C300/410

Western Tunnels & Caverns Project

Report

Grouting Summary & I &M Final Report - TCR GS6

CRL Document No. **C300-BFK-C4-RGN-CRT00_ST005-51230**

Contract MDL reference: C13.016

1. Contractor Document Submittal History

Revision	Date	Prepared by	Checked by	Approved by	Reason for Issue
4.0	05/12/16	[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.

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2b. Review by Stakeholder (if required):

Stakeholder Organisation	Job Title	Name	Signature	Date	Acceptance
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Acceptance by Crossrail of the designer/supplier [redacted] their contractu[redacted] constitute *Crossrail* approval of design, details, calculations, analyses, test methods or materials developed or selected by the designer/supplier.

Contents

APPENDICES

1. PURPOSE OF THIS REPORT

A number of summary reports (or written submissions) are required by the Works Information within the Compensation Grouting KC21 (C122-OVE-Z4-RSP-CR001-00010) and Instrumentation and Monitoring KX10 (C122-OVE-Z4-RSP-CR001-00007) Materials and Workmanship Specifications. The relevant Clauses are reproduced in Table 1.1.

The requirements that are addressed in this report are:

- Summary of pre-treatment, concurrent grouting and grout jacking records
- Summary of construction activities
- Comparison of measured movements with predicted movements
- Comparison of measured movements with Specification limits
- Proposal to de-commission Grout Shaft 6 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.

All BFK excavation (tunnelling) works within the plan extent of the compensation grouting arrays from TCR Station Grout Shaft 6 were completed by August 2014. No grout jacking was implemented after the completion of tunnelling since a high level tunnel (VEW) intercepted a number of TaMs severely limiting the option for grouting: this was accepted by CRL and the TaMs were de-commissioned (grouted up) prior to excavation of VEW. A general location plan of the grout shafts at TCR is provided in Figure 1.1.1.

This report aims to summarise the relevant construction, compensation grouting and monitoring information for Grout Shaft 6 at TCR Station and includes manual monitoring up to September 2015 when the manual monitoring within the GS6 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 all instrumentation, including HLC and crack meters installed in 17 Manette Street.

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

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

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

- Updated as-built record and status for all instrumentation

The “as-built record and status” will be supplied as co-ordinates and digital data for incorporation into UCIMS.

The HLCs have been used for construction control during compensation grouting works and a separate “close-out” report is not required, since the 2mm/year criterion does not apply. Examples of data from the HLCs in the GS6 area are included in Appendix B, together with crack meter data.

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

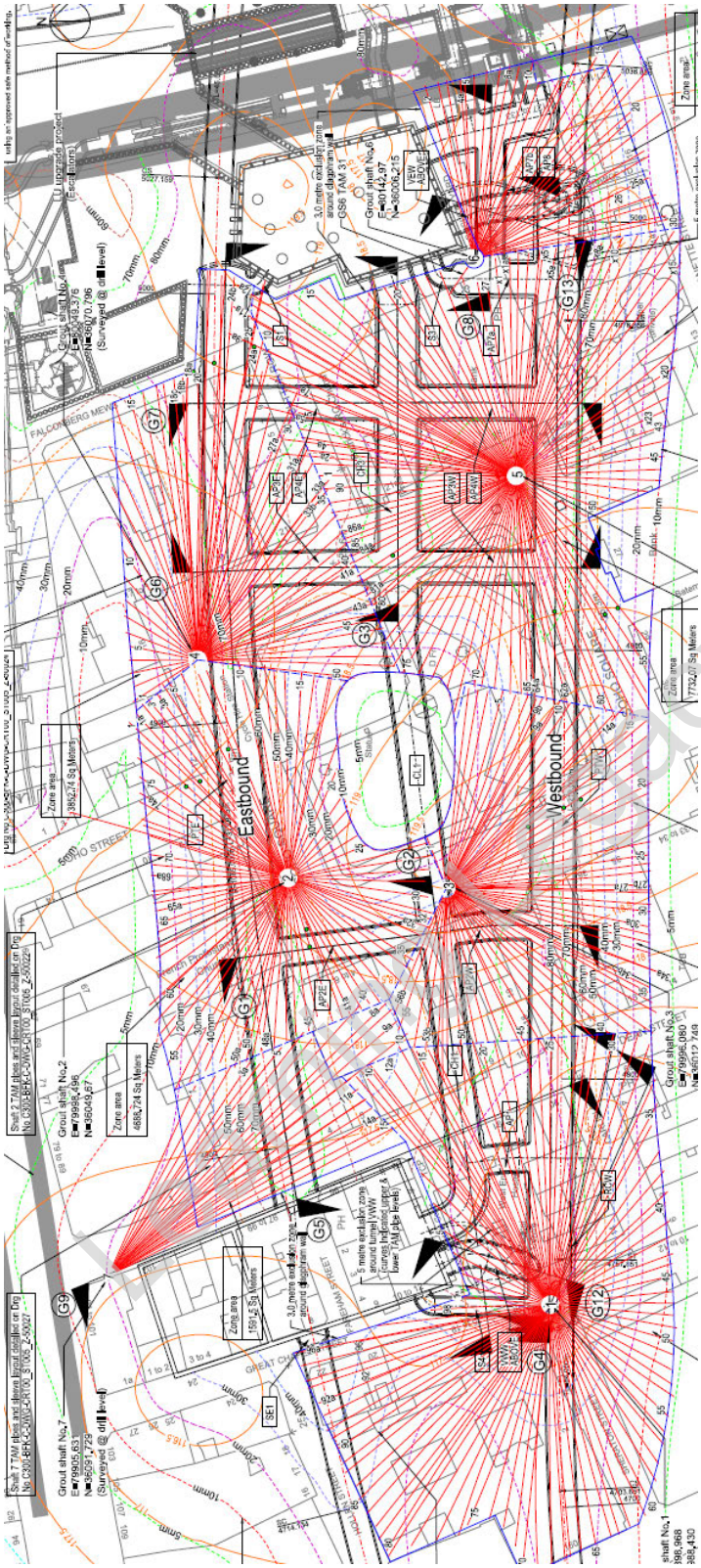


Table 1.1 Extracts from Works Information

KC21.3220 Compensation Grouting - General Requirements

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

KC21.3228 Reporting

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

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

KX10.2113 Final Report

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

KX10.2114 Close-Out Reports

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

2. CONSTRUCTION WORKS PROGRESS

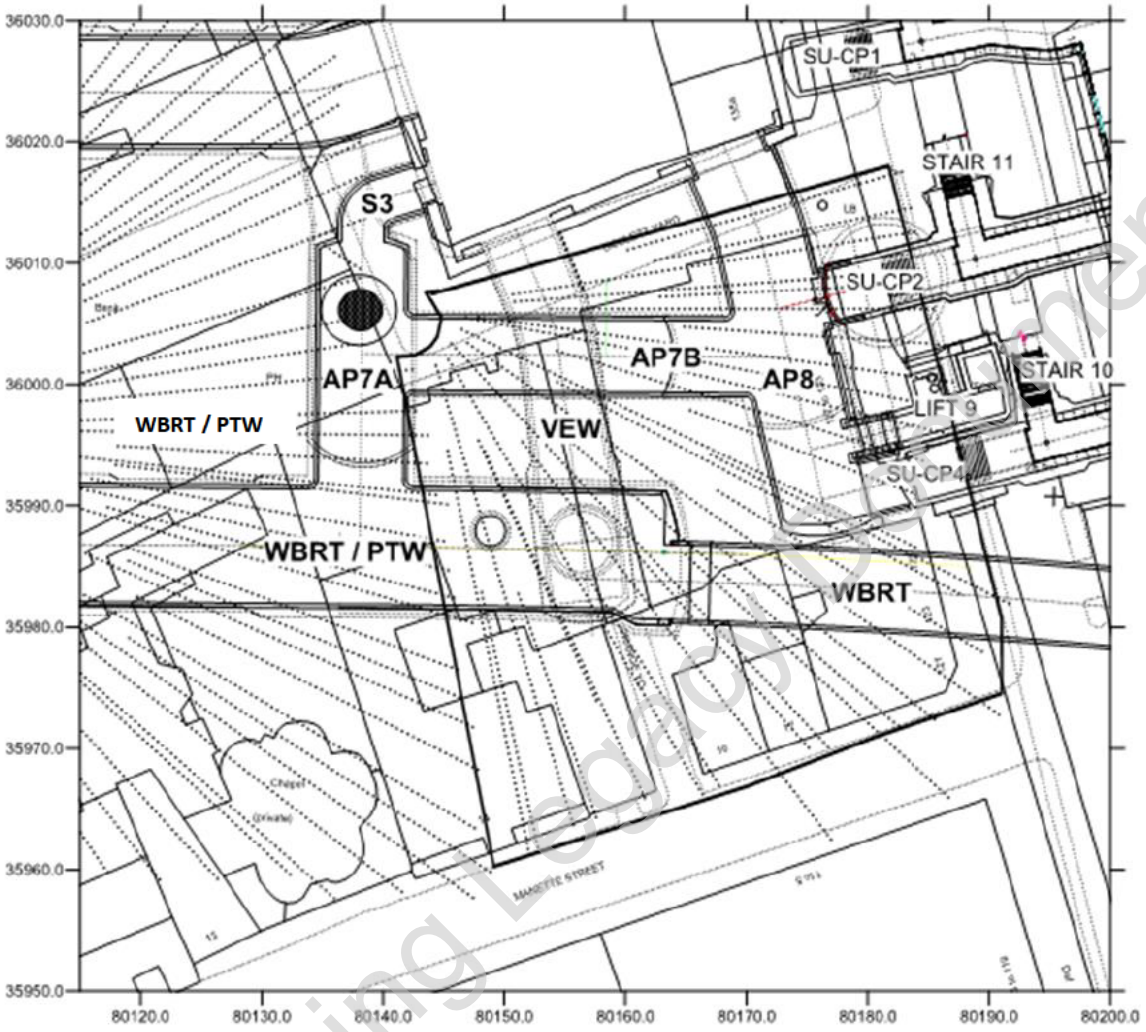
2.1. Tunnels

Table 2.1 and Figure 2.1.1 show the tunnel construction works undertaken within the footprint of the compensation grouting arrays installed from Grout Shaft 6 at TCR Station. Tunnel excavation commenced with the WBRT in June 2013 and was completed with VEW in August 2014. To facilitate comparison of monitoring data with construction activities 6 periods (A to F) 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. Period F is post construction from August 2014 until the cessation of monitoring in Spetember 2015.

Table 2.1 Progress of C300/C410 & TCRSU works at TCR GS6 area.

Period	Activity	Abbreviation	Start Date	End Date
A	Shaft sink		18/09/12	16/10/12
	TaM drilling		27/03/13	22/04/13
	TCRSU tunnels (see App. C)	SU_TUN	pre-18/09/12	21/12/2012
	TCRSU Goslett Yard Box (see App. C)	SU_GYB	pre-18/09/12	13/06/2013
B	WB Running Tunnel	WBRT	13/06/13	17/06/13
	TCRSU Goslett Yard Box (see App. C)	SU-GYB	13/06/13	12/08/2013
C	Access Passage 7A	AP7A	20/10/13	01/11/13
	Access Passage 7B	AP7B	10/11/13	16/11/13
D	Access Passage 8	AP8	01/02/14	16/02/14
			18/06/14	23/06/14
	Access Passage 7B	AP7B	02/03/14	06/03/14
	Access Passage 7A	AP7A	10/06/14	14/06/14
	Platform Tunnel Westbound	PTW	01/03/14	18/04/14
	Service Adit 3	S3	14/07/14	16/07/14
E	Ventilation tunnel East Westbound	VEW pre-grouting	16/07/14	16/08/14
	VEW excavation	VEW excavation	16/08/14	30/08/14

Figure 2.1.1 Tunnels within extent of grout array from Grout Shaft 6



2.2. Other construction works

Works by BFK prior to the commencement of tunnelling included:

- Sinking of Grout Shaft 6
- 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; Stair 12; CP4 stage 2; Stair 10, Lift 9)

2.3. Compensation Grouting

The volume of grout injected from TCR GS6 is plotted against time on Figure 2.3.1 together with a plot of when each of the tunnels was constructed. Figure 2.3.1 shows that pre-treatment comprised approximately 10m^3 injected prior to tunnelling, concurrent grouting just below 60m^3 and grout jacking about 50m^3. Concurrent grouting was undertaken with all tunnels except the WBRT, AP7A, AP7B and AP8 junctions and VEW. 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. The junctions are short lengths of tunnel and the extent of the exclusion zones over the tunnel face, as defined in the SCoGM, rendered concurrent grouting impractical. VEW is at a higher elevation than the other tunnels and it intercepted a number of the TaMs installed from GS6. An extensive grout jacking operation was undertaken immediately prior to the excavation of VEW.

Figures 2.3.2 to 2.3.4 show contours of the total grout intensity for each of the three types of grouting (pretreatment, concurrent and jacking respectively) and a cumulative total of all grout injected from TCR GS6 is shown in Figure 2.3.5. The grout intensity is the equivalent thickness of grout injected into the ground in millimetres. The methodology used to generate these contours is described in Appendix A. Comparison of the contour plots of grout intensity with observed settlements is discussed in Section 3.

Table 2.2 Construction Periods for works in TCR GS6 area.

Period	Start Date	End Date	Activities
A	18/09/2012	13/06/2013	Shaft sink, Tam Drilling, Pre-treatment, SU_TUN, SU_GYB
B	13/06/2013	20/10/2013	WBRT
C	20/10/2013	01/02/2014	AP7A, AP7B, Concurrent grouting
D	01/02/2014	16/07/2014	AP8, PTW, AP7A, AP7B & AP8 junctions, S3, Concurrent & Jack grouting
E	16/07/2014	07/09/2014	VEW, Jack grouting
F	07/09/2014	25/09/2015	Post construction

Figure 2.3.1 Volume of grout injected from TCR GS6 by grouting type.

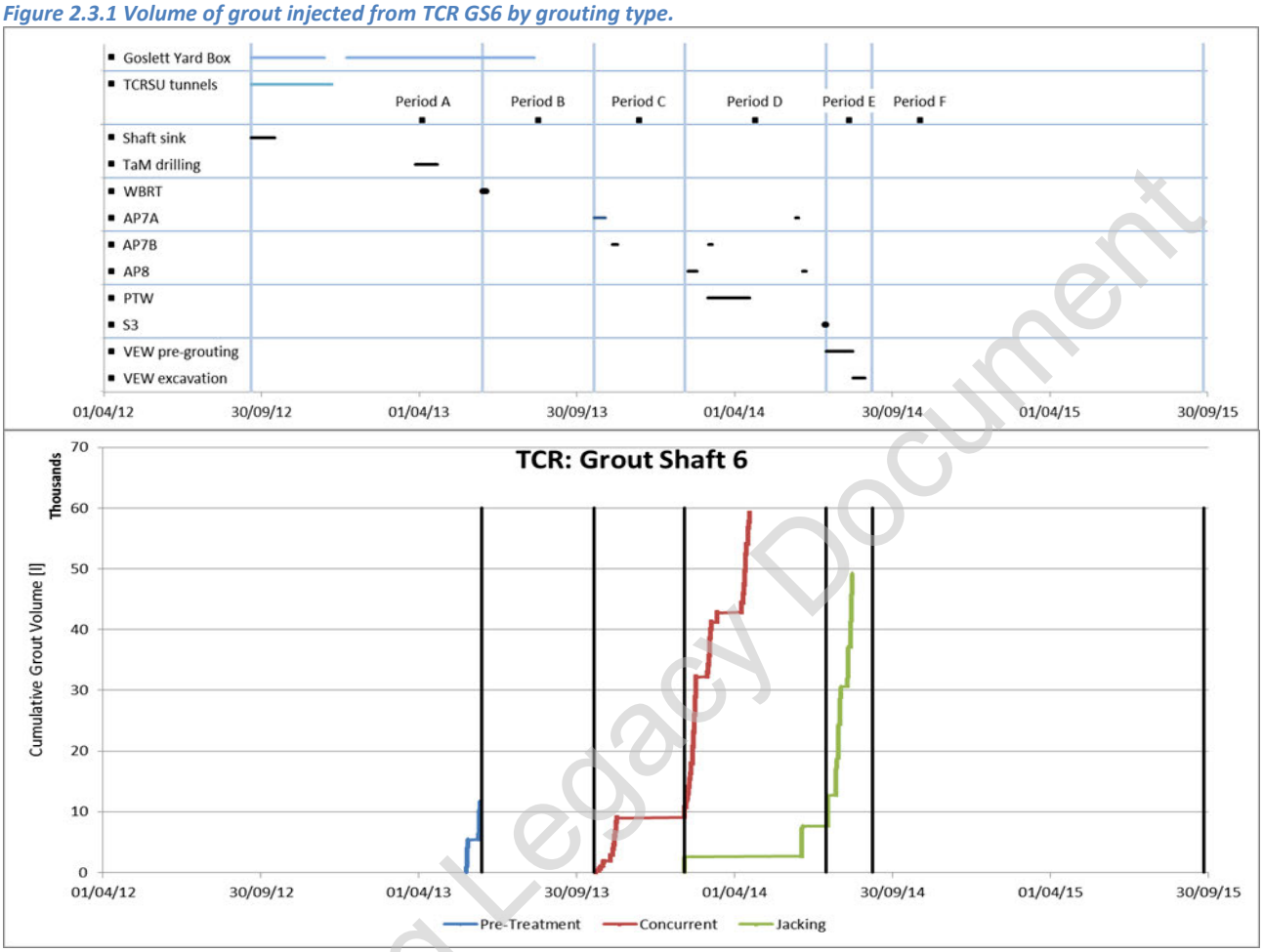


Figure 2.3.2 Distribution of grout injected from TCR GS6: Pretreatment grouting. Grout Intensity (mm).

