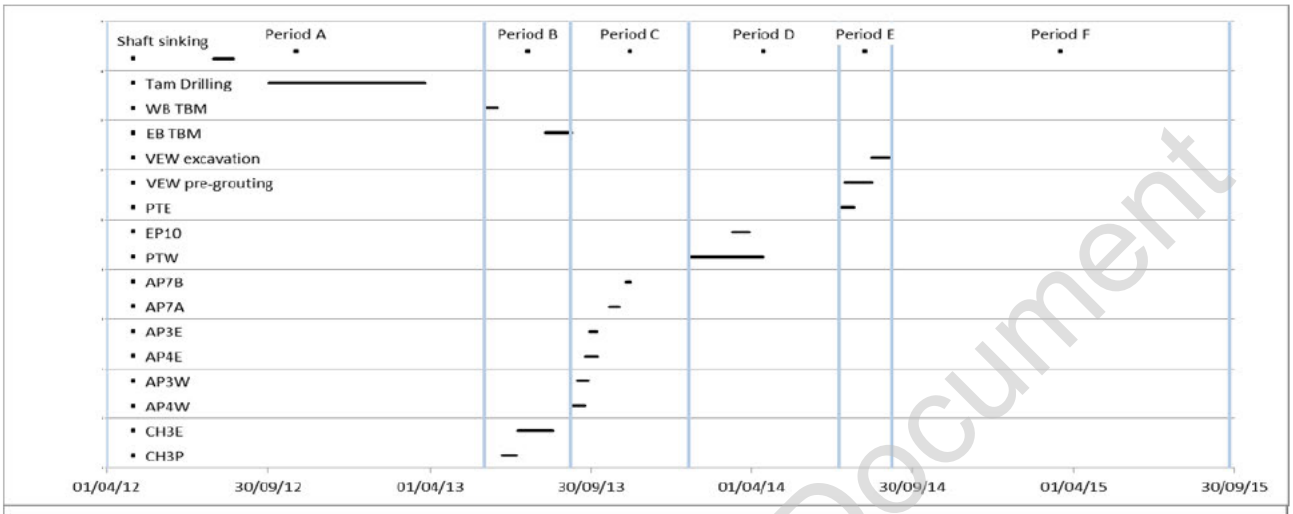


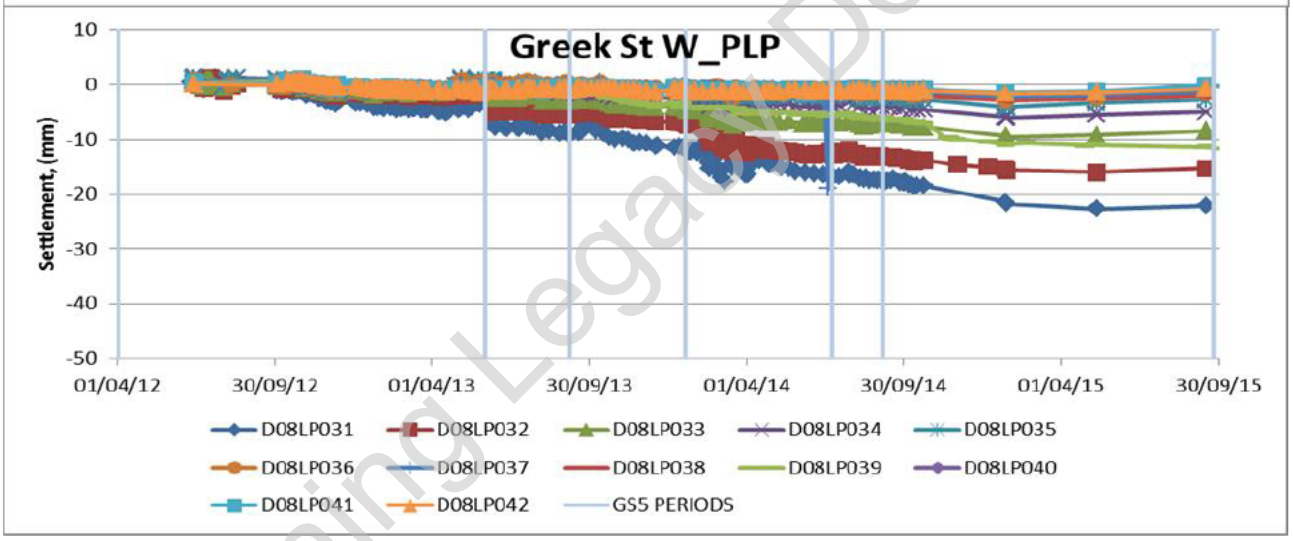


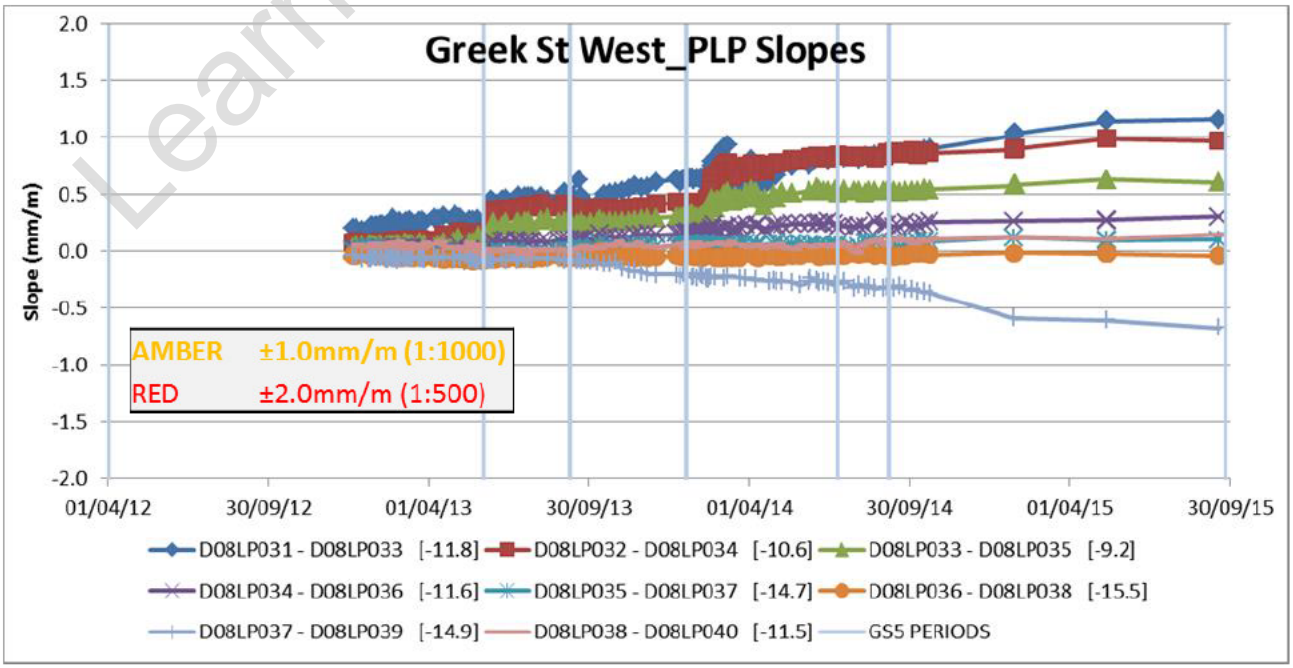
The following points are noted:

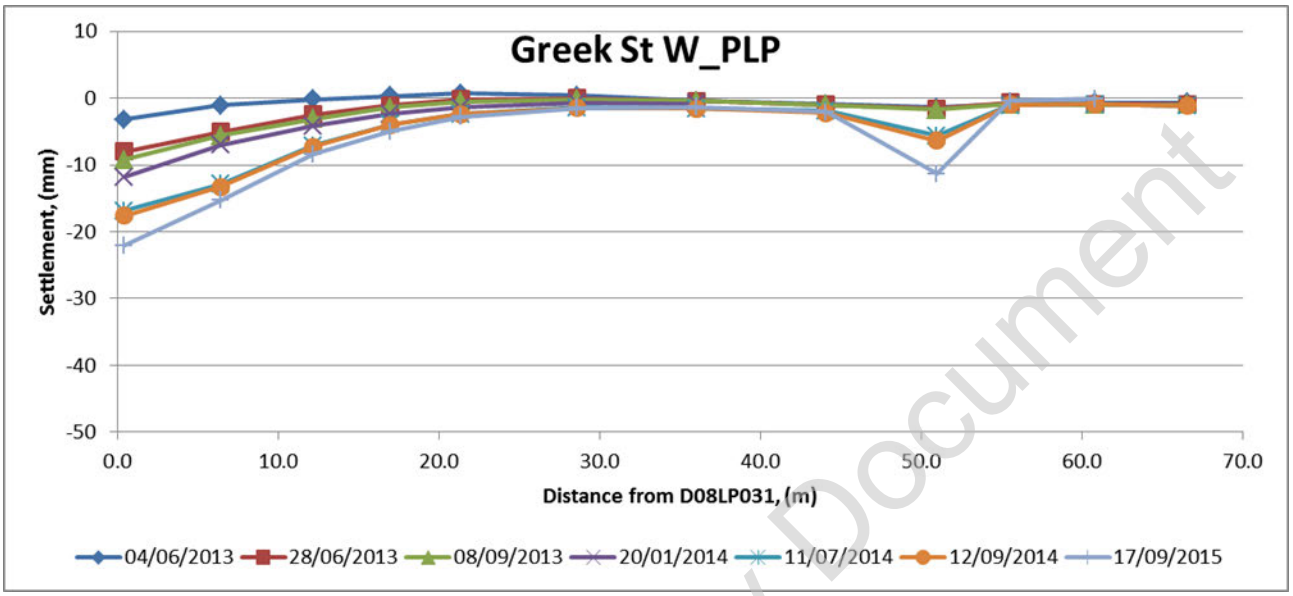
- Data are presented for the PLP located on the east kerb line of Bateman's Buildings and are located outside the plan extent of the GS5 arrays.
- Overall settlement was ~5mm or less throughout construction and subsequently.
- There is negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

5.5. Greek Street -west





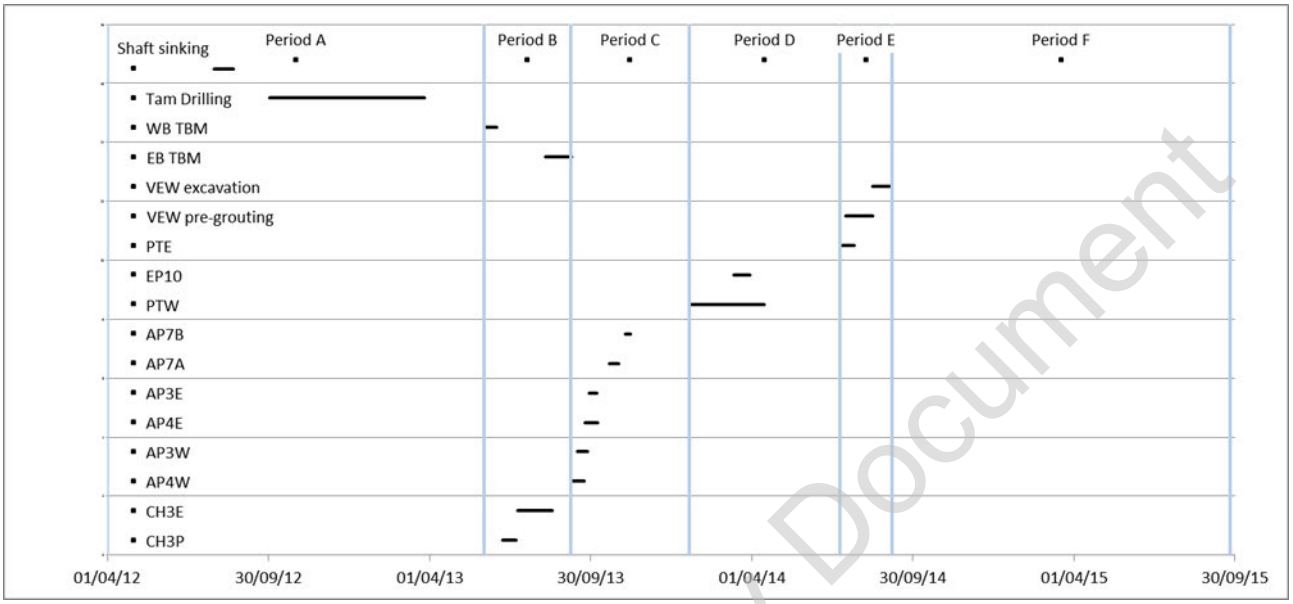


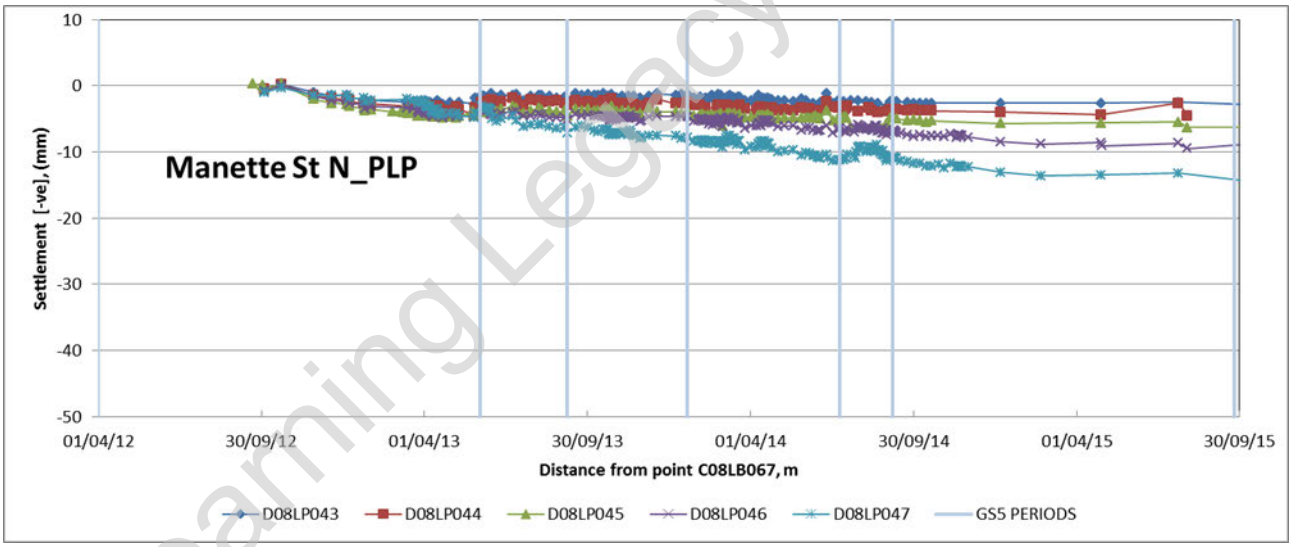


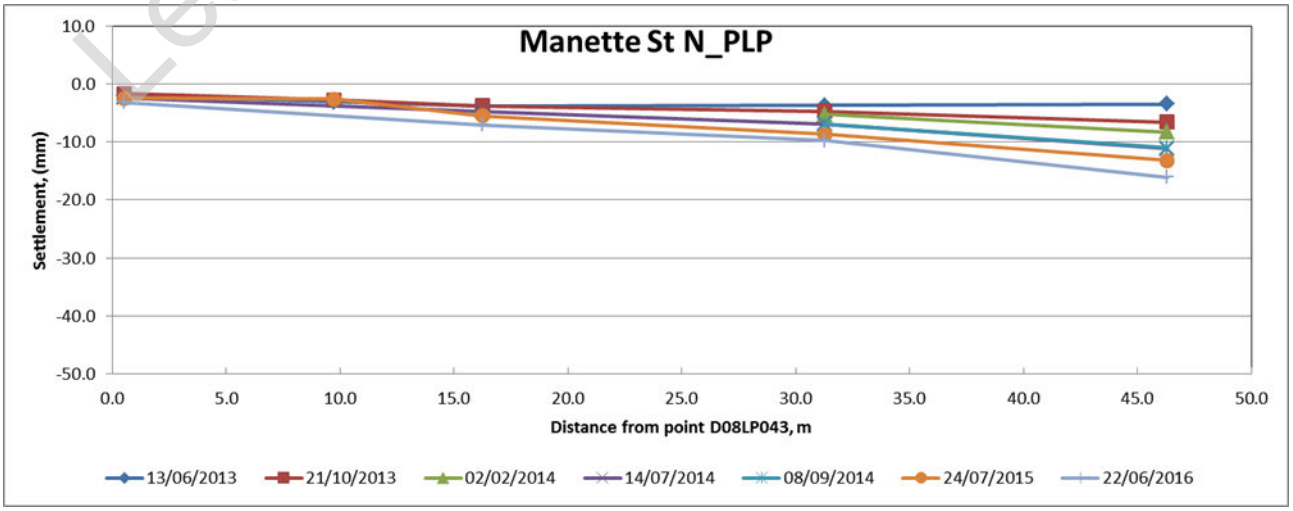
The following points are noted:

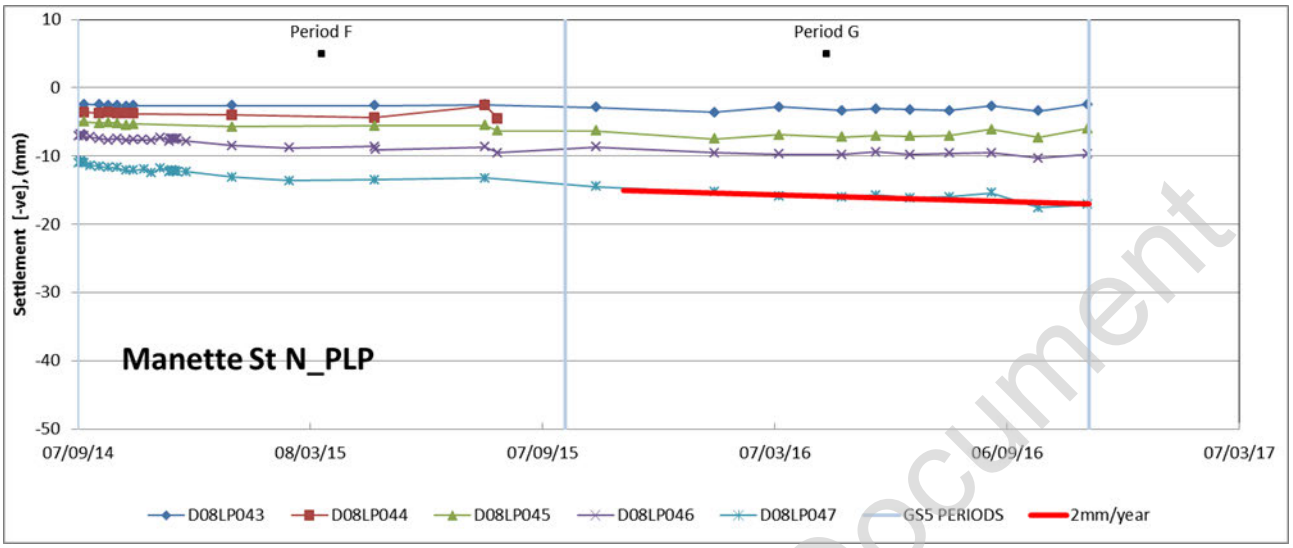
- The PLP on the west kerb line of Greek Street are within the grouting array from GS5. The adjacent building is part of 27 Soho Square (a piled building) which is excluded from the specified grouting zone.
- Overall settlement was minor at the end of Period A (~3mm), increased to ~10mm during Period B due to the WBRT and to ~13mm associated with AP3W and AP4W in Period C. Minor settlement during PTW and subsequent consolidation increased settlement to ~18mm at the end of construction (Period E).
- Post construction settlement has increased to 22mm, but appears to have stabilised rapidly.
- Beyond a distance of 25m on the profile plot, outside the plan extent of the grouting array, settlement was negligible (<5mm) except for one point at distance ~52m. The movement recorded on this point is not considered to be associated with BFK works.
- There are significant differential movements within the grouting zone and the time slope history is presented: this shows that slopes remained below the Amber trigger level throughout construction but the trigger was exceeded between B08LP031 and D08LP033 in the post construction period, stabilizing at a value of ~1.2mm/m.