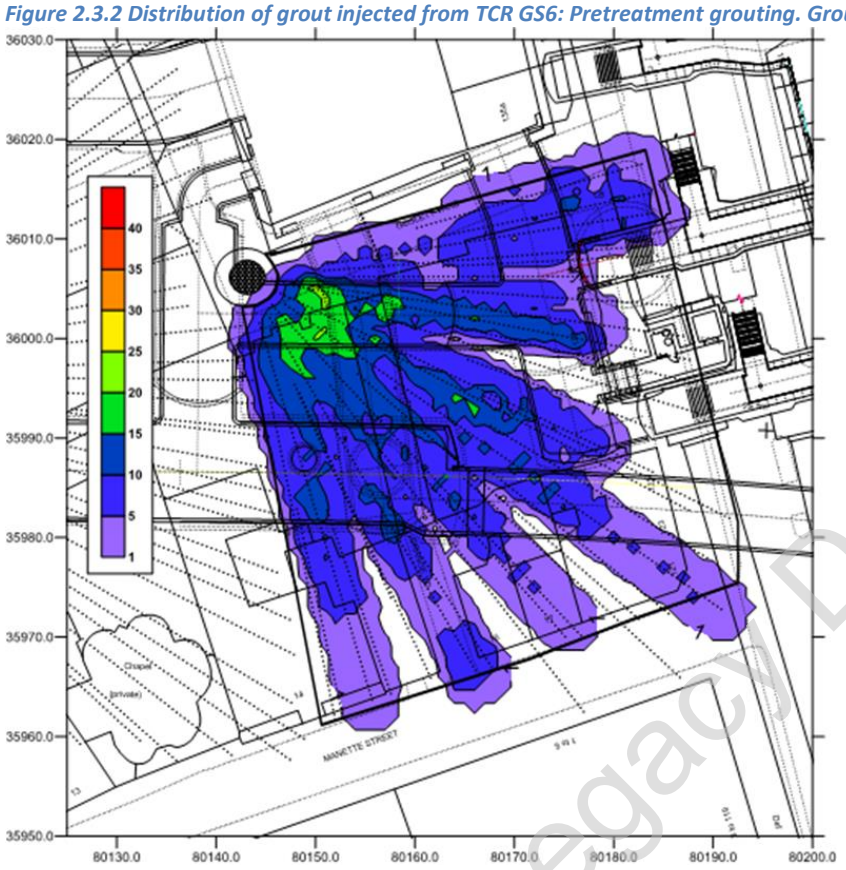


Figure 2.3.3 Distribution of grout injected from TCR GS6: Concurrent grouting. Grout Intensity (mm).

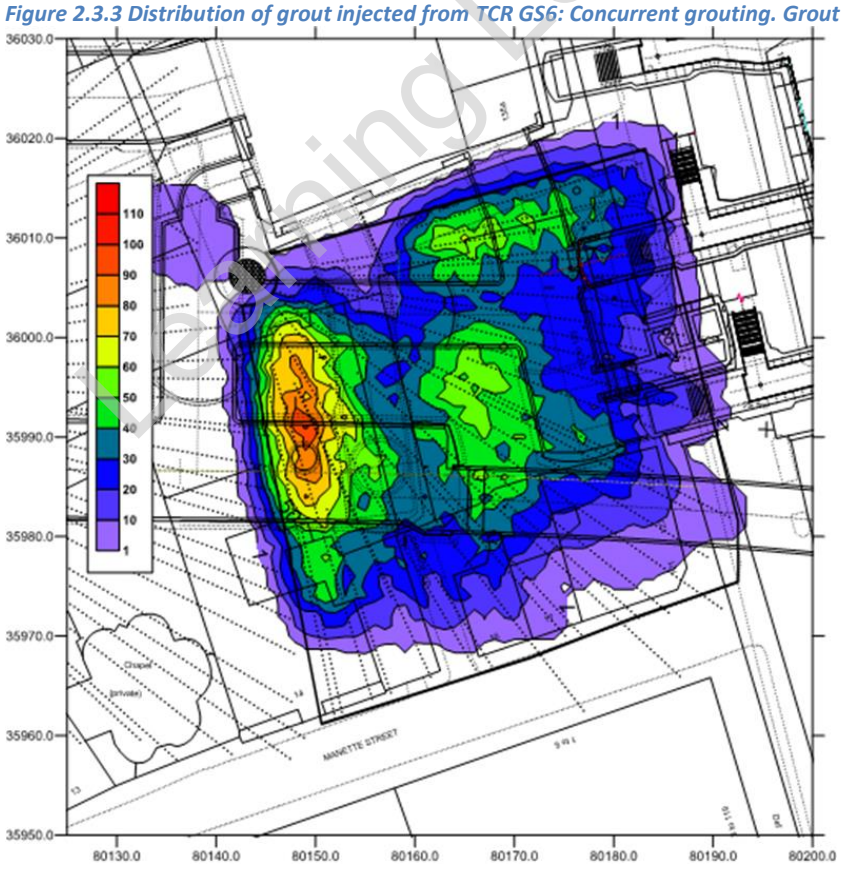


Figure 2.3.4 Distribution of grout injected from TCR GS6: Jack grouting. Grout Intensity (mm).

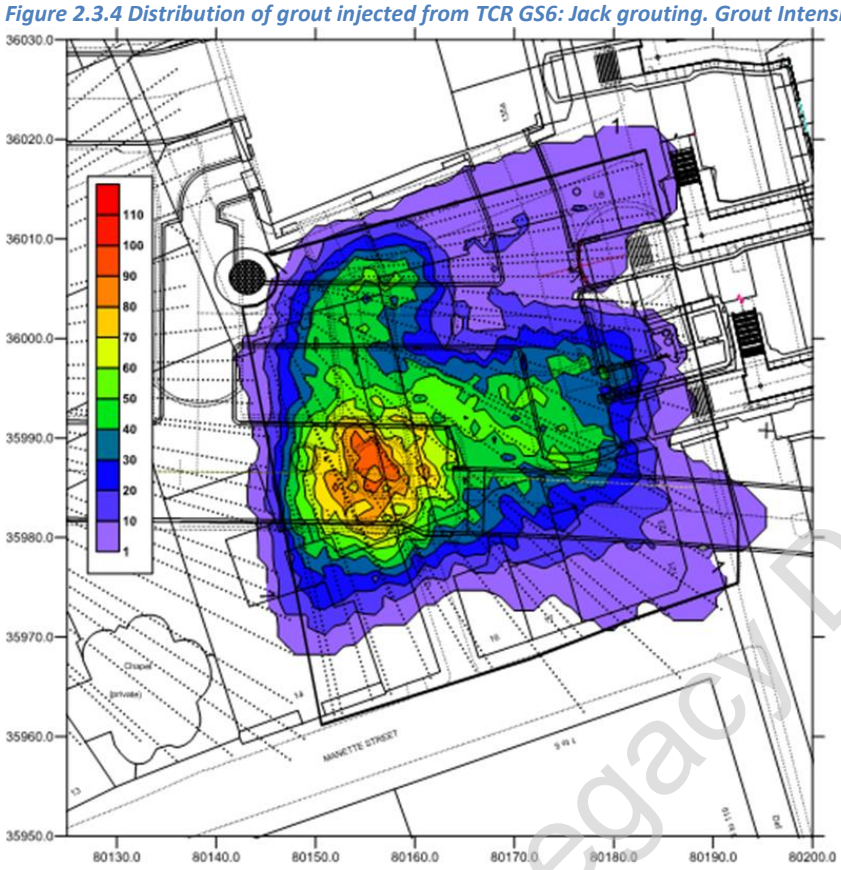
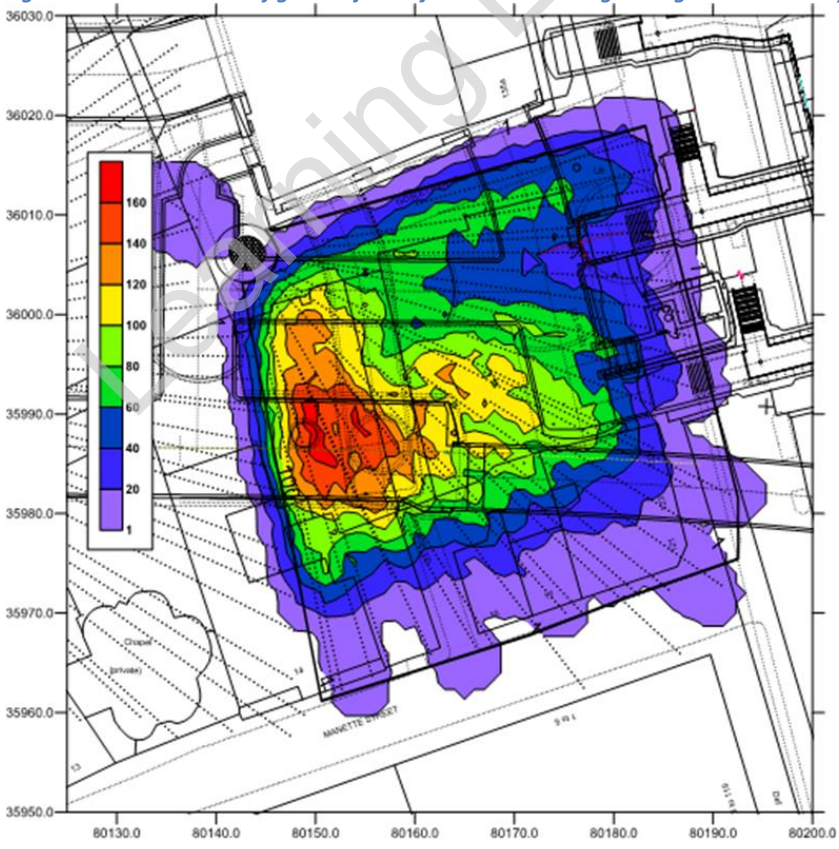


Figure 2.3.5 Distribution of grout injected from TCR GS6: All grouting. Grout Intensity (mm).



3. COMPARISON OF OBSERVED AND PREDICTED SETTLEMENT

3.1. Settlement Overview

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

The following points are noted:

- Settlements are generally significantly less than 50% of the predicted values, notwithstanding that the observed movements include a significant proportion of consolidation settlement over the 2½ year construction period.
- The most obvious differences between the predictions and the observations are:
    - the location of maximum settlement contour differs significantly: the prediction indicates over 100mm above VEW where 30mm was observed. Conversely, the maximum observed settlement of over 70mm (to the east of Charing Cross Road outside the GS6 area) is similar to the predicted value in that location;
    - the locations of the 10mm and 5mm contours to the south of the GS6 arrays are similar in the observation and prediction contours;
    - the spacing of the contours implies that actual slopes are much less than the volume loss prediction.

Figure 3.1.1 Predicted greenfield settlement contour (supplied by C122)

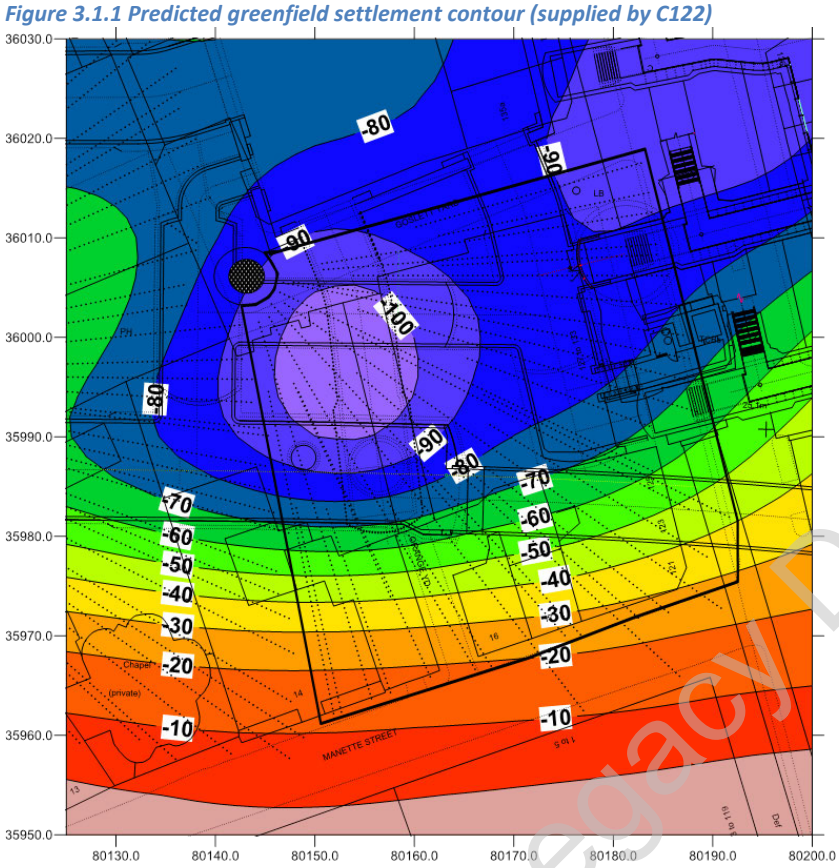
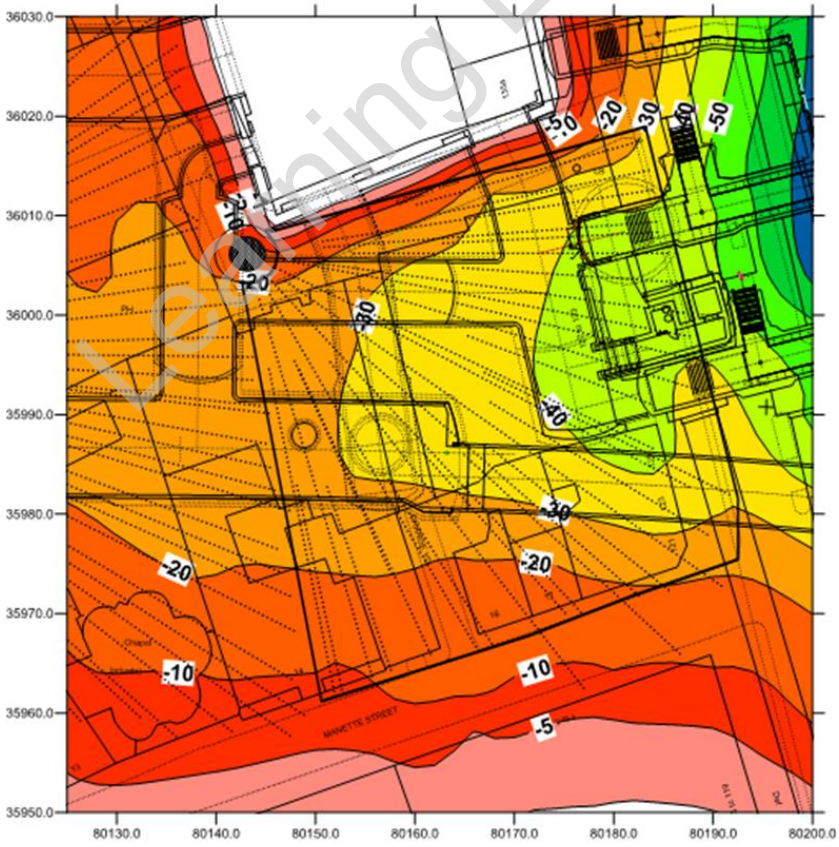


Figure 3.1.2 Observed settlement contour in September 2014 (end of construction – Period E)



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 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.