5.6. Manette Street north





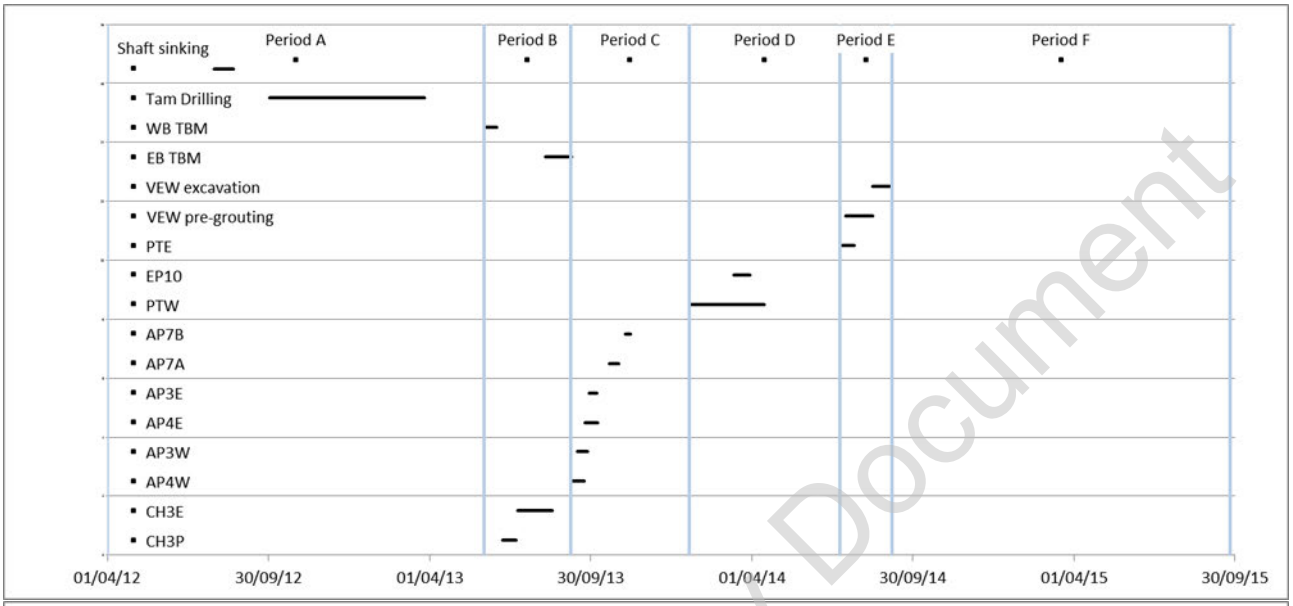


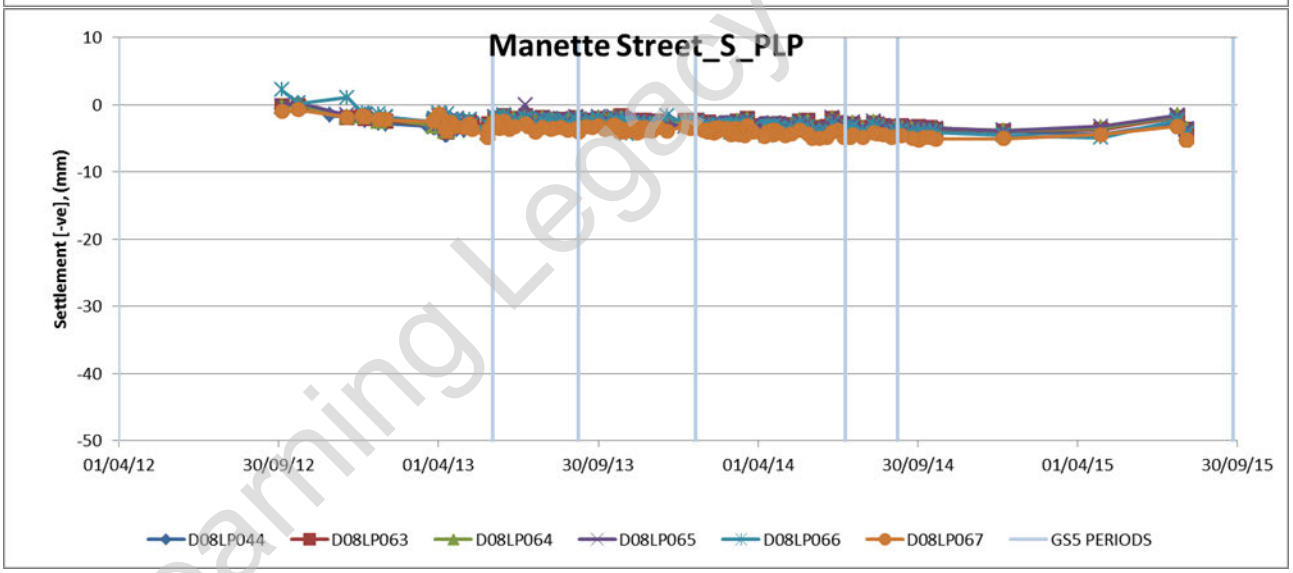


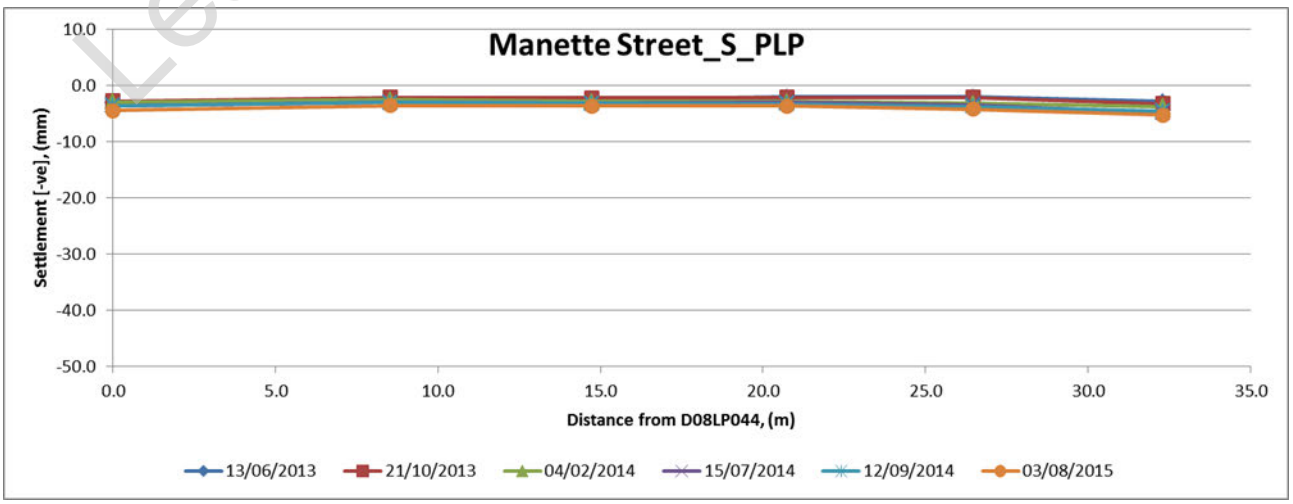
The following points are noted:

- Data are presented for the PLP located at the western end of the north kerb line of Manette Street. The points are on or outside the southern extremity of the GS5 arrays.
- For the points adjacent to the GS5 array (up to Distance = 30m), the maximum settlement was less than 10mm throughout construction.
- Post-construction, settlement increased gradually to 15mm at the end of Period F.
- By inspection of the profile plot, no slope triggers have been exceeded.
- Long term monitoring – Period G
    - Monitoring continued on these points during Period G and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring.
    - The rate of settlement gradually decreased and over the final 12 months of Period G the rate is 2mm/year.
    - The long term monitoring indicates only a marginal change in differential settlement and, by inspection, slopes remain much less than 1mm/m.

5.7. Manette Street south



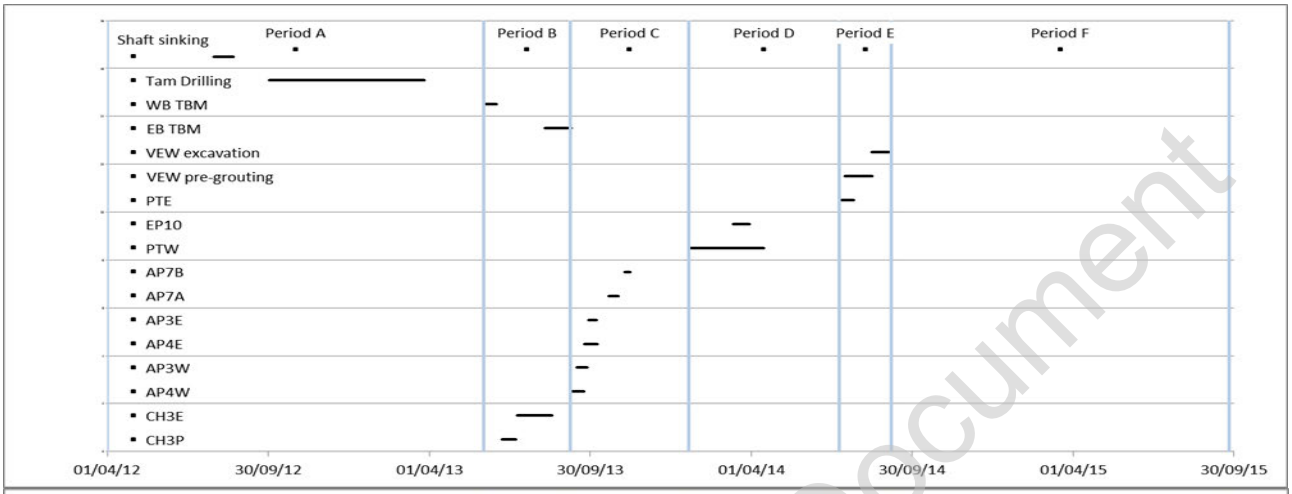


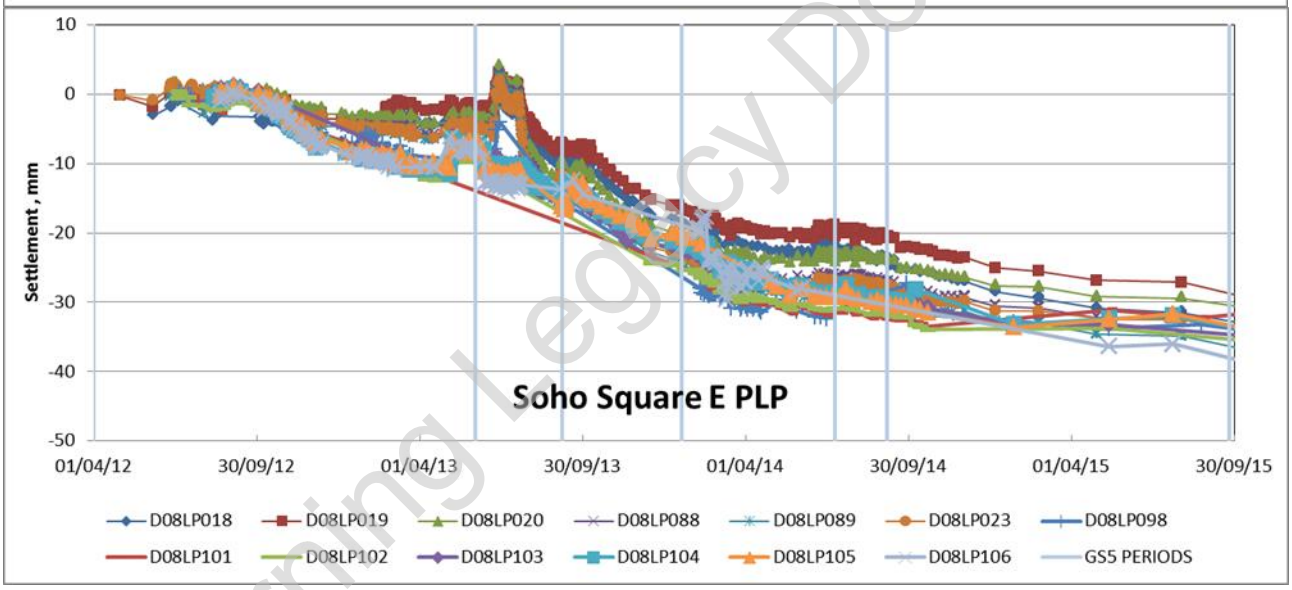


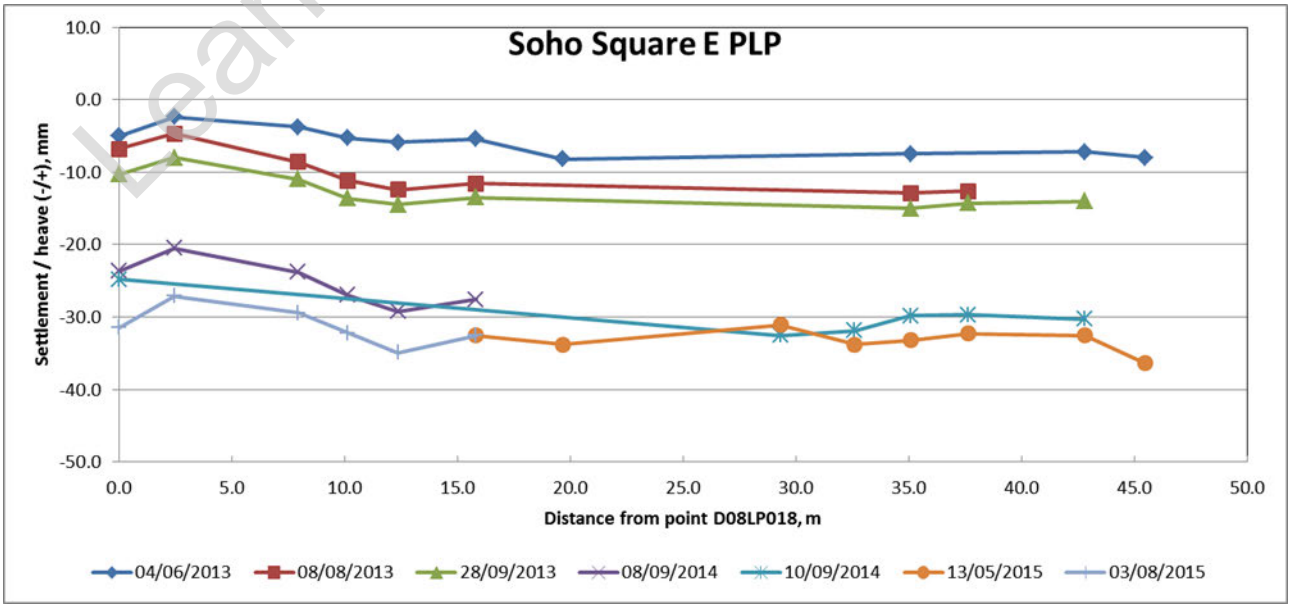
The following points are noted:

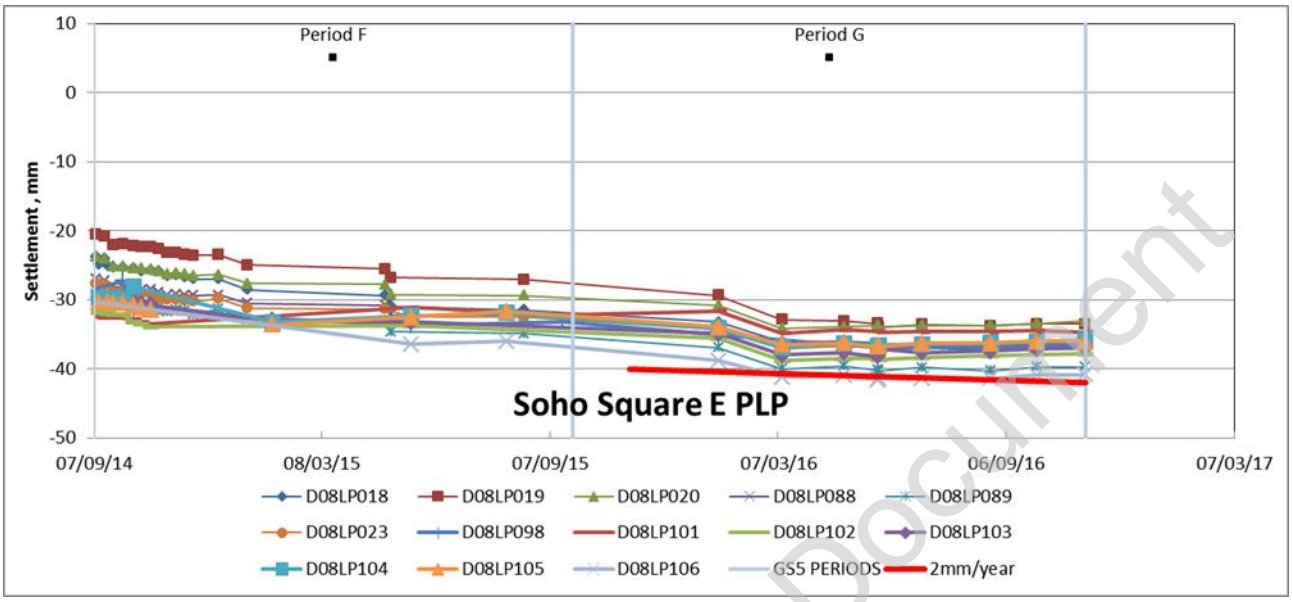
- Data are presented for the PLP located at the western end of the south kerb line of Manette Street. The points are on or outside the southern extremity of the GS5 arrays.
- Maximum settlement was less than 5mm throughout construction and subsequently.
- There was negligible change in settlement post-construction.
- By inspection of the profile plot, no slope triggers have been exceeded.