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: 18/09/12 – 13/06/13 Shaft sink, Drilling and Pre-treatment, SU_TUN, SU_GYB

Period A includes all of the BFK preparatory work prior to the commencement of tunnelling, including the drilling and pre-treatment of TaMs from TCR GS6. Extensive works had been undertaken for the LU TCRSU project prior to and during Period A. Adjustments have been applied to the BFK monitoring based on the contour shown in Figure 3.2.1: the effects are significant within and to the east of the GS6 area where up to 70mm settlement is indicated. 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.

No calculated short term movements associated with the TCRSU works completed in Period A is available. The measured movements based on BFK monitoring during Period A are shown in Figure 3.2.2(a). The maximum settlement of ~12mm is at the east end of the GS6 array adjacent to the TCRSU tunnelling works. Part of the excavation for Stair 11, Stair 10, Lift 9 and Cross Passage 4 were undertaken during Period A. There is significant settlement throughout the area associated with excavation within the Goslett Yard Box below level -3 (see Figure 2.1.1 for locations).

The observed settlements at the end of Period A (adjusted to allow for movements arising from TCRSU works prior to the start of BFK monitoring) are shown on Figure 3.2.2(b). . A maximum settlement of over 30mm is indicated at the eastern extremity of the GS6 arrays, reducing to the west with less than 5mm at the western extremity. Figure 3.2.3 shows the contours of grout intensity from pre-treatment. In general, grout intensity up to 15mm was injected, but additional injections were made in the vicinity of the shaft, giving a grout intensity of up to 25mm.

Figure 3.2.1 Observed settlement based on TCRSU data

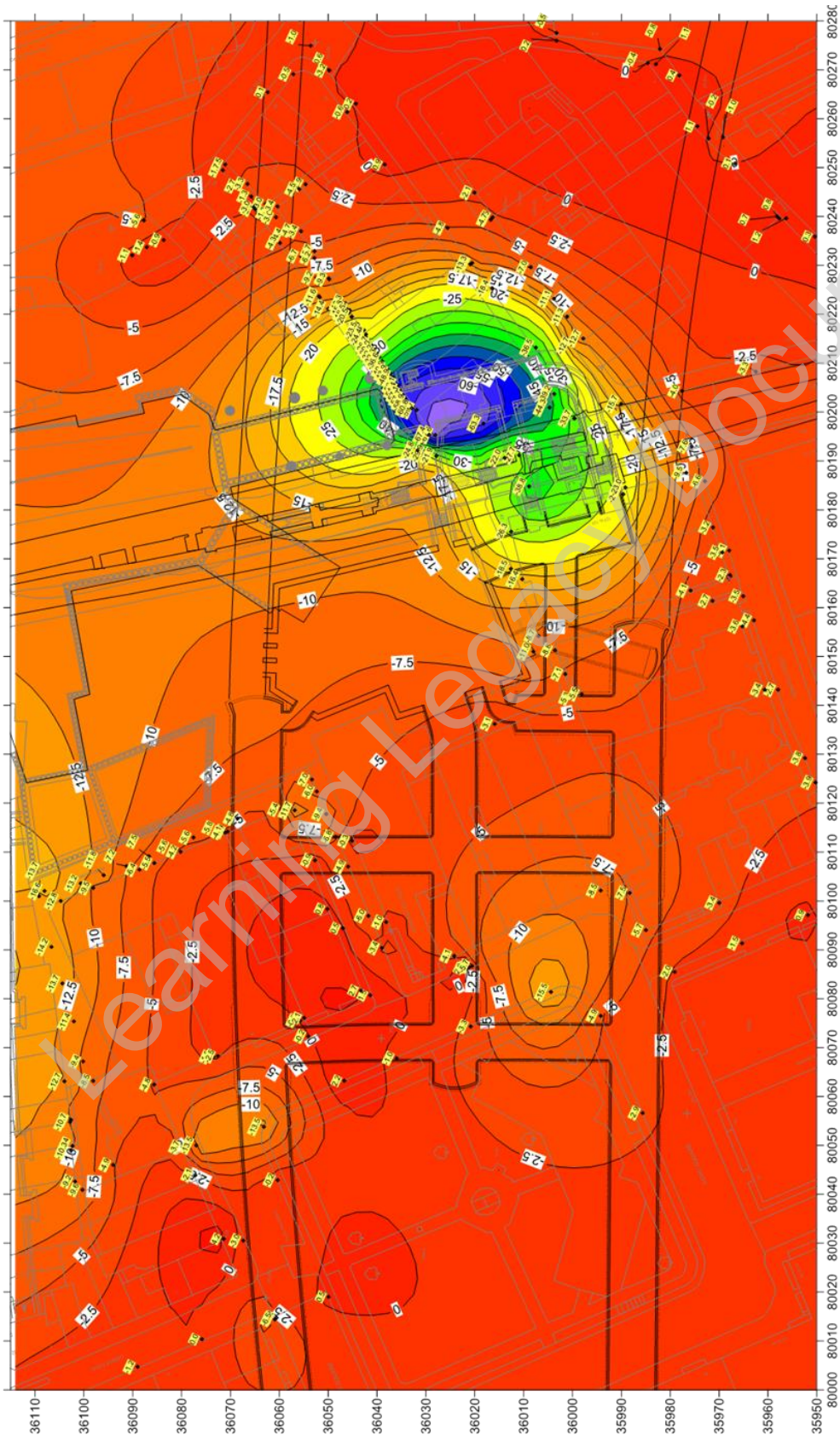


Figure 3.2.2 Period A: (a) Change in measured settlement (b)Total measured settlement

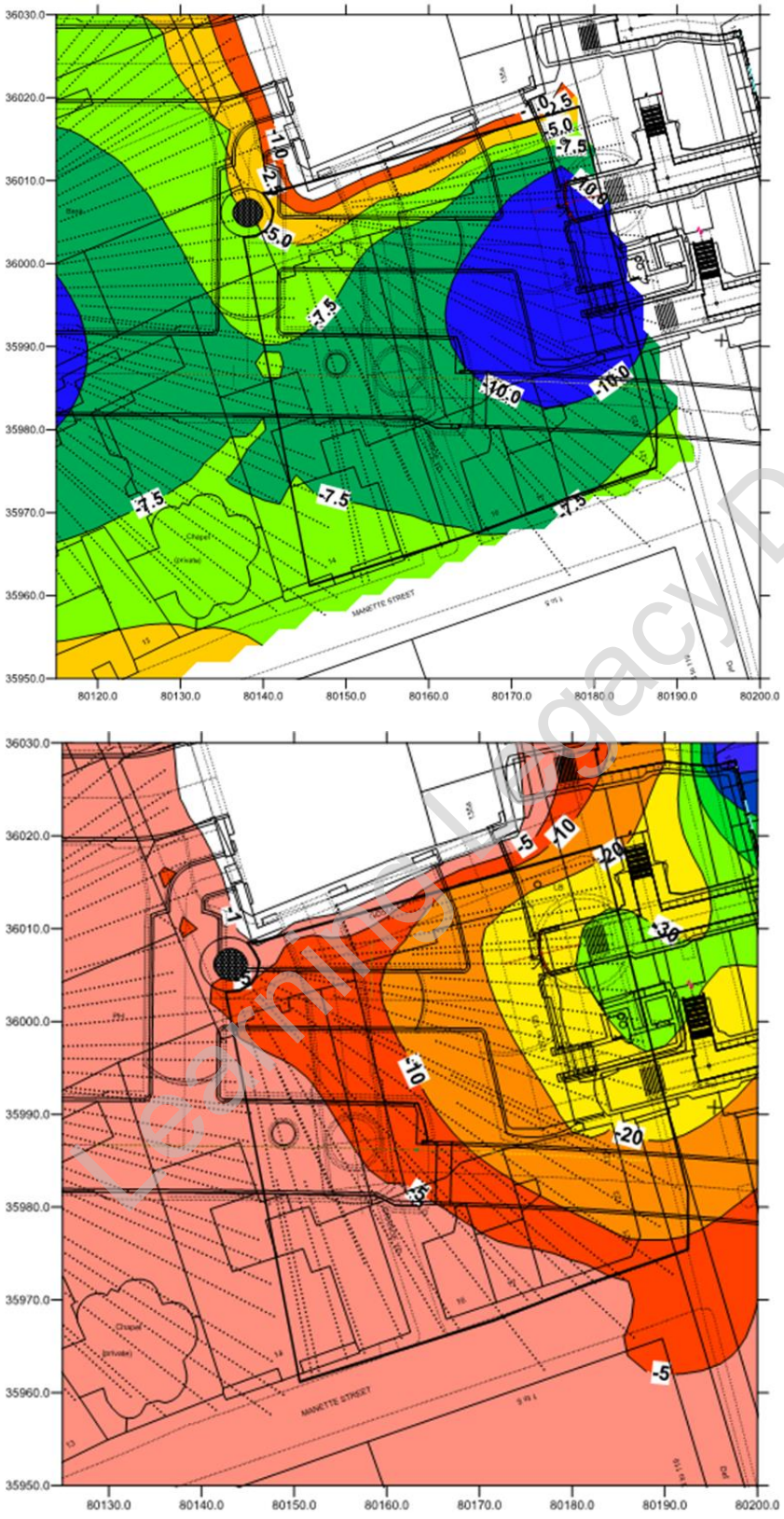
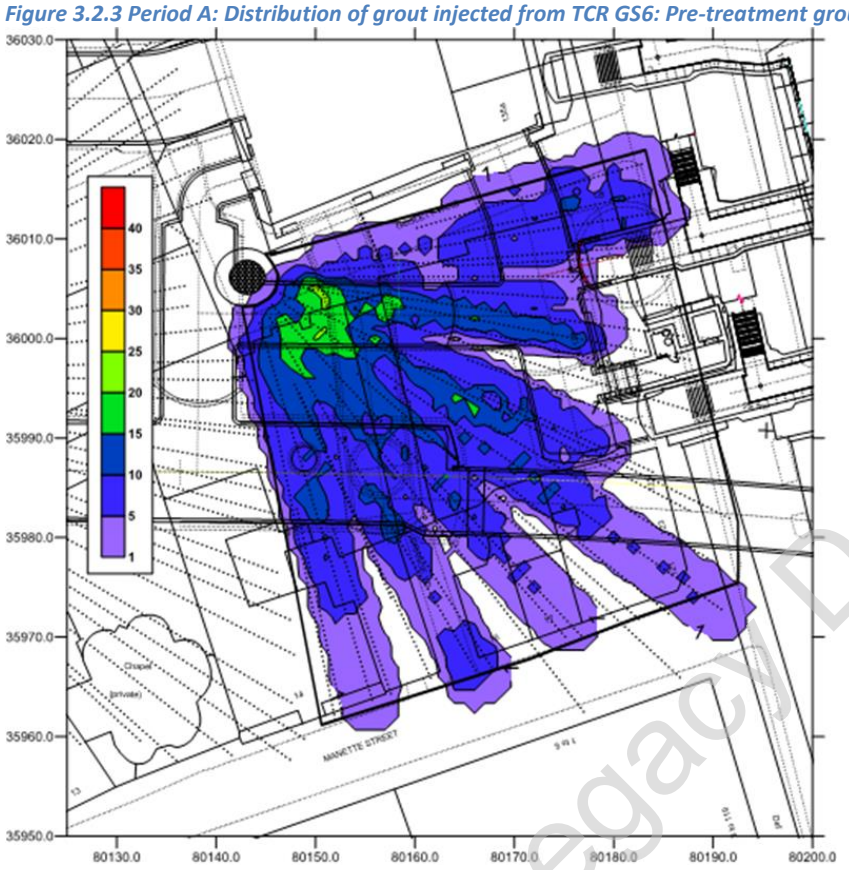
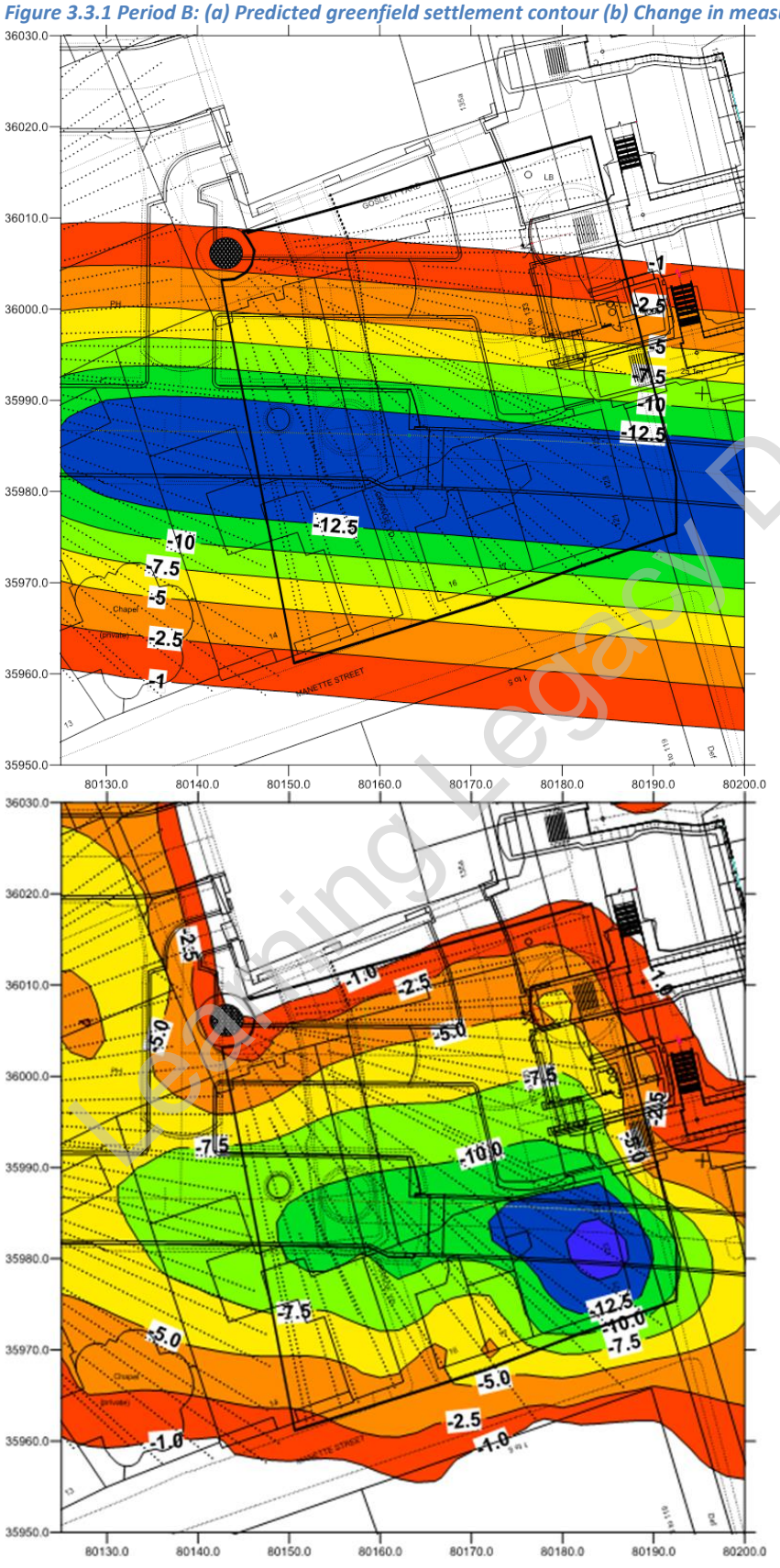


Figure 3.2.3 Period A: Distribution of grout injected from TCR GS6: Pre-treatment grouting. Grout Intensity (mm).