5.8. Soho Square east outer









The following points are noted:

- Data are presented for the PLP located on the outer kerbline on the east side of Soho Square, south of Sutton Row. The whole transect is within the extent of the GS5 array.
- Settlement increased to ~12mm during in Period A but was reduced to about 9mm at the end of Period A by pre-treatment grouting.
- During Period B, the construction of WBRT (without concurrent grouting) generated less than 5mm settlement, concurrent grouting with CH3P generated a reduction in settlement of up to 8mm followed by settlement of over 10mm associated with CH3E. The net effect of the works within Period B was a small increase in the maximum settlement to ~17mm.
- In the first half of Period C, construction of AP3W, AP4W, AP3E and AP4E show no evidence of significant volume loss settlement, however, settlement increased steadily throughout the Period and reached to a maximum of ~24mm at the end of Period C.
- The impact associated with PTW in Period D is evident in the settlement time history plot with pre-heave followed by settlement followed by heave giving a small net movement, increasing the maximum settlement to 32mm.
- Since the completion of PTW, during the remainder of Period D through Periods E and F, the rate of post construction settlement has gradually decreased.
- The differential movements are small throughout construction and subsequently and, by inspection of the profile plot, no slope triggers have been exceeded.
- Long term monitoring – Period G
    - Monitoring continued on these points during Period G and the data are presented from the end of construction (start of Period F) and are compared to the specified rate of settlement (2mm/year) for the termination of monitoring.
    - The rate of settlement has gradually decreased: over a 12 month period it is greater than 2mm/year, but over the latest 8 months the rate is less than 2mm/year.
    - The long term monitoring indicates only a marginal change in differential settlement and, by inspection, slopes remain much less than 1mm/m.

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 5. There were only two Amber trigger on building facades during construction: these were located at the north end of the east Greek Street façade and both of them were transitory during construction of PTW as a result of the extent of the exclusion zone for concurrent grouting. These two slopes exceeded the 1mm/m trigger again following completion of construction and one further slope on the north Soho Square façade of 1 Greek Steet reached, or was marginally above, the Amber trigger value. Given the nature and location of the slope trigger breaches, it can be directly concluded that there were no deflection ratio triggers exceeded.

Of the three Amber slope triggers on PLP, one occurred during construction associated with construction of PTW and was transitory. The other two PLP slope triggers occurred months after the end of construction and consequently there were no slope triggers extant at the end of construction. Given the nature and location of the slope trigger breaches, it can be directly concluded that there were no deflection ratio triggers exceeded.

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

7. CONCLUSION

Following the completion of tunnelling, monitoring data was reviewed as required on a daily, weekly, and / or monthly basis during the post construction period at SRG, CTC and ERP meetings: no further grout jacking was deemed necessary or desirable.

An abridged version of this report was submitted in October 2014, about 3 months after the end of tunnelling, to justify the de-commissioning of TCR Grout Shaft 5. This report was accepted by CRL and the grout shaft was subsequently de-commissiioned.

General manual monitoring was terminated under C300-PMI-01858, however, there were exceptions within the GS5 area for the House of St. Barnabus and St. Patrick's Church. CRL instructed an increased frequency of monitoring (monthly) in April 2016 (C300-PMI-1914) and the termination of monitoring in November 2016. The data is presented in Sections 4 and 5 and is summarised in Section 3.8. The rate of settlement is demonstrated to have reduced to 2mm/year in this area in accordance with the Works Information, albeit not over the stipulated 12 month period in all locations.

Appendix A

Assumptions used to produce contour plots of grout intensity

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

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

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

Or, rearranging:

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

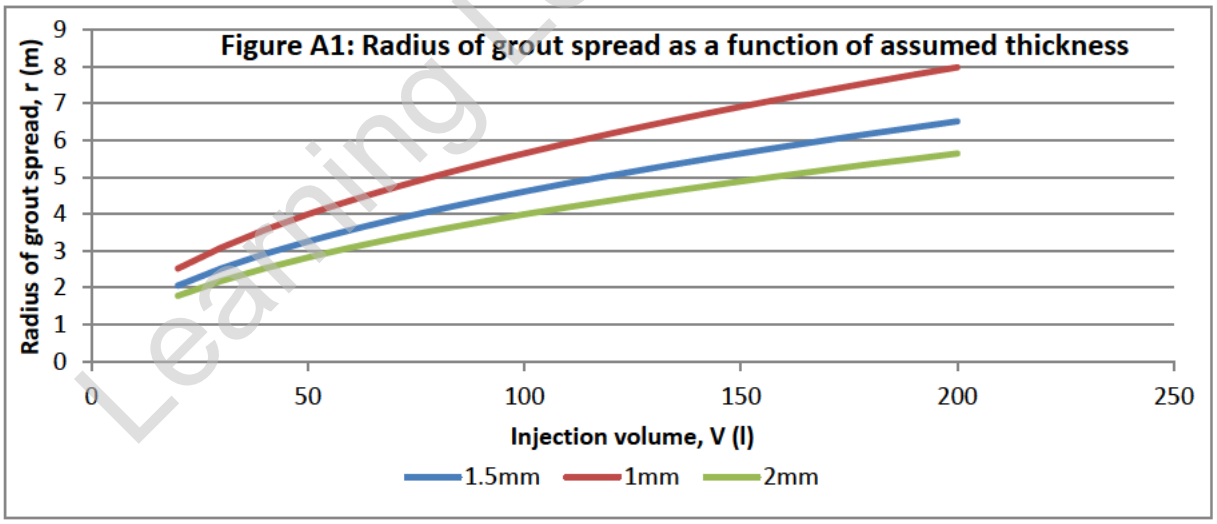


Figure A1: Radius of grout spread as a function of assumed thickness

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

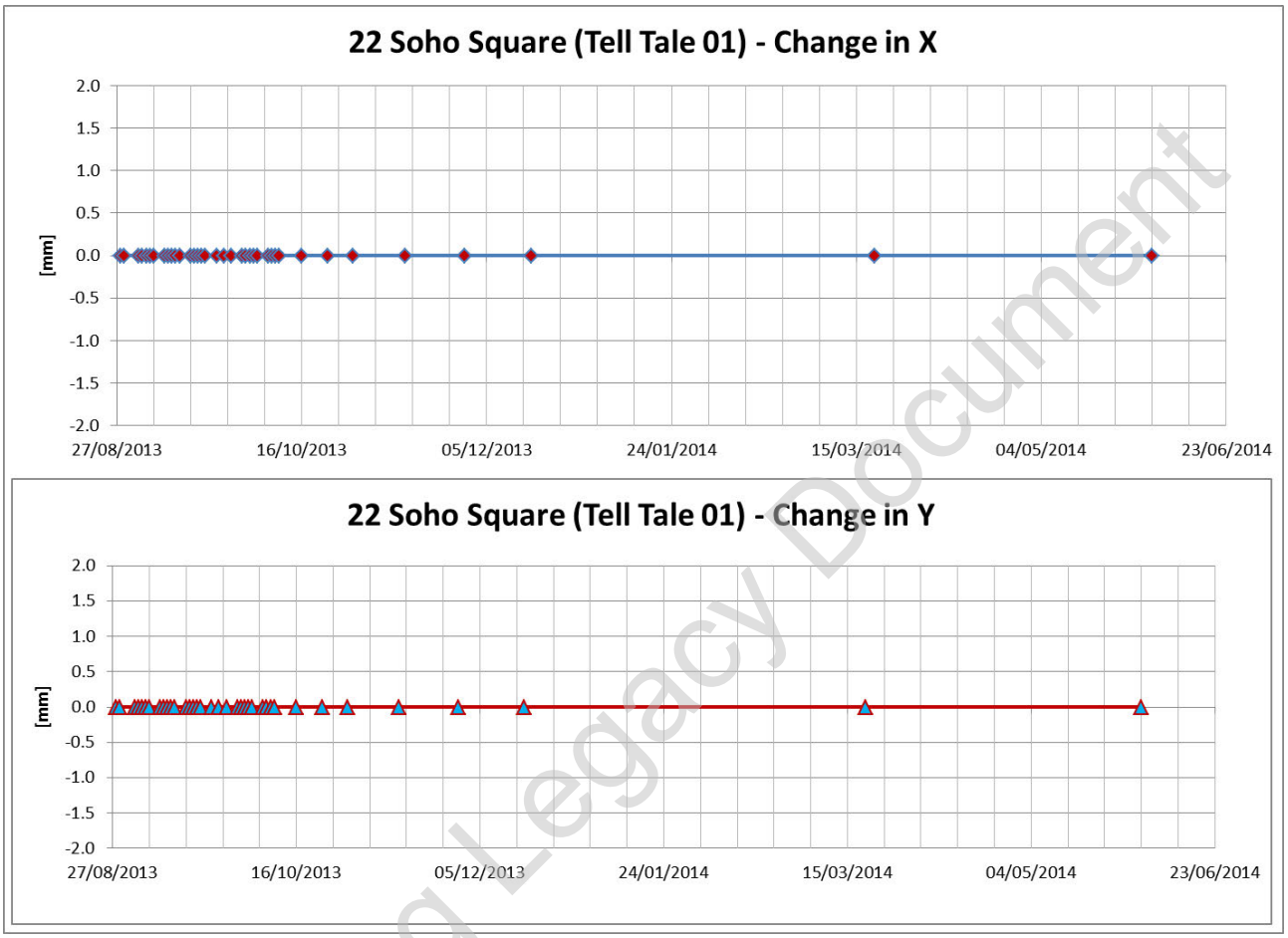
The contribution of each injection within a specified data set are summed at each node within a grid. This grid file is then contoured within Surfer.

Appendix B

Crackmeter data and example plots of HLC

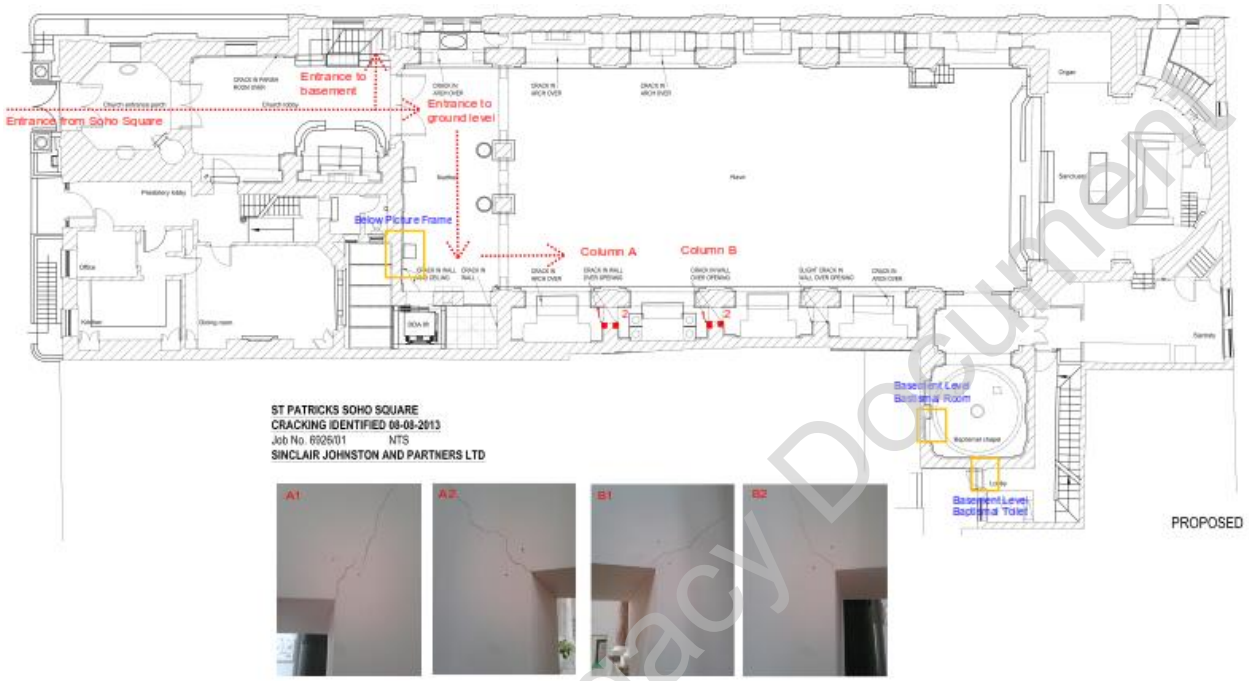
Crackmeter Building Location Plan – St. Patrick's Church and 22 Soho Square

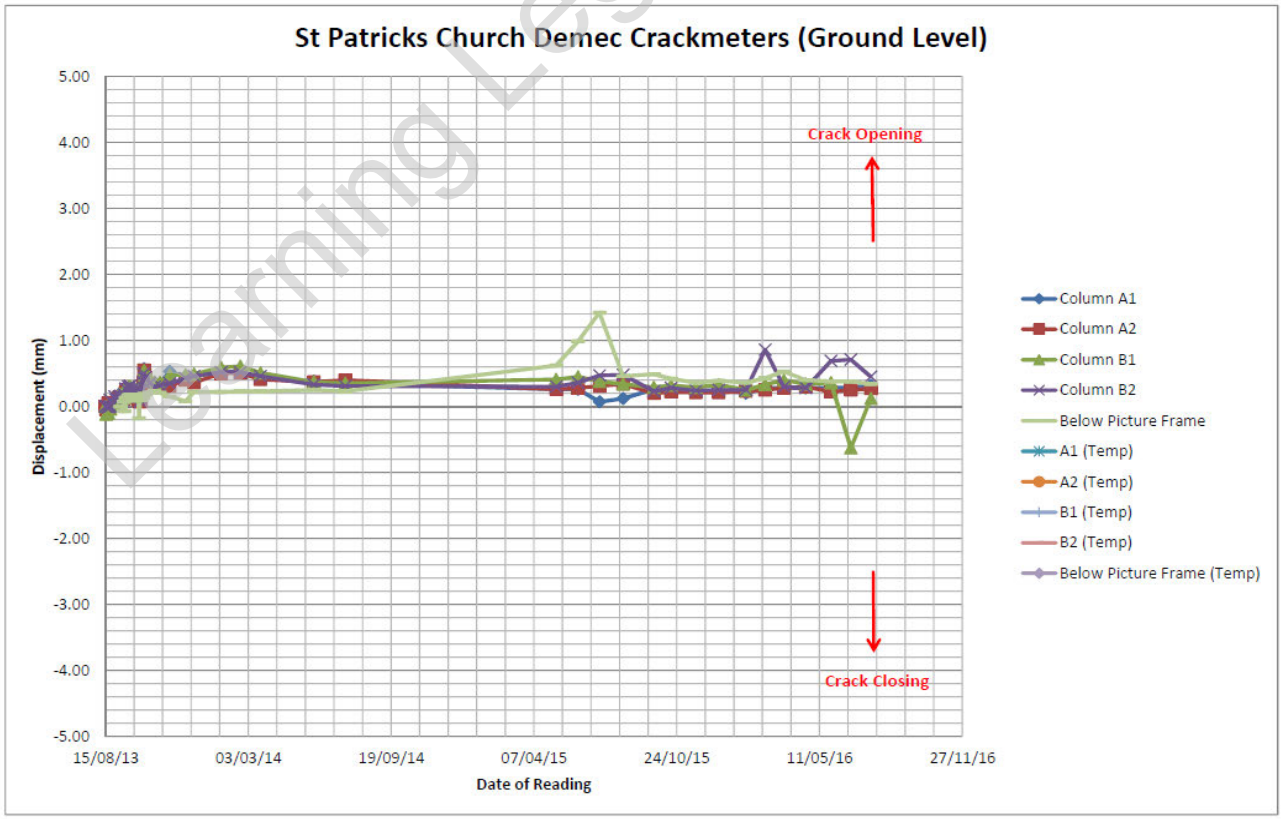
22 Soho Square - Manual Crackmeters

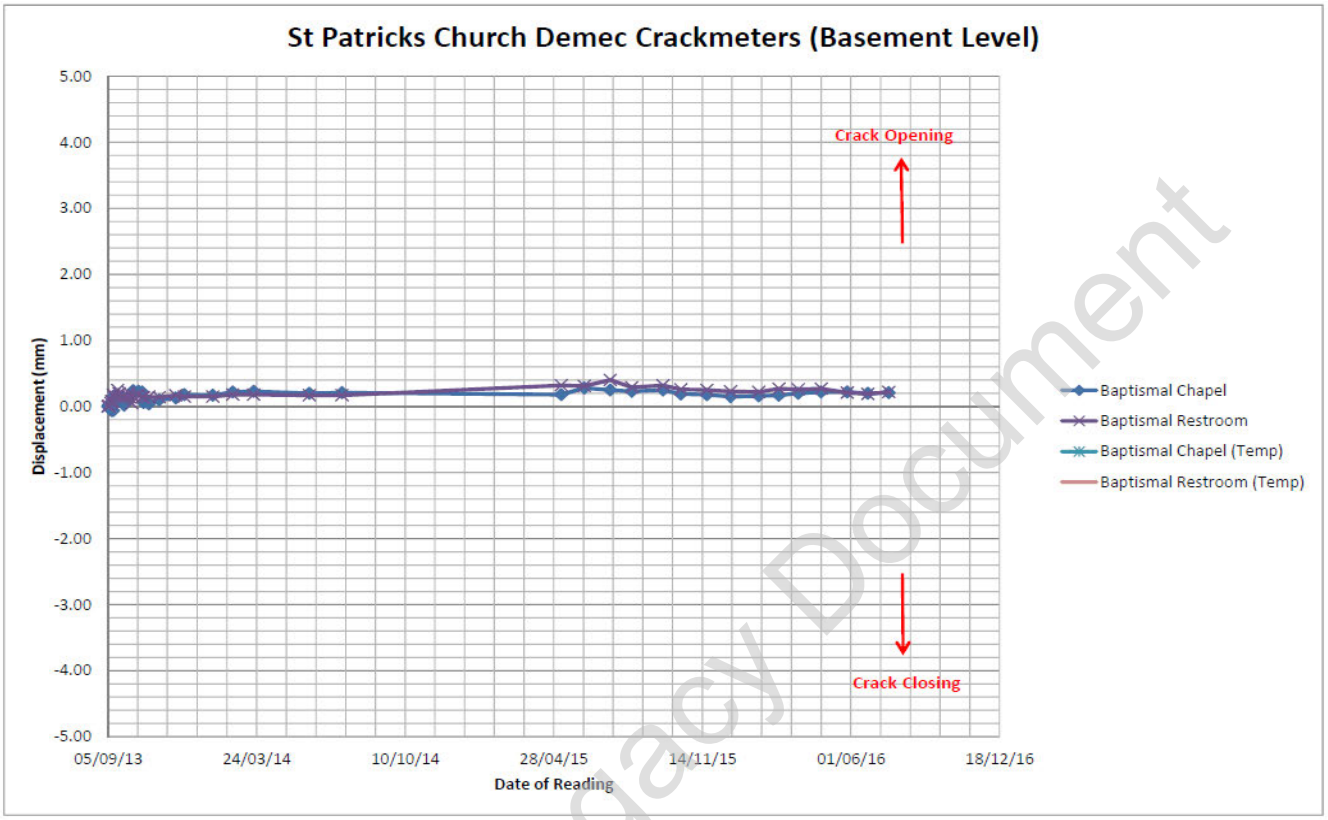


St. Patrick's Church – Crackmeters

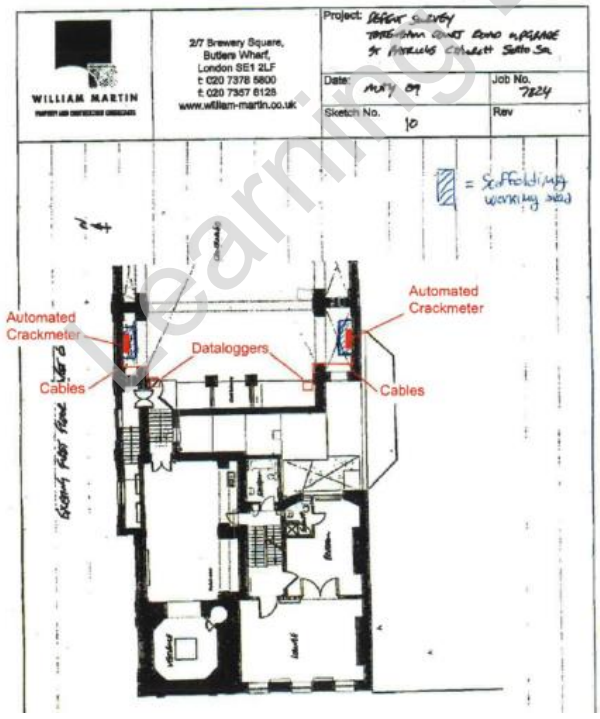
(see Installation Reports: C300-BFK-C4-RGN-CRT00_ST005-51163 and C300-BFK-C4-RGN-CRT00_ST005-50895)