3.3. Period B: 13/06/13 – 20/10/13 WBRT, SU_GYB

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



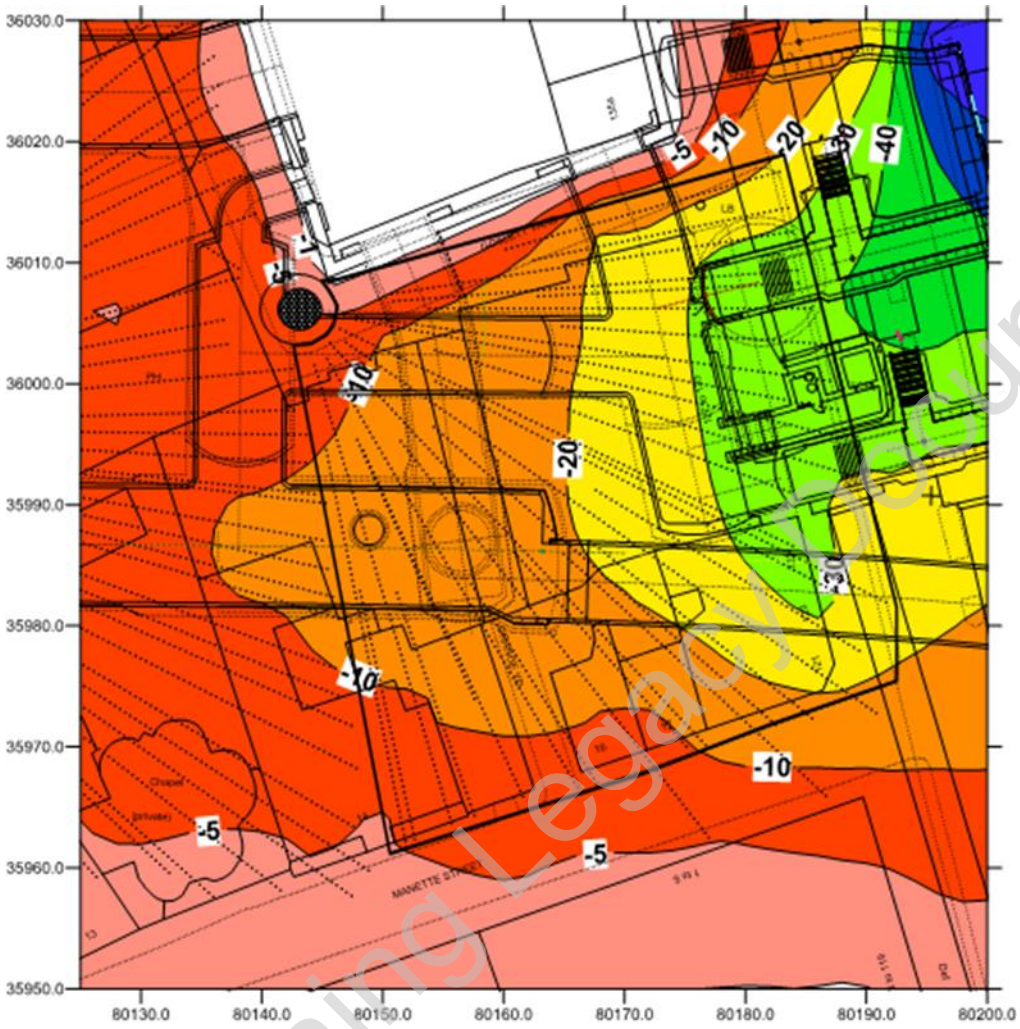


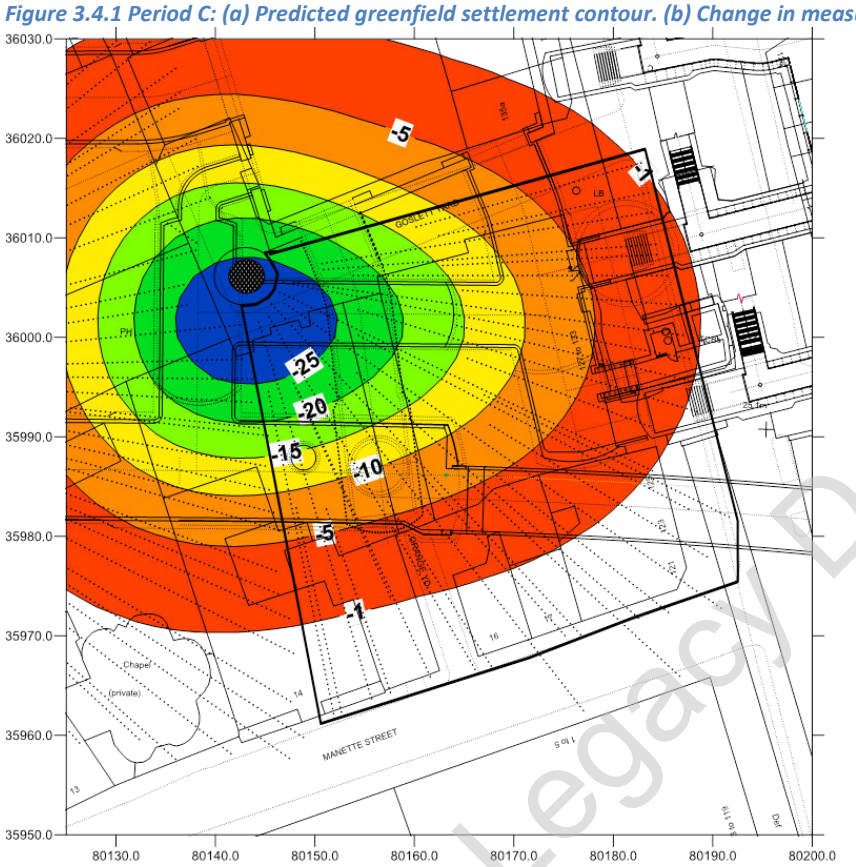
Figure 3.3.1(a) shows that up to 15mm volume loss settlement was anticipated for the WBRT. Figure 3.3.1(b) shows the recorded settlement which has a maximum of ~15mm locally at the eastern end of the GS6 area. Settlement was less than 10mm at the western end of the array. No compensation grouting was undertaken and it can therefore be inferred that the actual volume loss was close to the specified limit of 1%. It is notable that the magnitude of settlement varies in a similar manner to the previously recorded settlement from TCRSU works completed prior to the WBRT drive. It should also be noted that immediately to the east of the GS6 area the TBM had to pass over the operational LU Northern line platforms with less than 0.5m clearance and hence particular care was needed in controlling the operating parameters in this area.

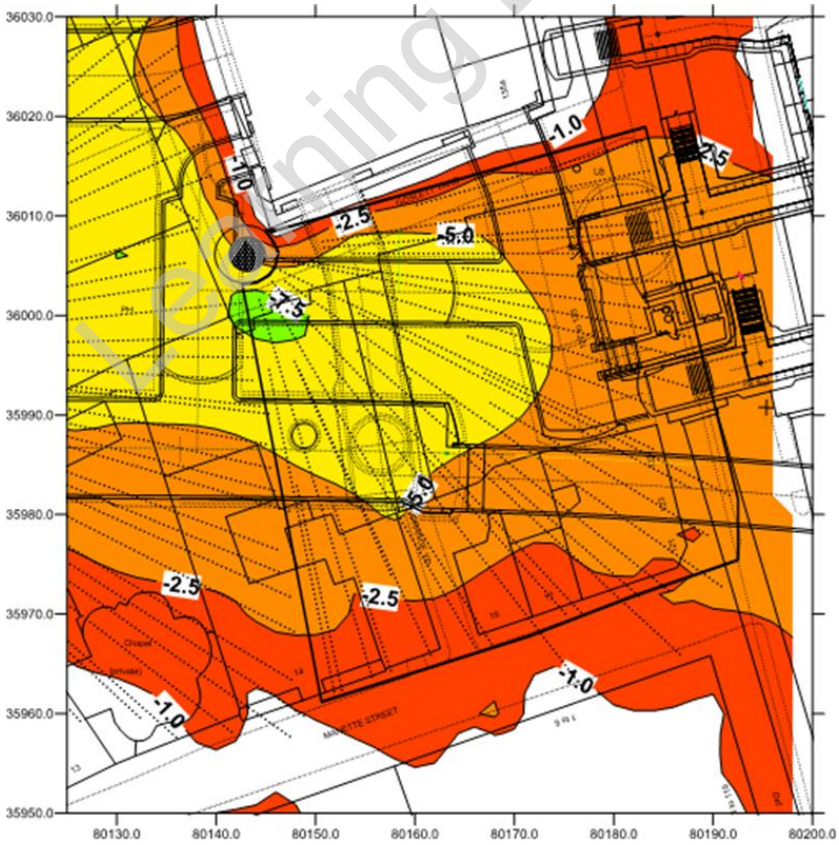
Excavation within the TCRSU Goslett Yard Box continued to completion during Period B and some of the observed settlement may be associated with these works.

The maximum movement within the TCR GS6 area at the end of Period C had increased to more than 35mm. (Figure 3.3.1(c)). Over the majority of the area, the settlement from the WBRT widened the contours implying a reduction in slopes.

3.4. Period C: 20/10/13 – 01/02/14: AP7A, AP7B, Concurrent Grouting

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





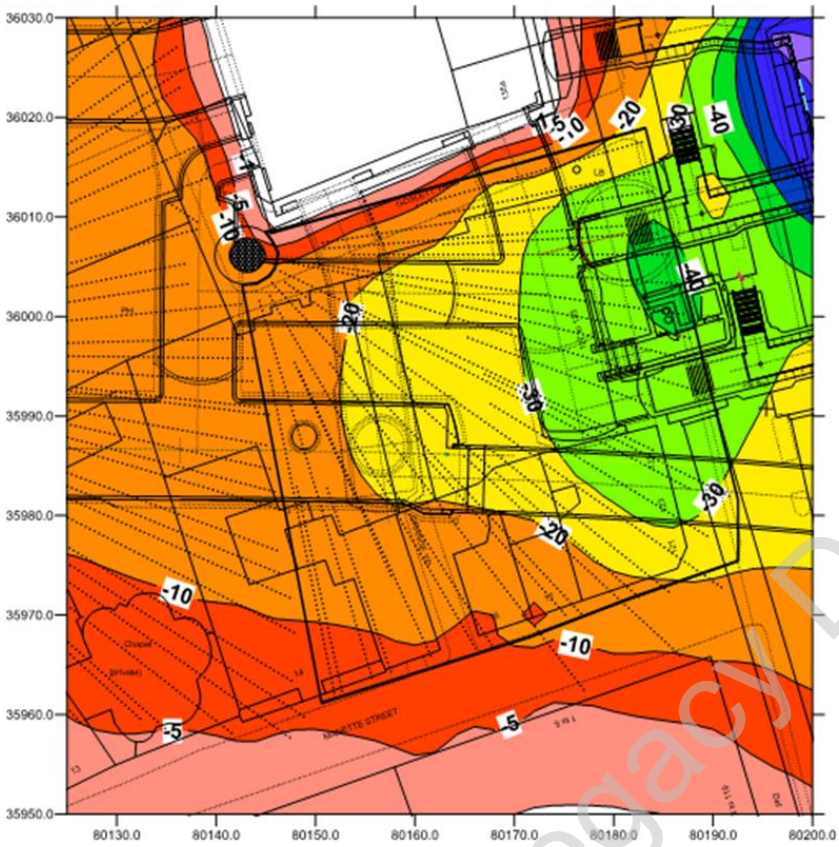


Figure 3.4.2 Period C: Distribution of grout injected from TCR GS6: Concurrent Grouting. Grout Intensity (mm).

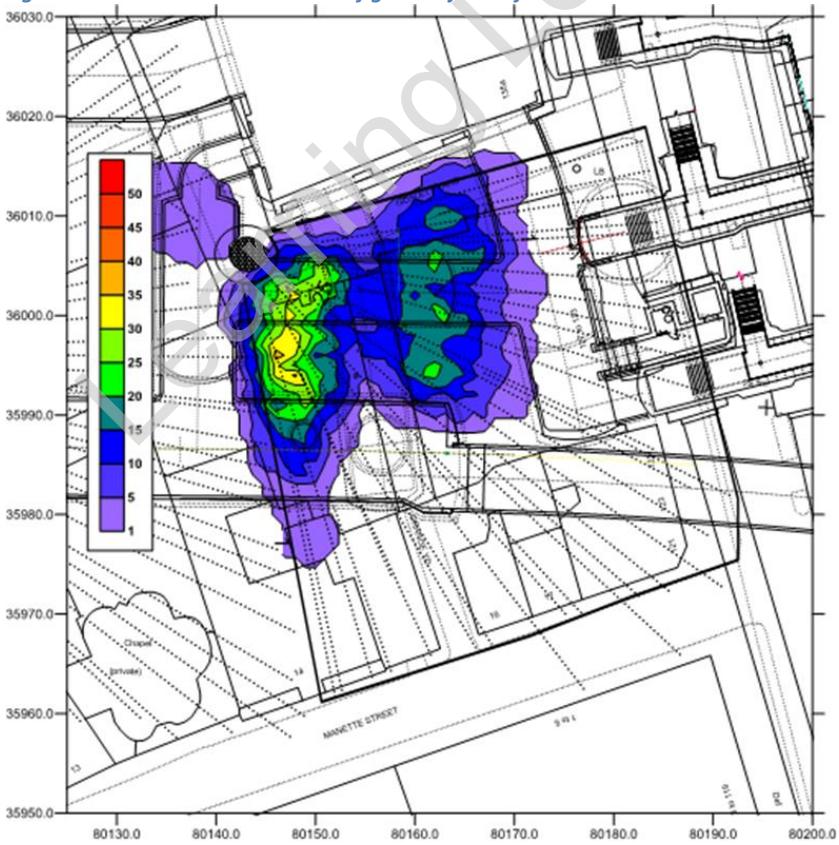


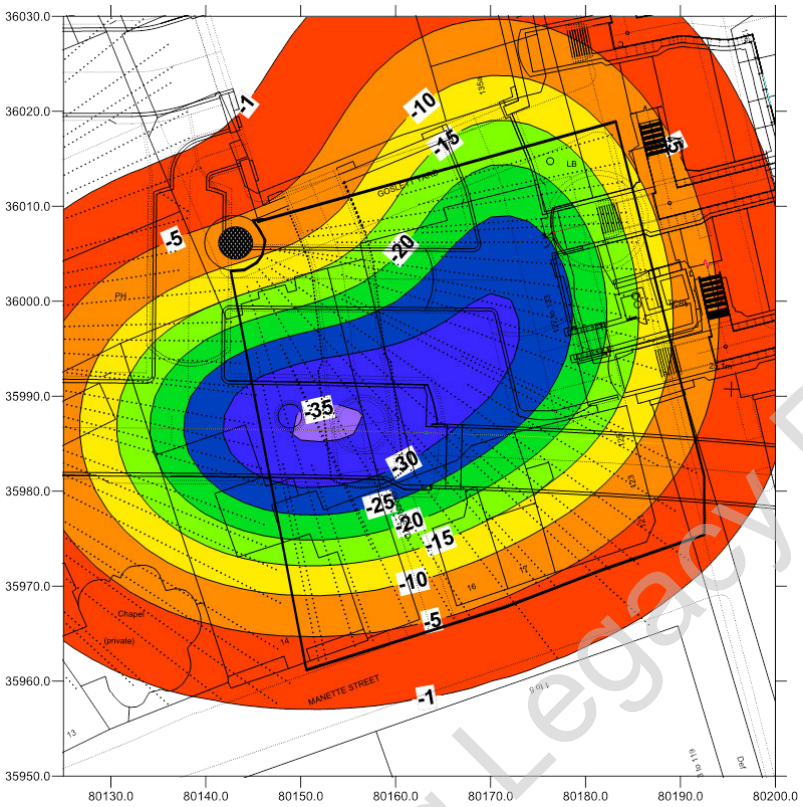
Figure 3.4.1(a) shows that over 25mm volume loss settlement was anticipated for AP7A and AP7B. Figure 3.4.1(b) shows the recorded settlement which has a maximum of 7.5mm over the junction between the two tunnels. The 2.5mm settlement contour encompasses the majority of the GS6 area: it is inferred that this more widespread movement is due to ongoing consolidation following the TCRSU works and the WBRT.

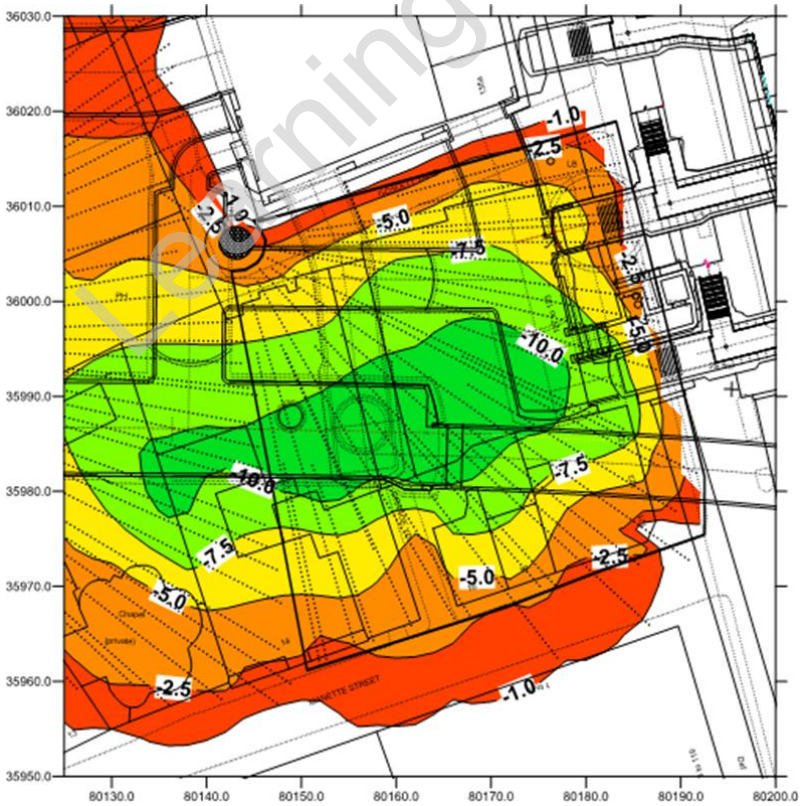
The maximum movement within the TCR GS6 area at the end of Period C had increased to 40mm (Figure 3.4.1(c)) on the Charing Cross Road facade.

The distribution of the concurrent grouting undertaken with AP7A and AP7B is shown in Figure 3.4.2. The effect of the exclusion zones around the TCRSU works and the grout shaft itself are evident in the contours.

3.5. Period D: 01/02/14 – 16/07/14 AP8, PTW, AP7A & AP8 junctions, S3, Concurrent & Grout Jacking

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





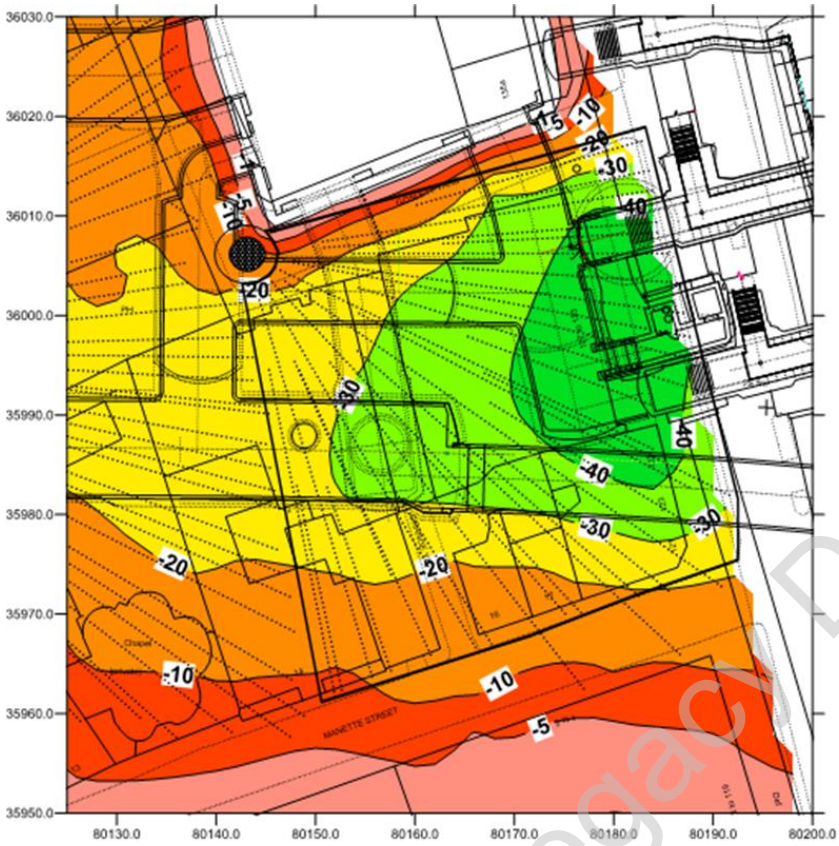


Figure 3.5.2 Period D: Distribution of grout injected from TCR GS6: Concurrent grouting. Grout Intensity (mm).

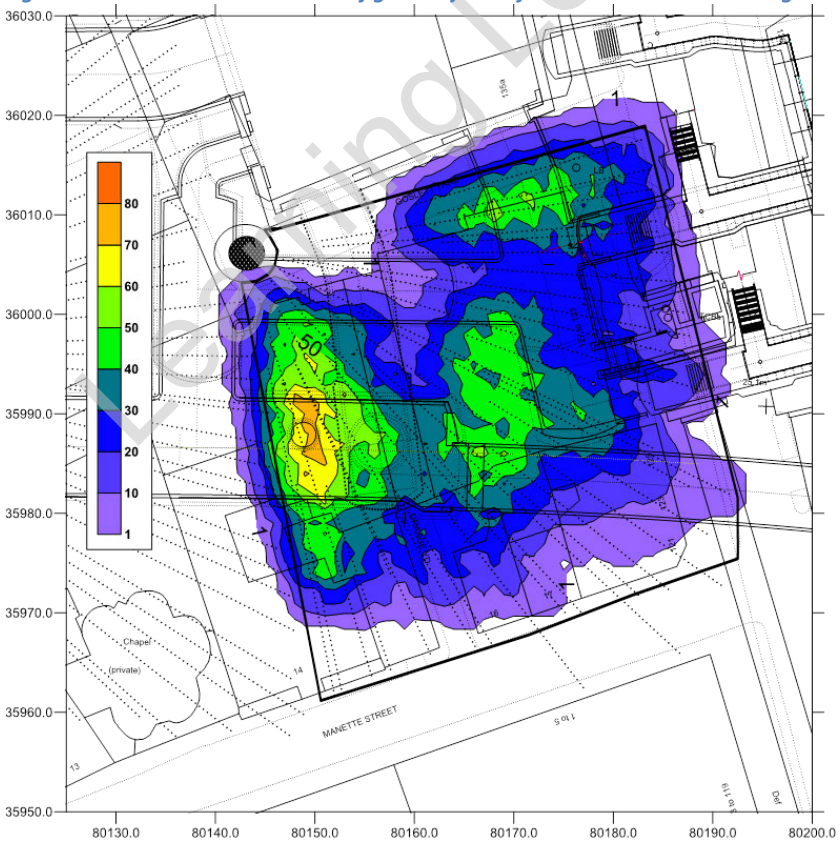
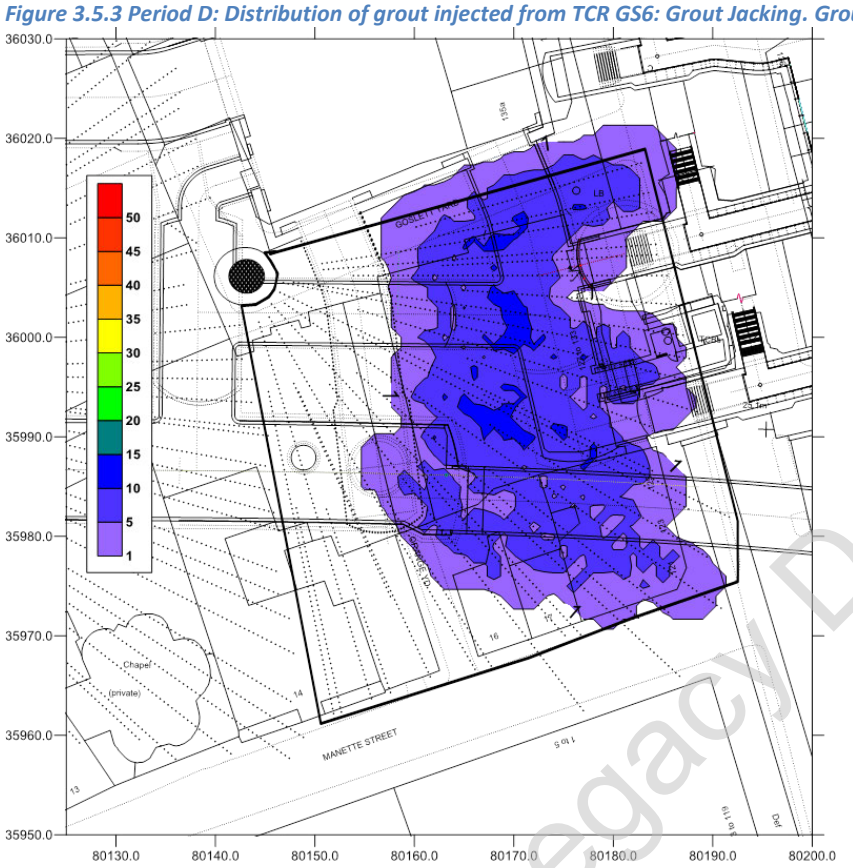


Figure 3.5.3 Period D: Distribution of grout injected from TCR GS6: Grout Jacking. Grout Intensity (mm).

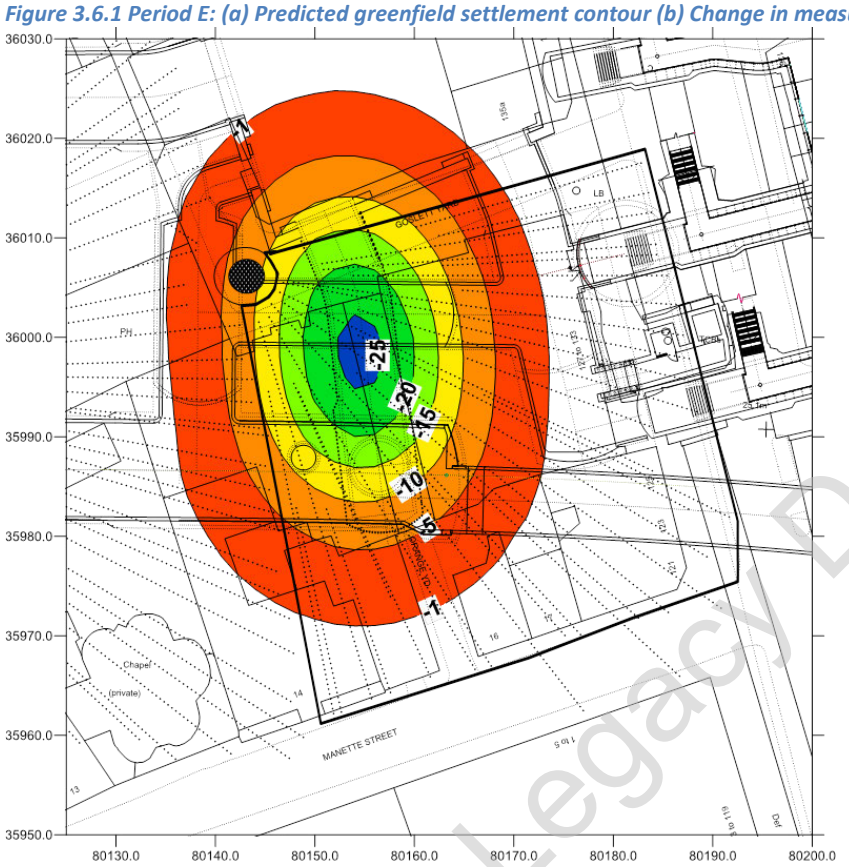


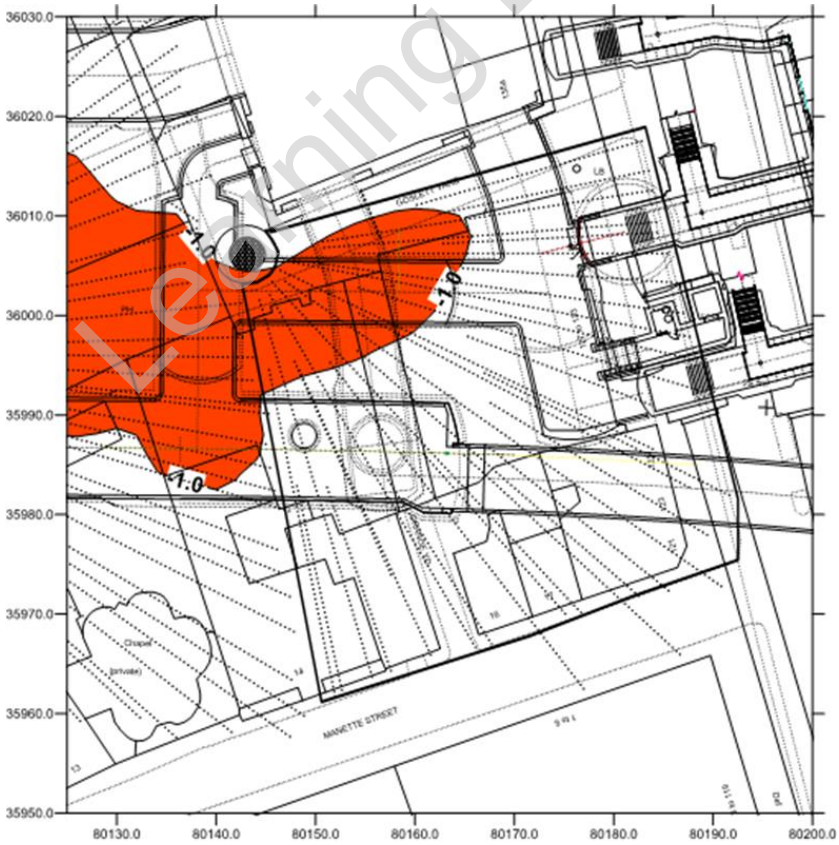
The volume loss settlement from construction of AP8, PTW and the associated junctions is shown in Figure 3.5.1(a) and indicates a maximum combined effect of 35mm within the area of TCR GS6. The maximum observed increase in settlement in Period D was just over 10mm (Figure 3.5.1(b)): volume loss settlement was controlled by concurrent grouting (Figure 3.5.2) and grout jacking (Figure 3.5.3).

The maximum total settlement (Figure 3.5.1(c)) increased by about 10mm, to over 40mm, with a similar pattern to that at the end of Period C.