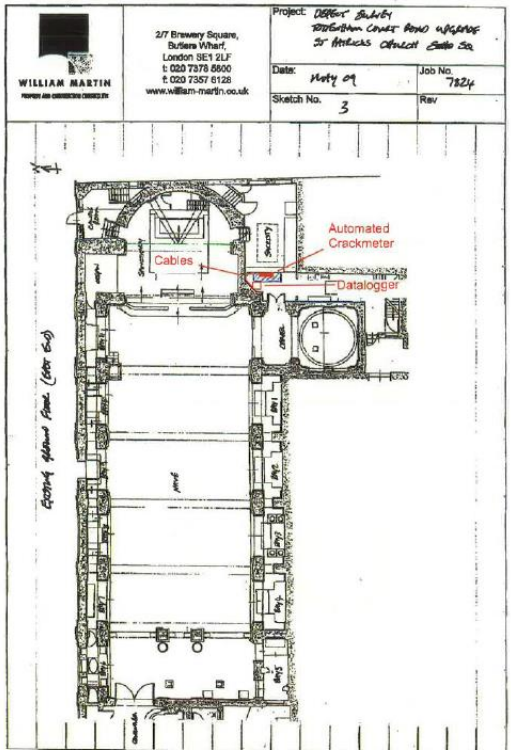


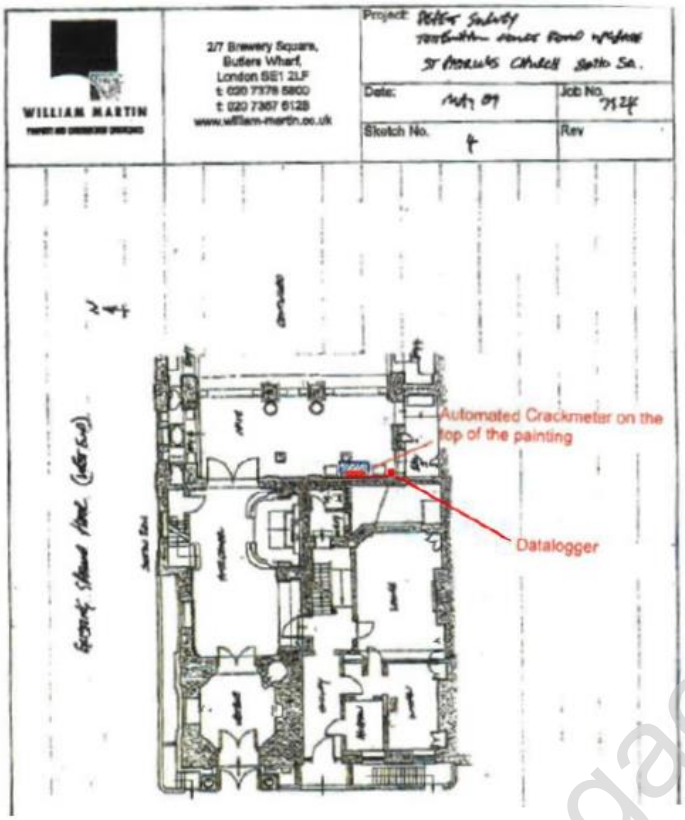


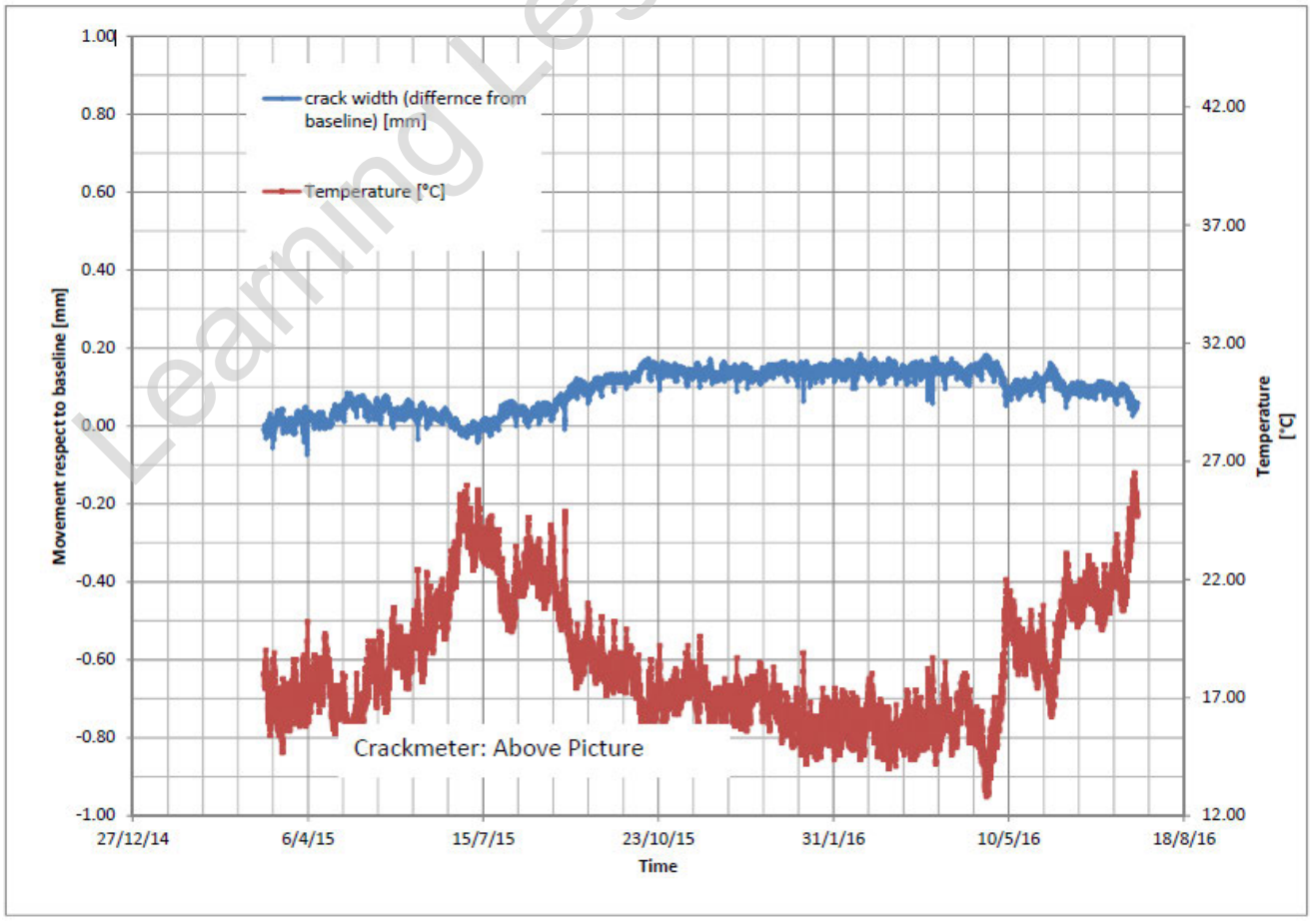


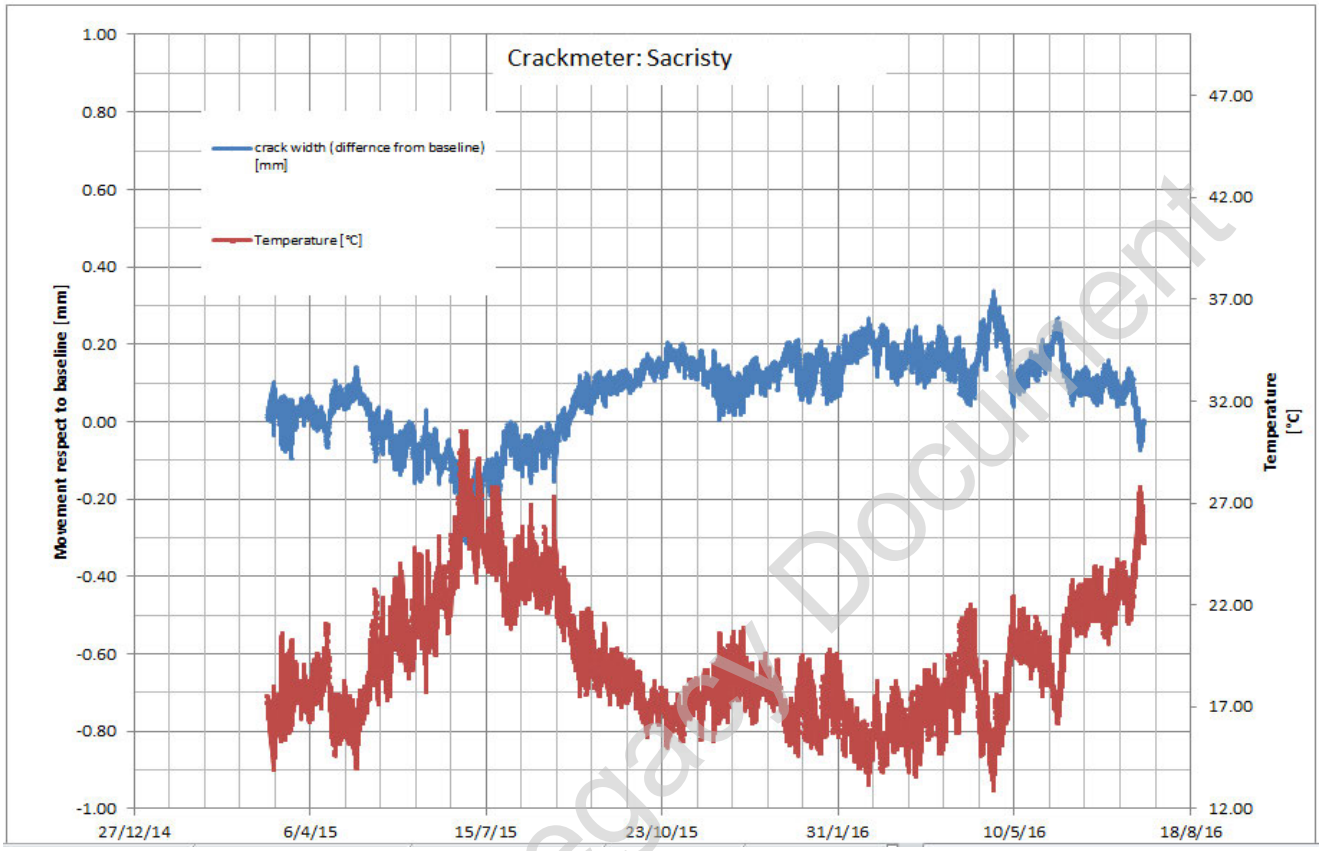
St. Patrick's Church – Automated Crackmeters