3.6. Period E: 16/07/14 – 07/09/14: VEW, Grout Jacking

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





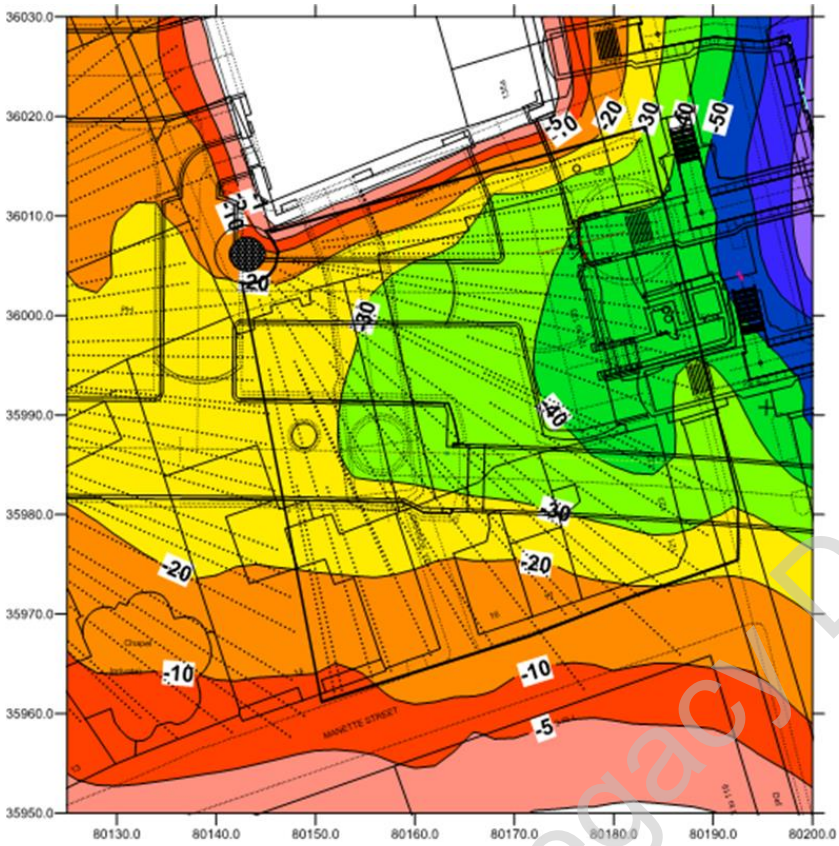
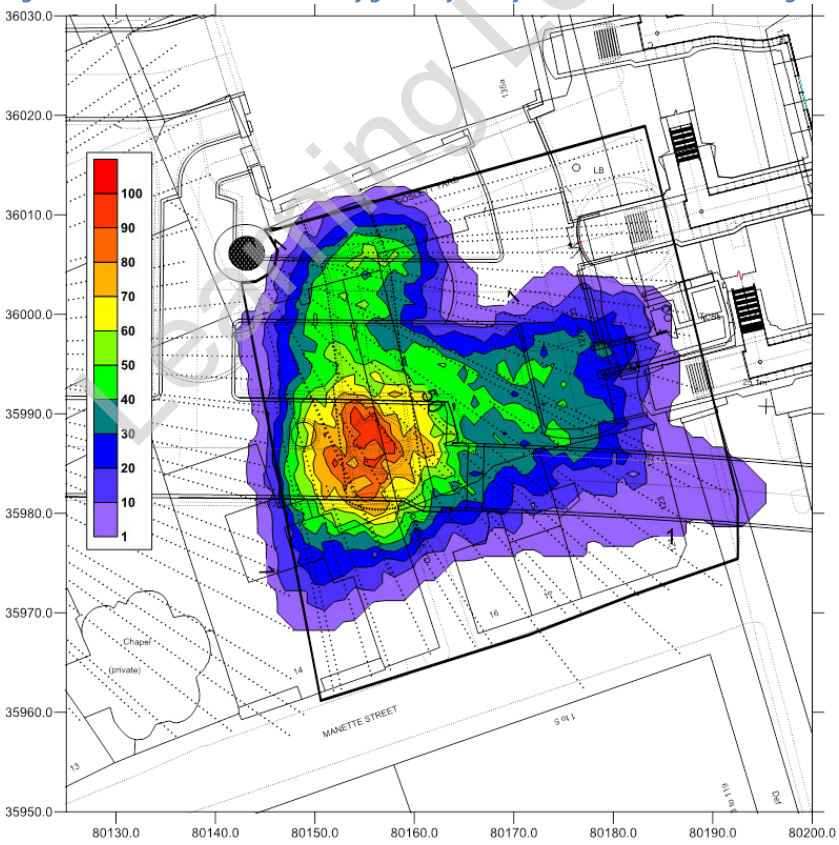


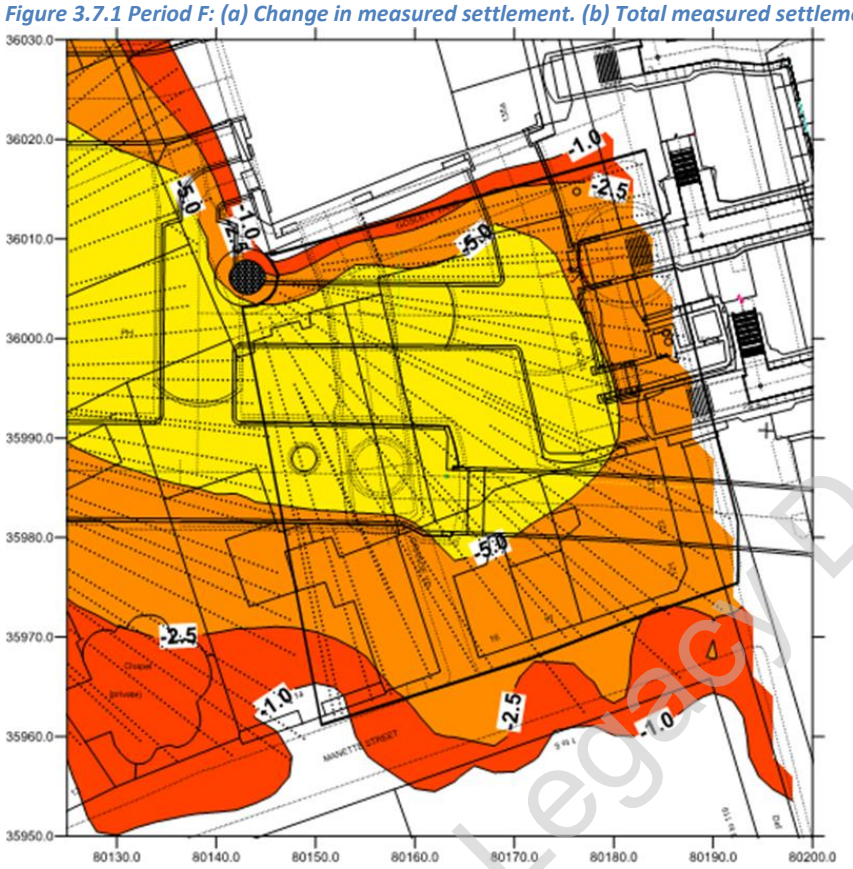
Figure 3.6.2 Period E: Distribution of grout injected from TCR GS6: Grout Jacking. Grout Intensity (mm).



Maximum predicted volume loss settlement from VEW amounted to 25mm with a relatively limited zone of influence due to the shallow cover over this tunnel (Figure 3.6.1(a)). Concurrent grouting was not possible since the TaMs were located at an elevation very close to the crown of the tunnel. An extensive grout jacking was undertaken targeting and achieving uplift equal to 50% of the potential volume loss settlement. Further grout jacking was undertaken targeted at reducing the net increase in settlement during Period D. The distribution of grout injected is shown in Figure 3.6.2 with intensity over VEW generally over 50mm and locally as much as 100mm (Figure 3.6.2). The success of this operation is evidenced by the change in settlement within the Period shown in Figure 3.6.1(b) which shows negligible change. The total settlement contour in Figure 3.6.1(c) is therefore virtually identical to that at the end of Period D, with a maximum in excess of 40mm.

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

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



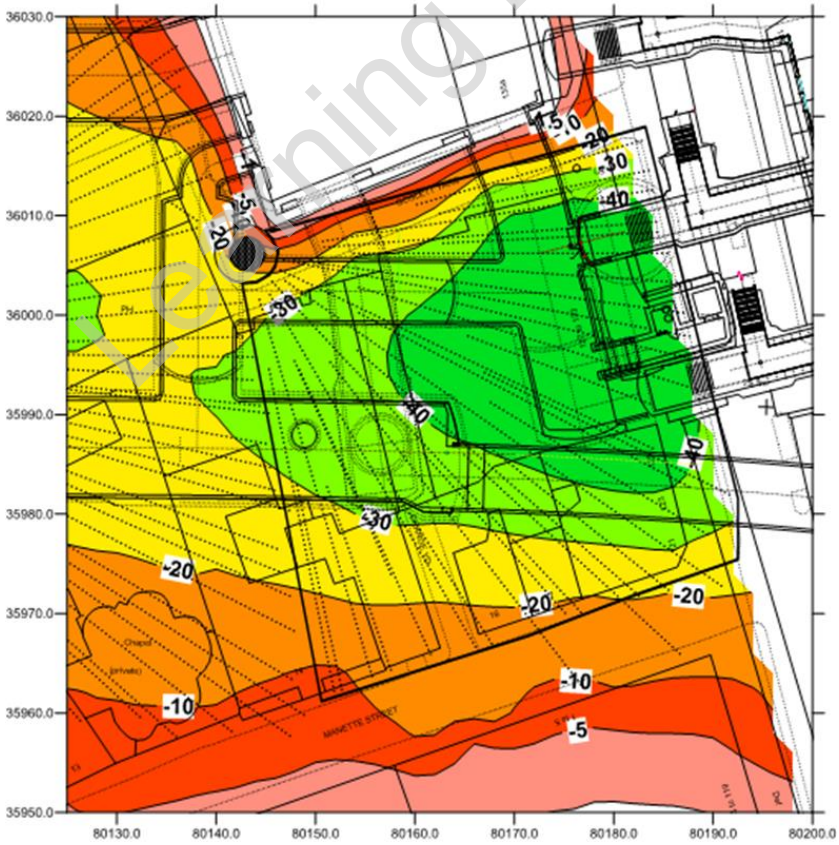


Figure 3.7.1(a) shows an increase of settlement of over 5mm from consolidation settlement over most of the GS6 area during the 12 months since the completion of tunnelling.

The total settlement at the end of Period F is shown on Figure 3.7.1(b) with around 50mm on Charing Cross Road reducing to a maximum of about 30mm over the western end of the arrays.

No grout jacking was possible since the TaMs were backfilled prior to the construction of VEW in Period E.

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 D. Details are given in Table 4.1. There have been no breaches of Deflection Ratio triggers.

Slope triggers are as follows:

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

Table 4.1 Details of Amber trigger breaches on BRE

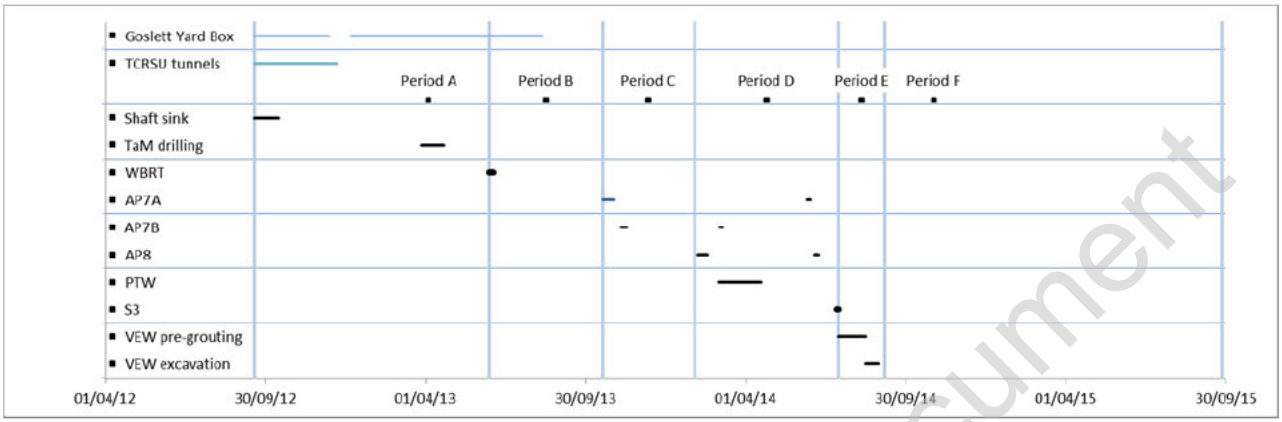
BUILDING FACADES		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Manette Street – North:					
D08LB028-D08LB029	Amber	Post construction increase - stabilised	24/07/15	1.13	1.11
D08LB092-D08LB093	Amber	Marginal - Mean 0.99mm/m over 152 readings between 18/11/13 and 24/07/15	18/11/13	1.26	0.96
Manette Street - South: NONE					
Charing Cross Road - west:					
D08LB083-D08LB082	Amber	Post construction increase - stabilised	21/10/14	1.06	1.06
D08LB094-D08LB095	Amber	Initial slope of 0.82mm/m due to TCRSU works prior to TaM drilling	10/05/13	1.82	1.79
D08LB096-D08LB097	Amber	Initial slope of 0.81mm/m due to TCRSU works prior to TaM drilling	15/04/13	1.13	0.99
D08LB046-D08LB037	-	3 isolated readings >1.0mm/m – trigger not verified	N/A	1.02	0.91
Goslett Yard - South: NONE					
Orange Yard -east					
D08LB030-D08LB031	Amber	Less than 1.1mm/m during and at the end of construction. Post construction increase - stabilised	08/07/14	1.24	1.24

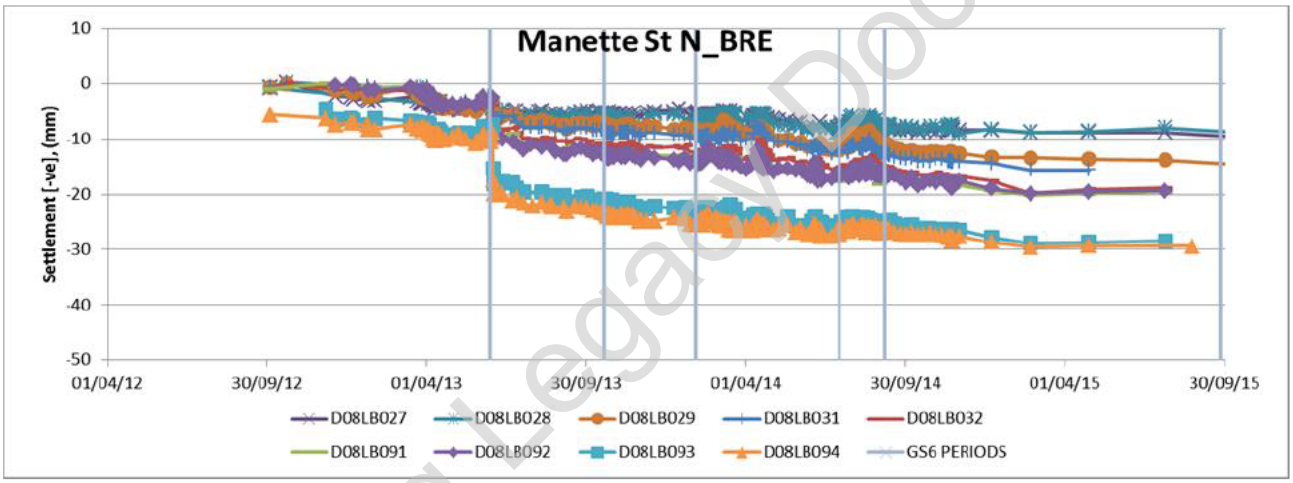
Figure 4.1. Locations of BRE building slope Amber triggers.

BRE monitoring data from the facades within the footprint of GS6 are presented in the following sections, namely Mannette Street north and south, Charing Cross Road west, Goslet Yard South and Orange Yard. The plots presented for each comprise, as appropriate:

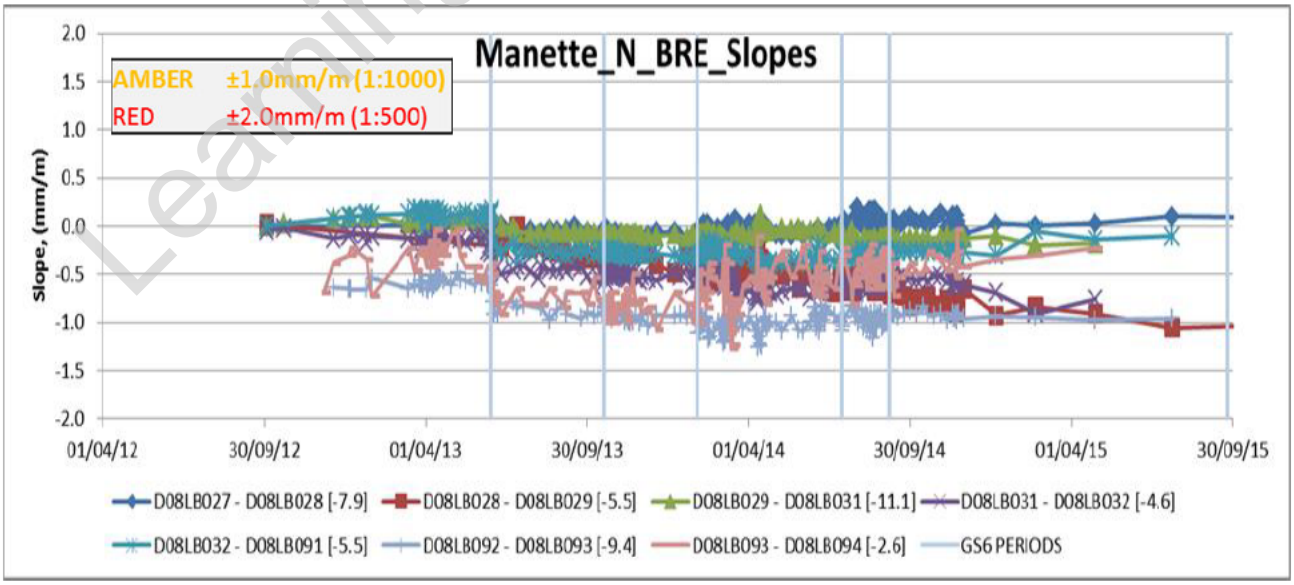
1. Summary of tunnel construction and associated construction periods
2. Time settlement history
3. Settlement profile plots with series as close to the end of each construction period as is available
4. Time slope history over the full construction period with the distances between the points in metres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

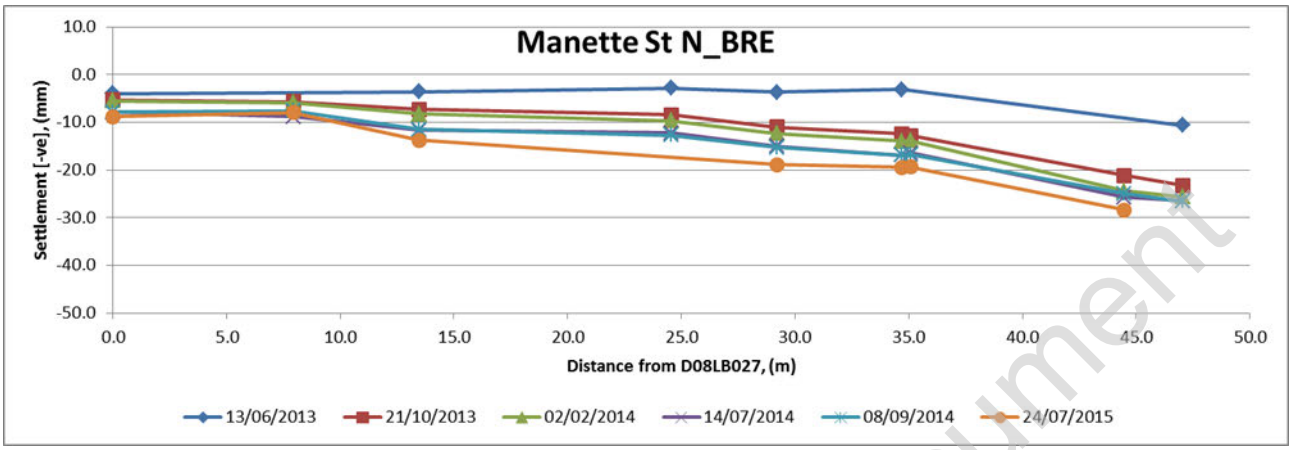
4.2. Manette Street - North





NB. Monitoring continued beyond Sept 2015 for points in GS5 area – refer GS5 report (C300-BFK-C4-RGN-CRT00_ST005-51229)

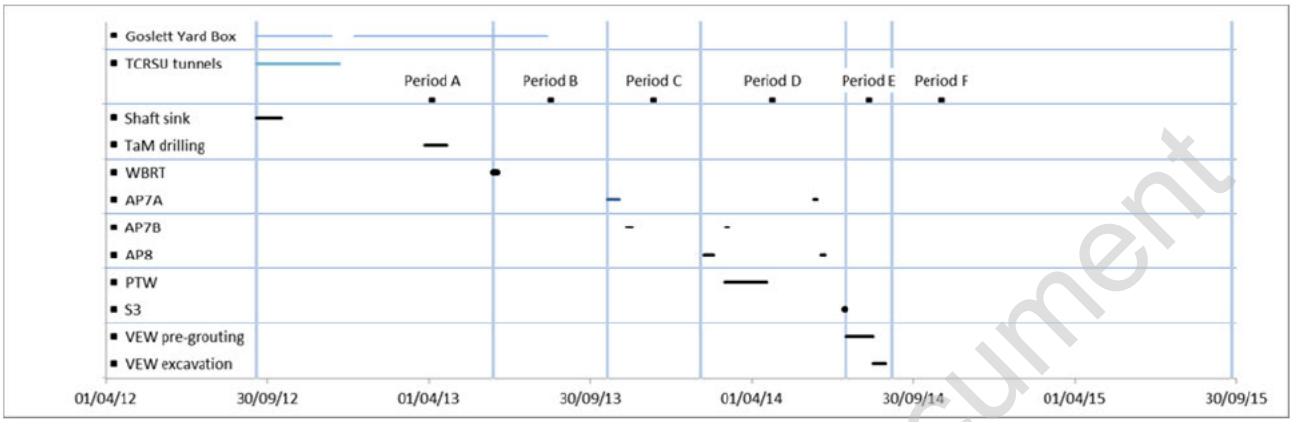


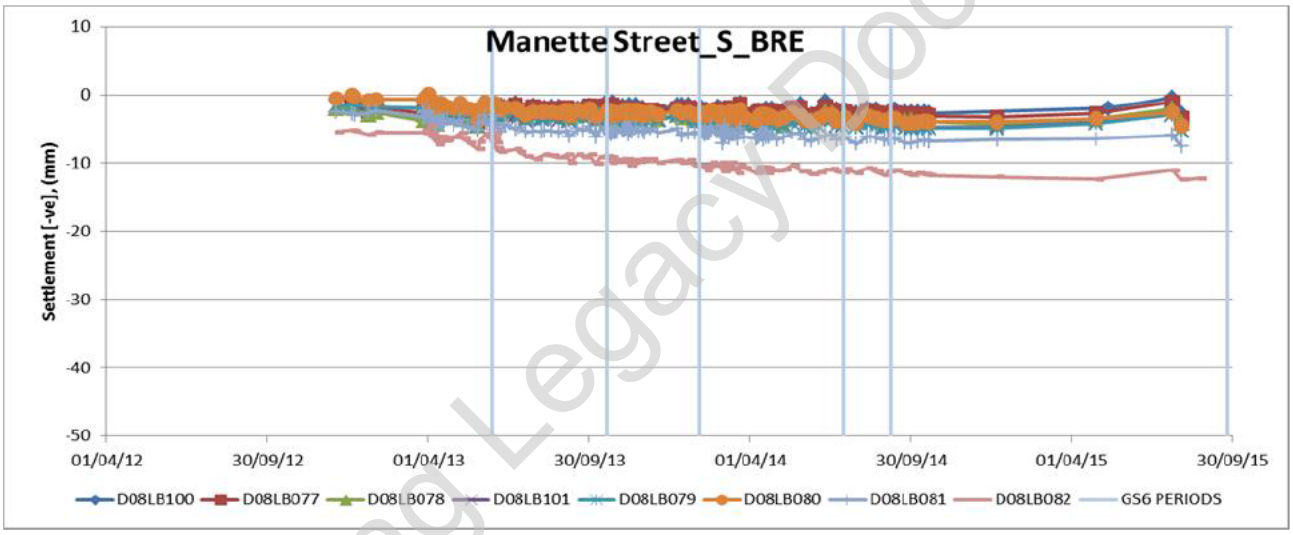


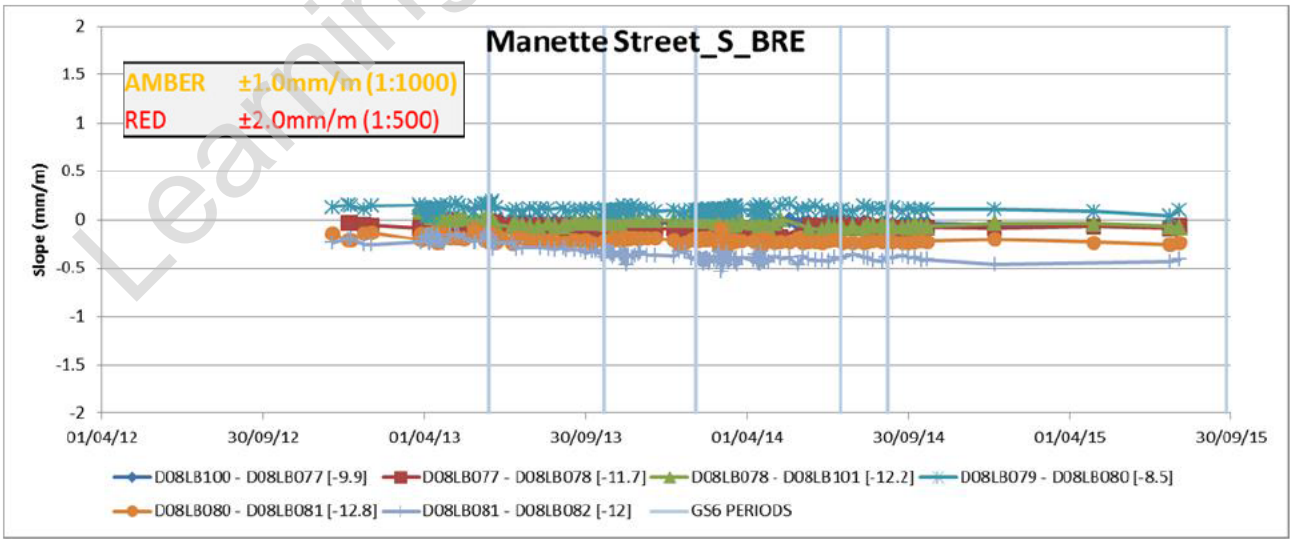
The following points are noted:

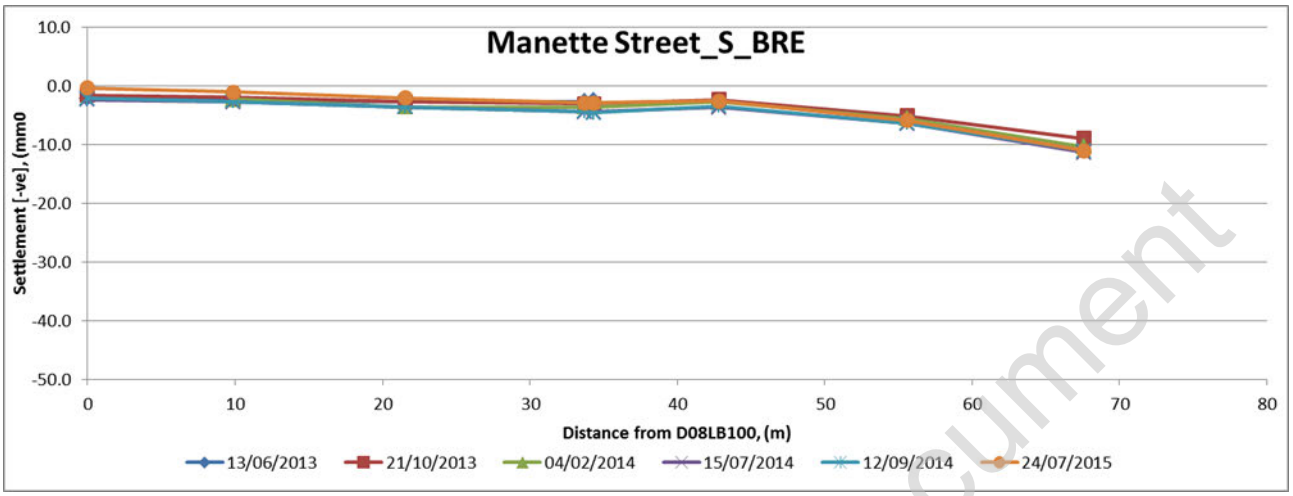
- Data are presented for the BRE located on the north facade of Manette Street as shown on Figure 4.1.
- Overall settlement was ~10mm or less at the end of Period A, primarily as a result of TCRSU works. A small net increase (~3mm) is associated with TaM drilling and subsequent pre-treatment.
- Settlement increased to a maximum of 23mm in Period B, associated with the WBRT excavation, without concurrent grouting.
- No significant increase in settlement is evident as a result of any of the tunnels constructed in Periods C, D or E as a result of concurrent grouting. Settlement increased gradually between tunnel drives and reached about 28mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions, with ~30mm maximum settlement.
- It is noted that significant slopes (D08LB092 - D08LB093 at ~0.6mm/m and D08LB093 - D08LB094 at ~0.4mm/m) existed prior to any potential effect from BFK works, as a result of movements generated by the TCRSU works. These two slopes inceased to close to the Amber trigger value following the WBRT.
- Slopes were less than the Amber trigger value at the end of construction but a transitory slope trigger occurred between D08LB092 and D08LB093, as detailed in Table 4.1. Post construction movements generated a further trigger between D08LB028 and D08LB029.
- By inspection, no Deflection Ratio triggers were breached.