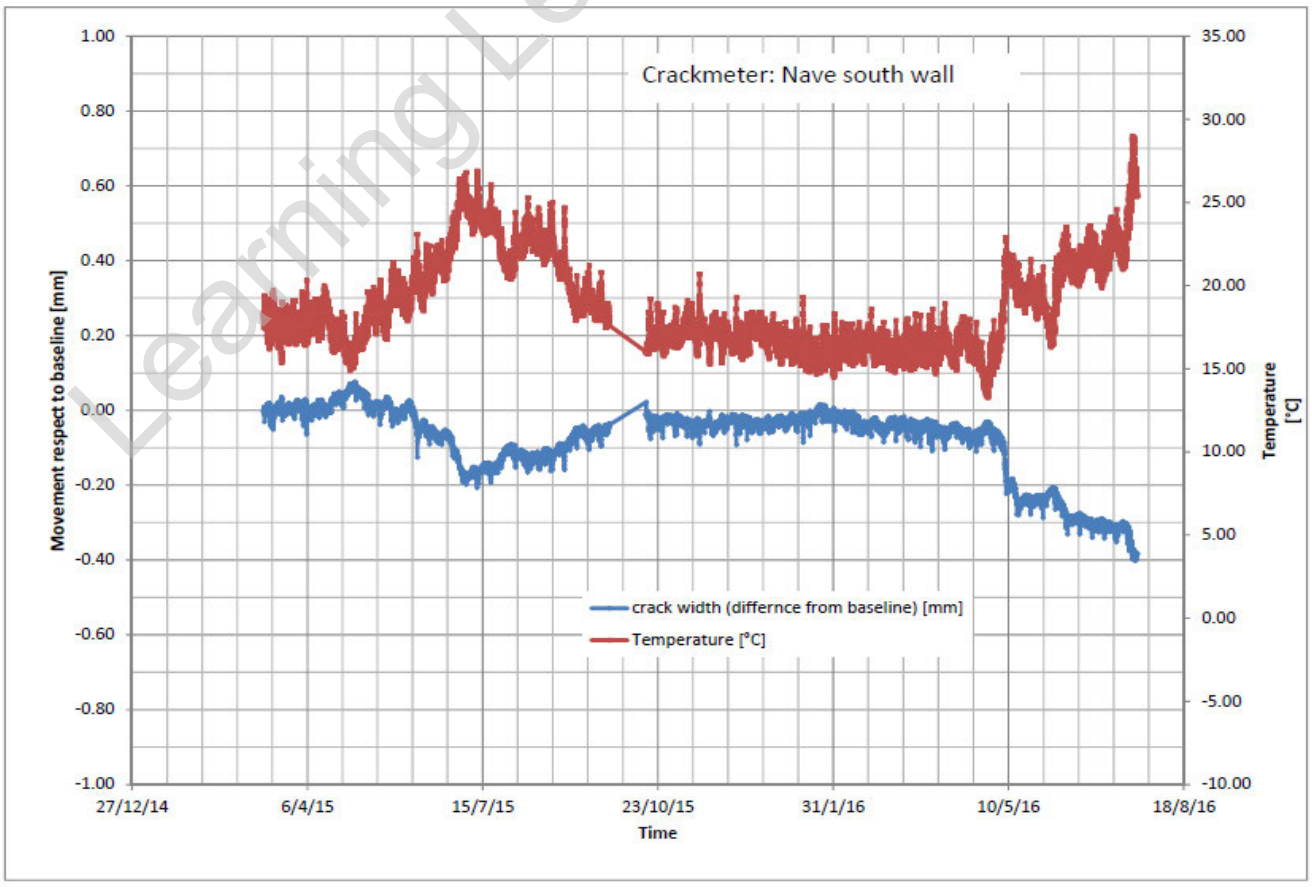


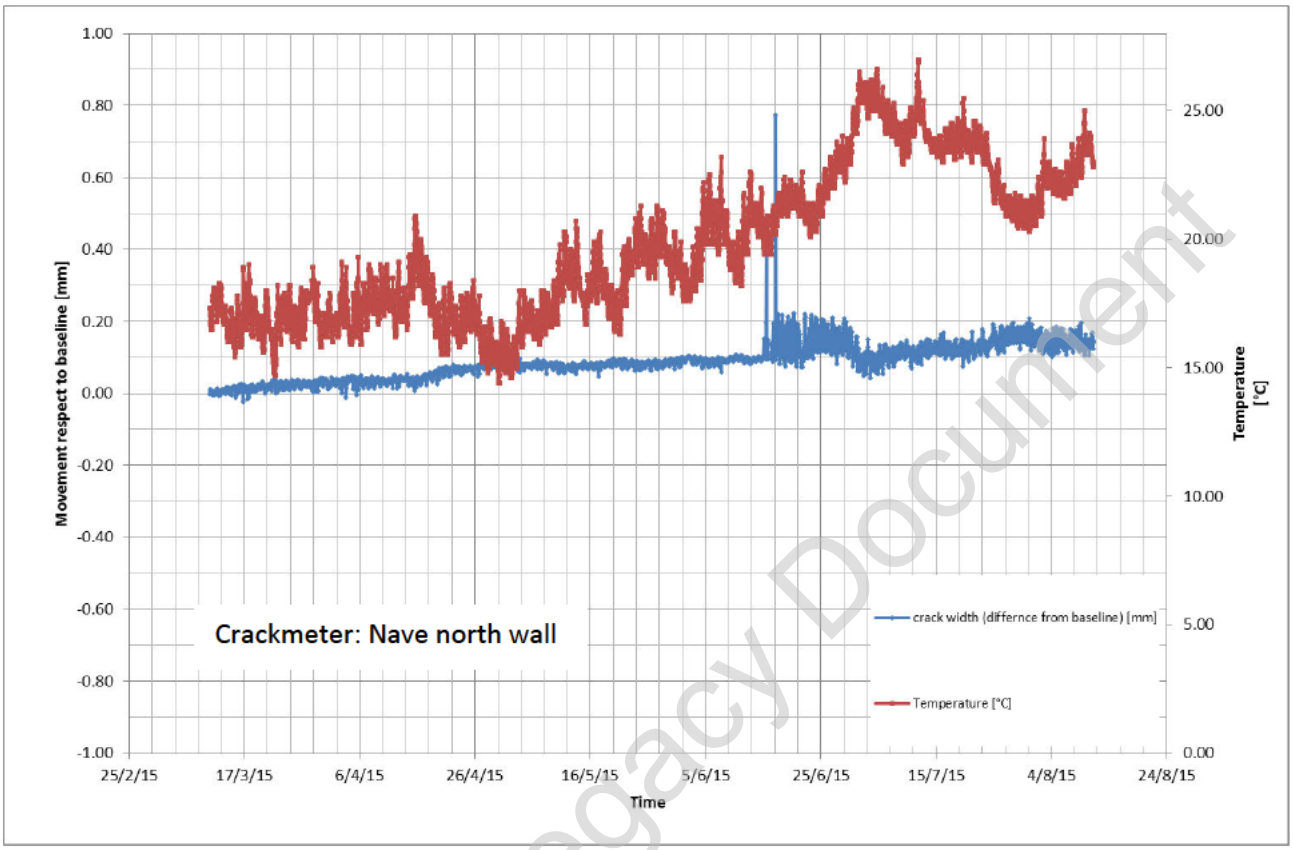




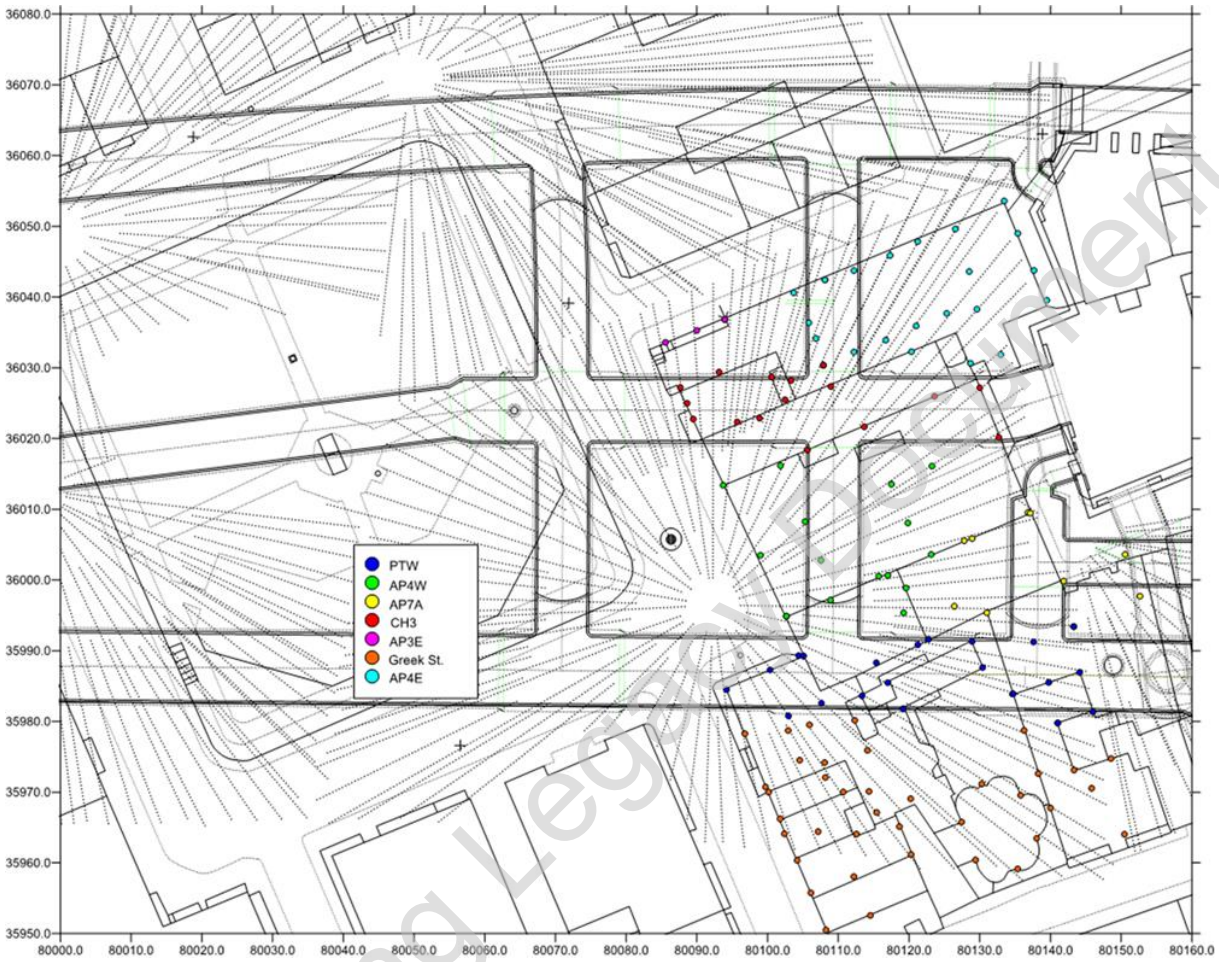




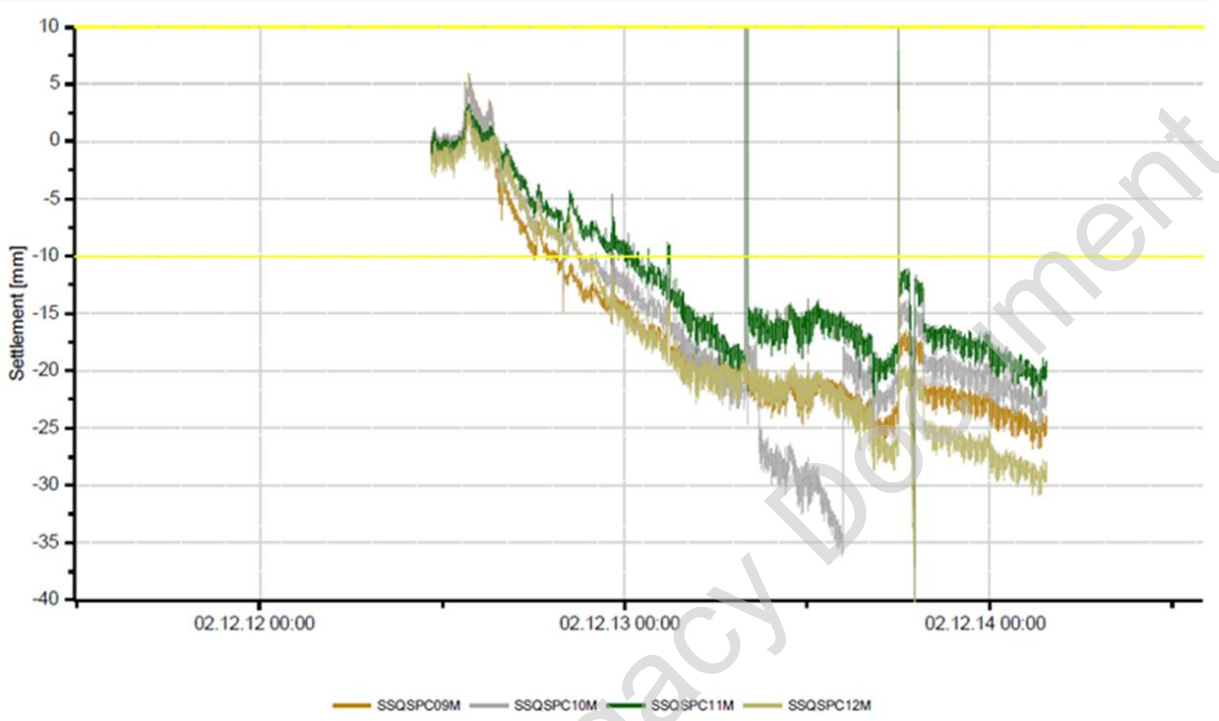




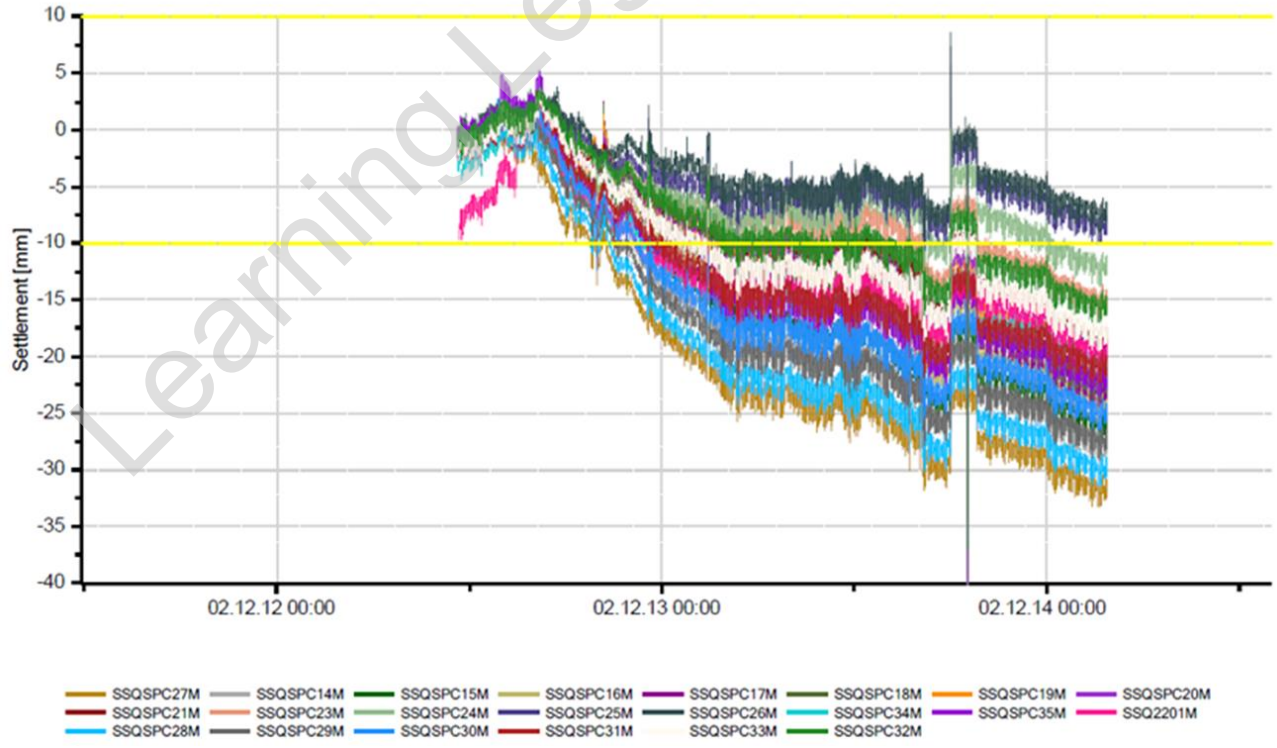
Location of HLC in GS5 area

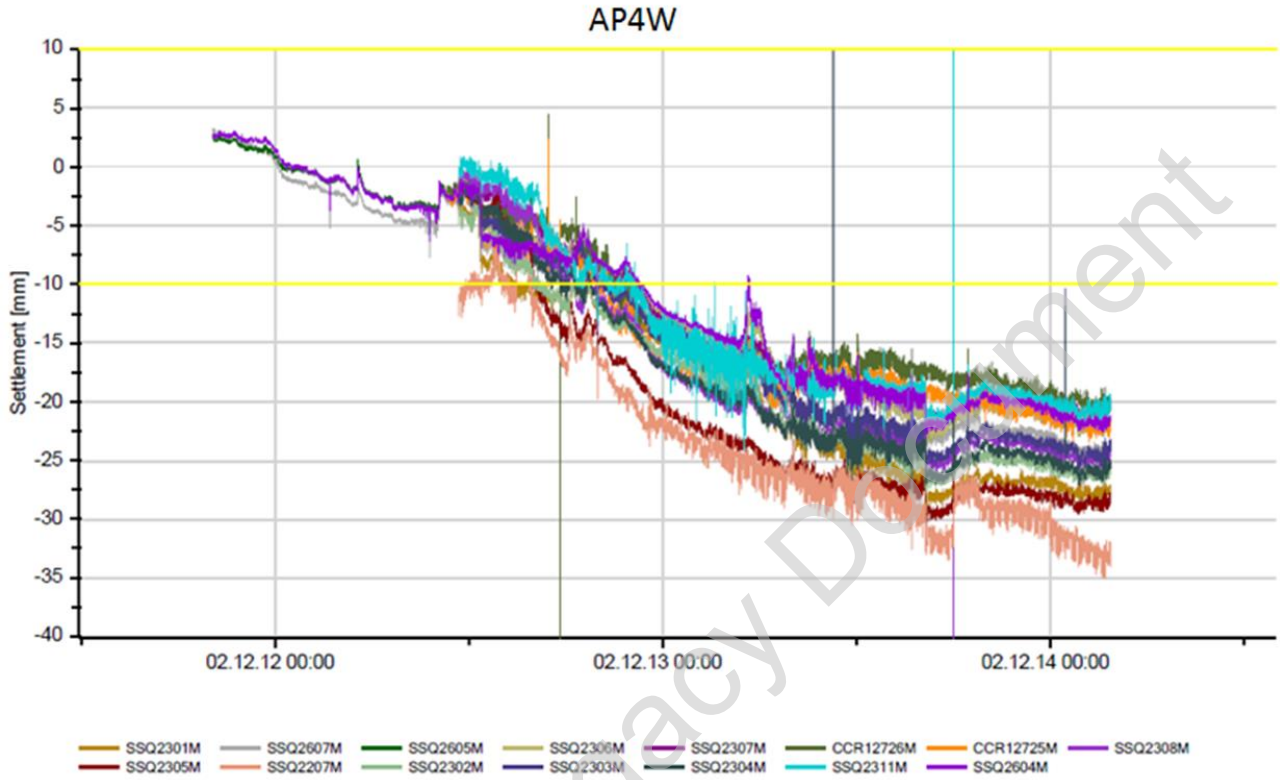


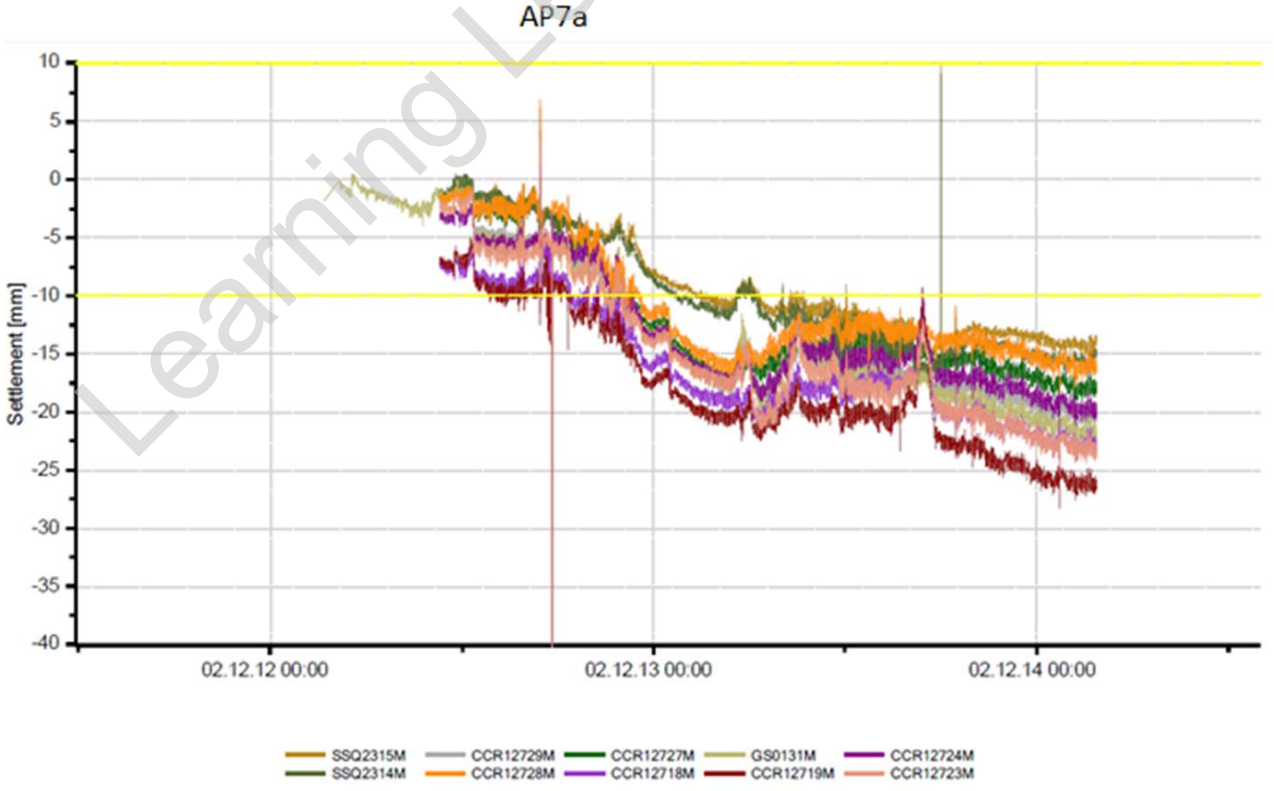
AP3E

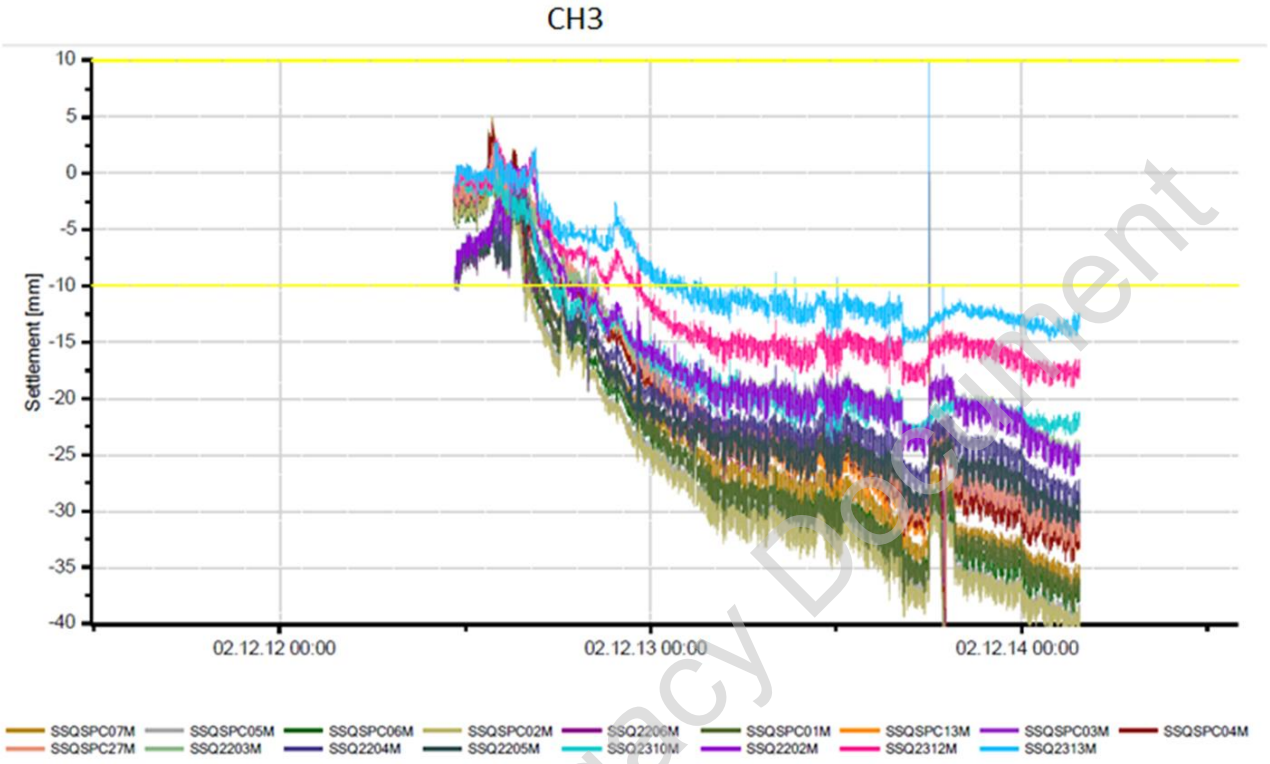


AP4E









Appendix C

Summary of TCRSU construction dates (Provided by C122)

Table C1 – TCRSU construction dates

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

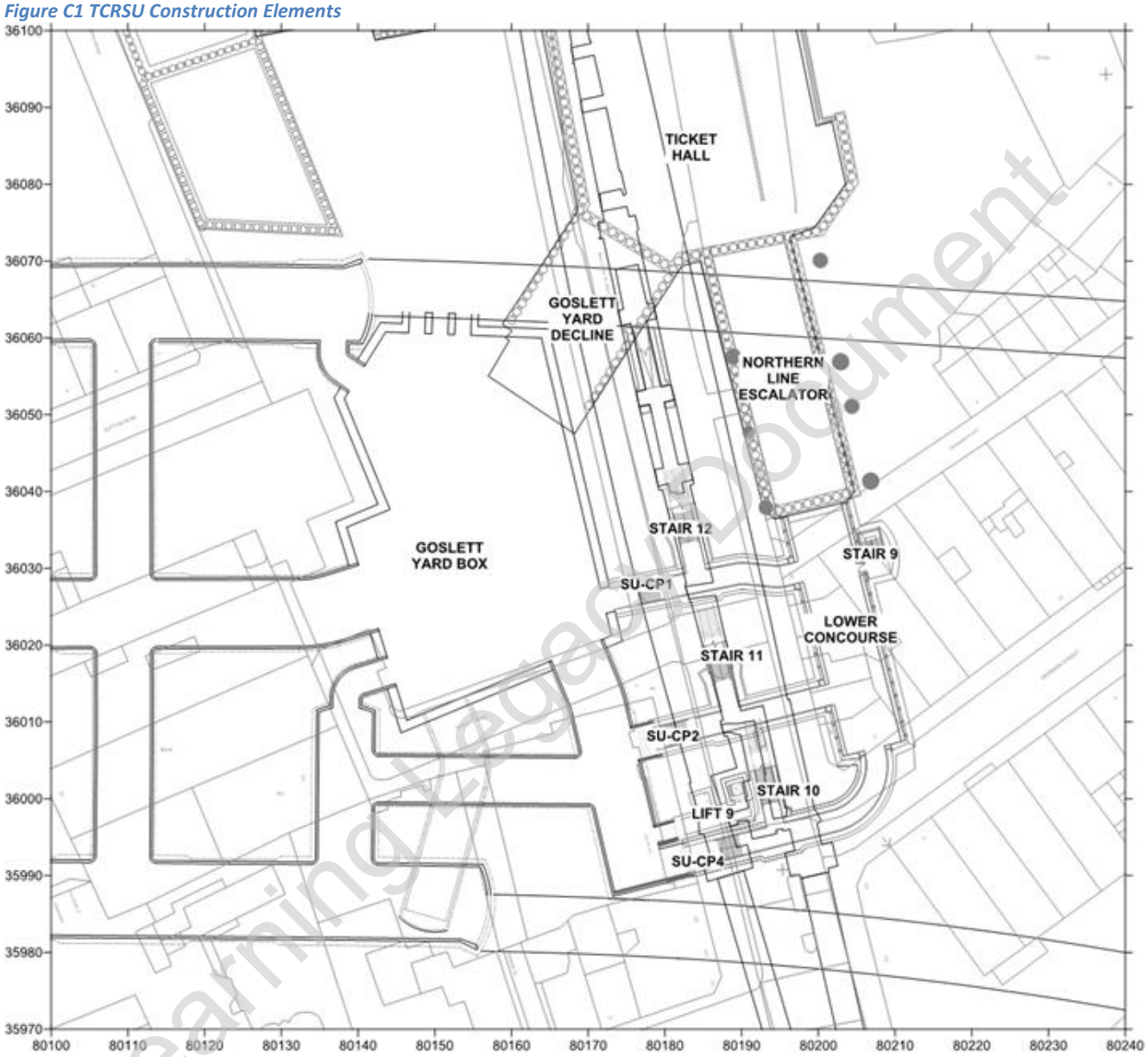
Table 2: Goslett Yard Detailed Excavation Dates

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

Table 3: Underground

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

Figure C1 TCRSU Construction Elements



Appendix D

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