4.3. Manette Street South





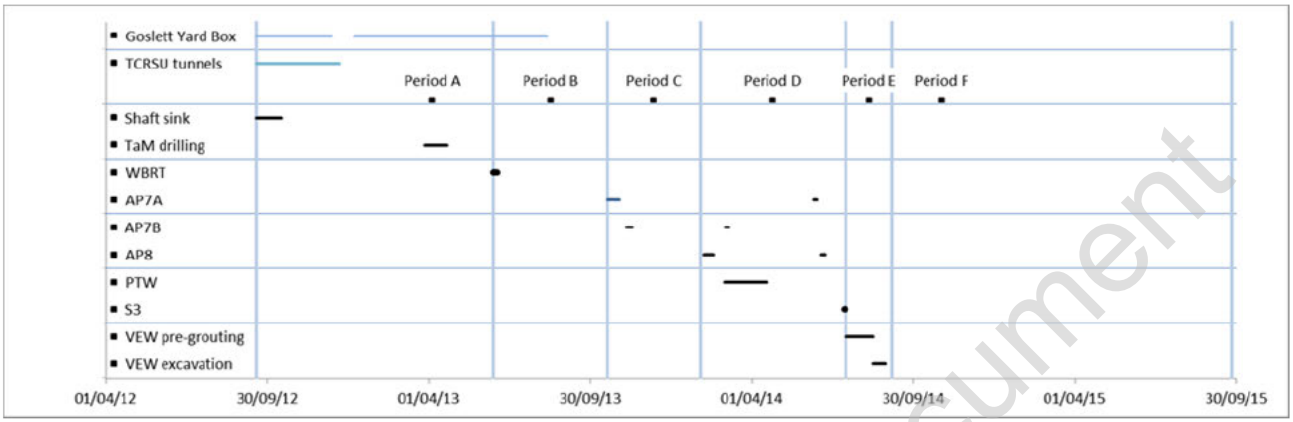


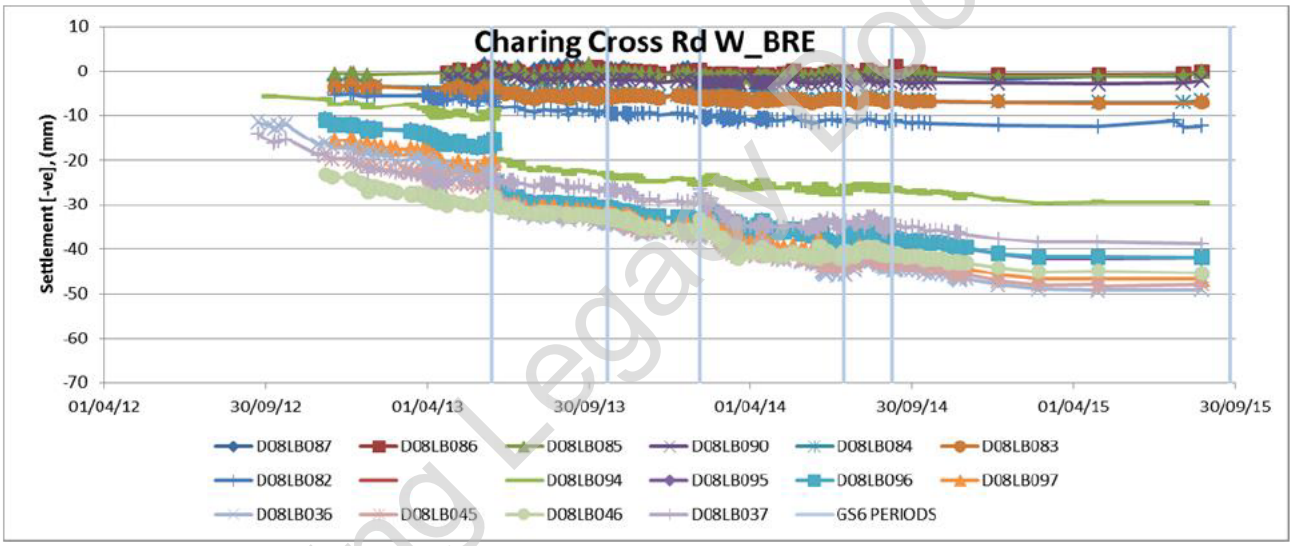


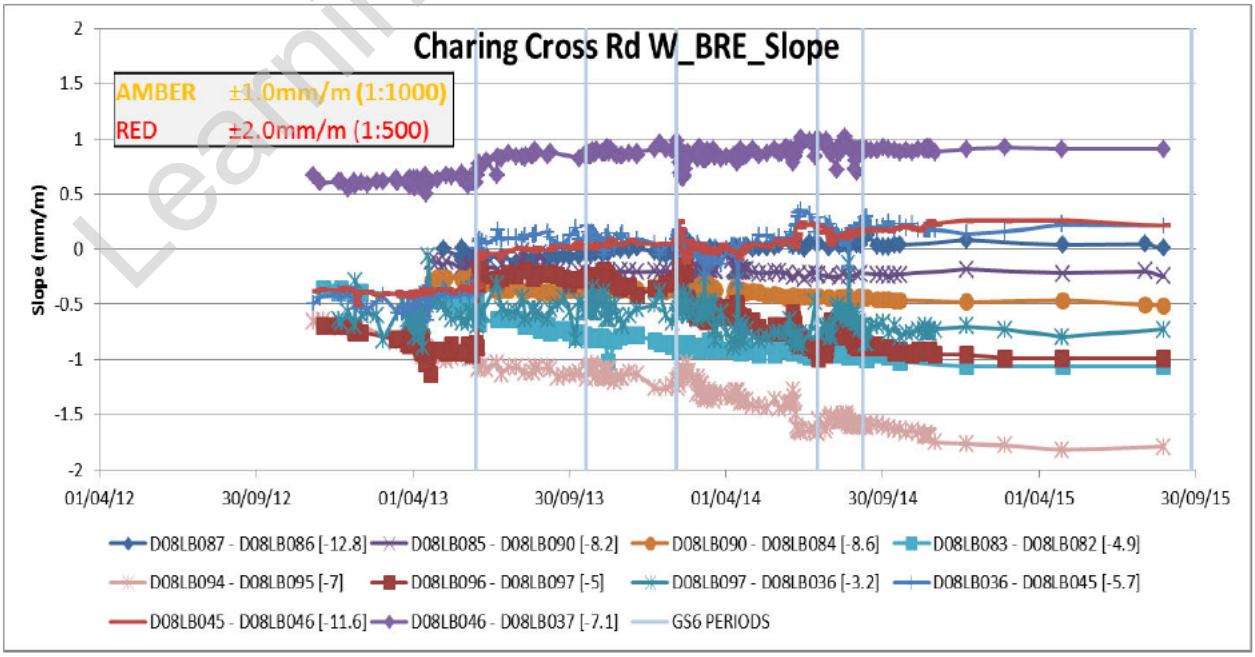
The following points are noted:

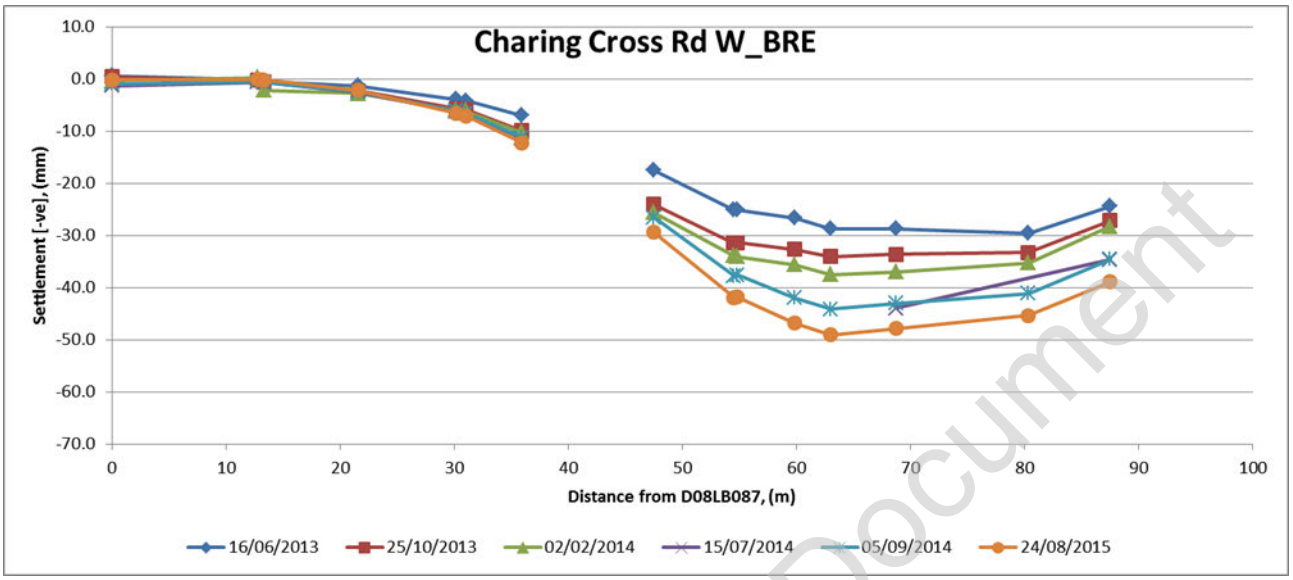
- Data are presented for the BRE located on the south façade of Manette Street. None of the points are within the extent of the GS6 arrays, as shown on Figure 4.1. It is noted that the Compensation Grouting area was amended from the centre of Manette Street to the façade on the north side of the road due to an obstruction encountered during drilling for TaM installation.
- Overall settlement was ~8mm or less at the end of Period A, primarily as a result of TCRSU works. No net effect is evident from TaM drilling and subsequent pre-treatment.
- Settlement increased to a maximum of 10mm in Period B, associated with the WBRT excavation, without concurrent grouting.
- No significant increase in settlement is evident as a result of any of the tunnels constructed in Periods C, D or E as a result of concurrent grouting. Settlement increased gradually between tunnel drives and reached about 12mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions, with a maximum settlement of ~12mm.
- No slope Amber trigger values were exceeded during construction or subsequently.

4.4. Charing Cross Road - West





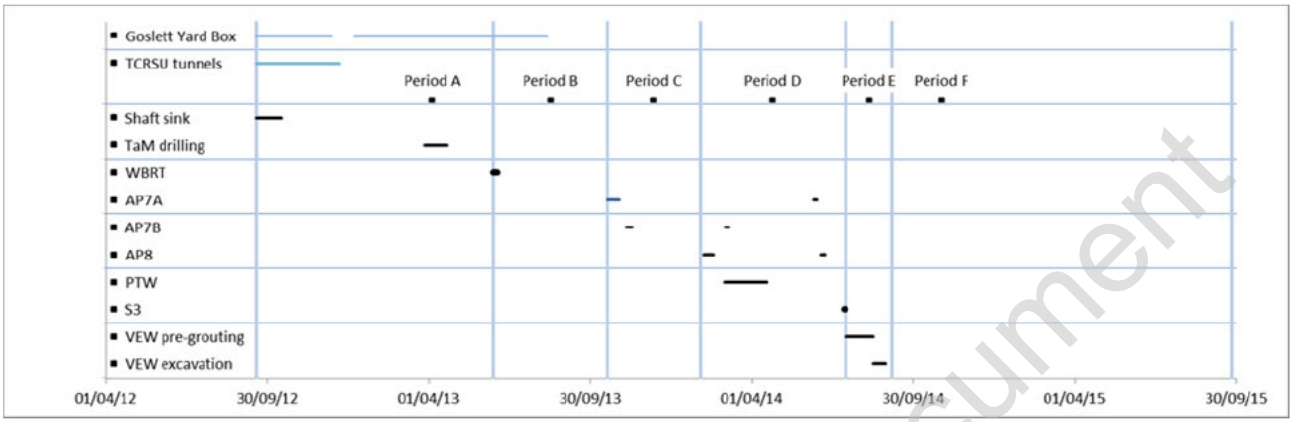


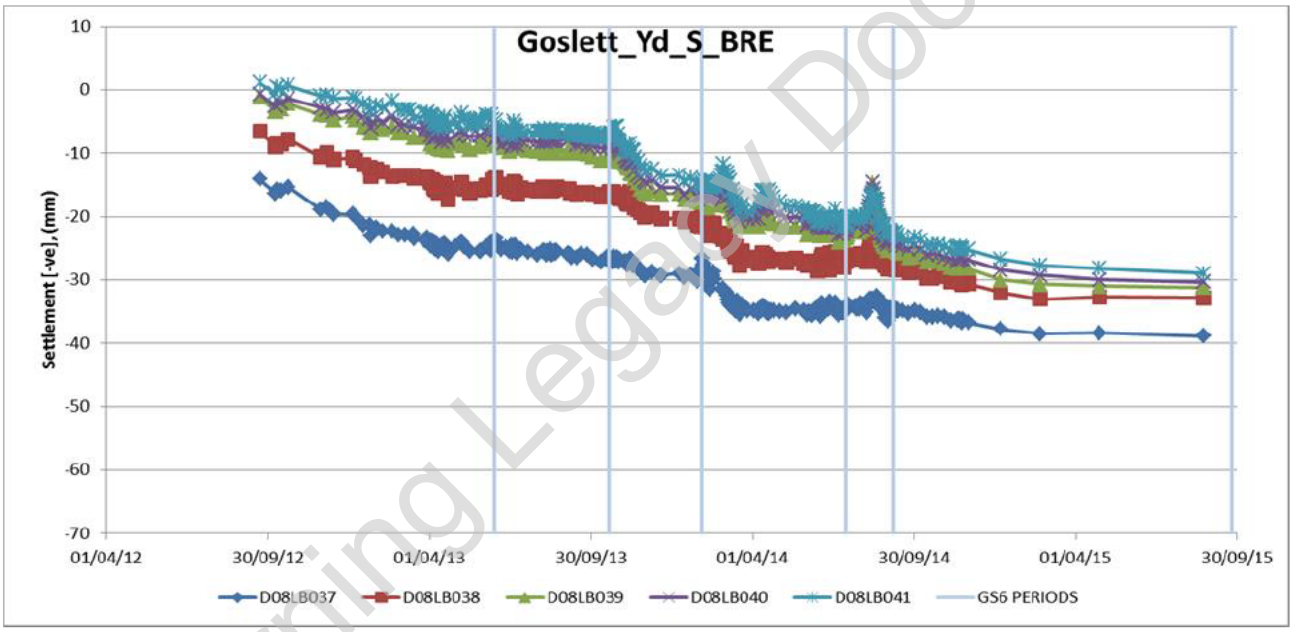


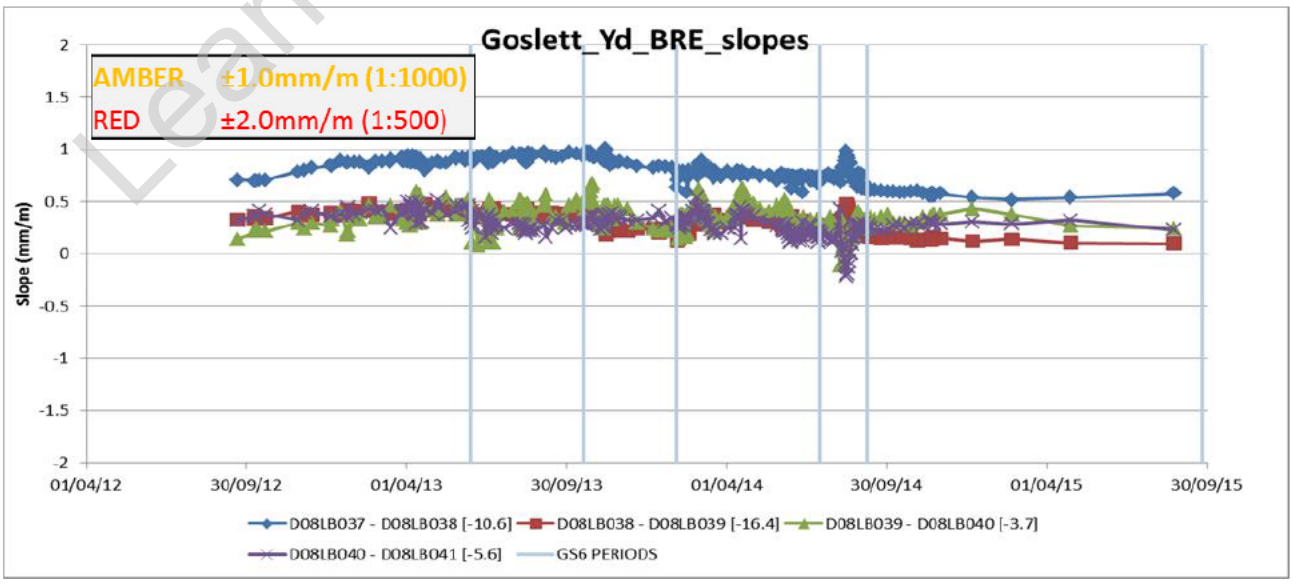
The following points are noted:

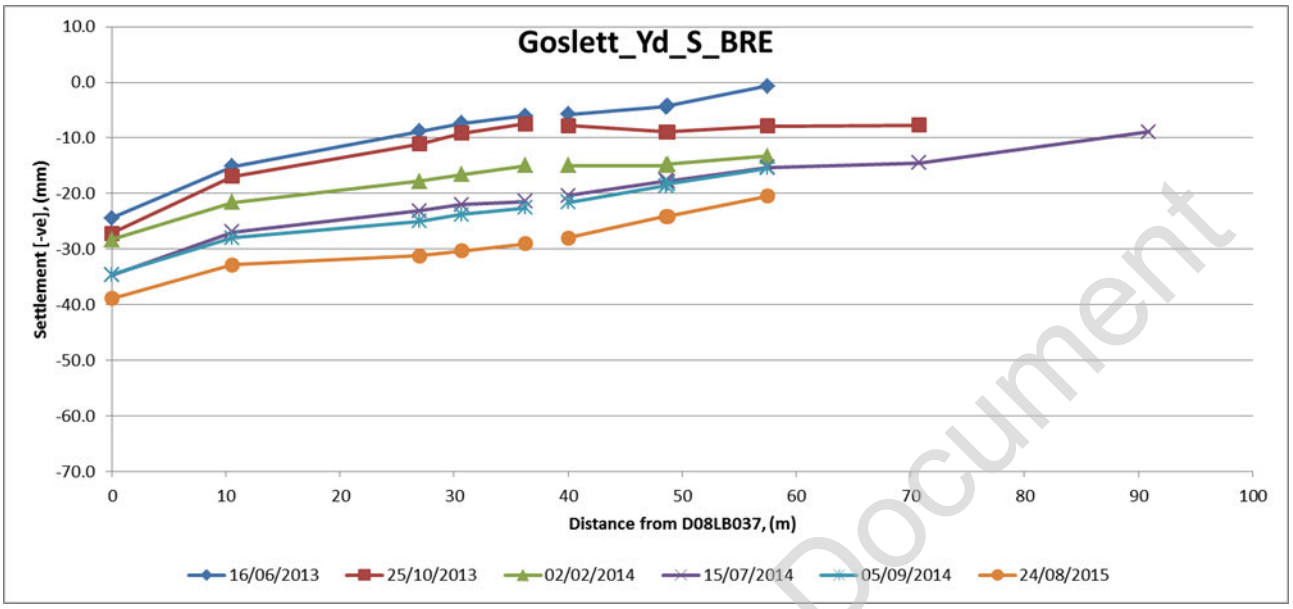
- Data is presented for the BRE located on the west facade of Charing Cross Road. Only the points north of Manette Street (i.e. from distance 45m on the profile plot) are within the extent of the GS6 arrays, as shown on Figure 4.1.
- Overall settlement was ~30mm at the end of Period A, primarily as a result of TCRSU works. No net effect is evident from TaM drilling and subsequent pre-treatment.
- The maximum settlement only increased slightly to 33mm in Period B, although settlement increased by up to 15mm on some points, associated with the WBRT drive without concurrent grouting.
- Further increases in settlement are evident in Period D at the time of AP8 and PTW construction. Settlement also increased gradually between tunnel drives and reached about 45mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing stable conditions, with a maximum settlement of ~50mm.
- It is noted that significant slopes (over 0.8mm/m D08LB096 - D08LB097 and D08LB094 - D08LB095) existed prior to any BFK works with a potential effect, as a result of movements generated by the TCRSU works. This slope exceeded the Amber trigger level temporarily during TaM drilling but this was reduced below the trigger level by subsequent pre-treatment.
- A further slope exceeded the Amber trigger during Period B associated with the WBRT, as detailed in Table 4.1. Post construction movements generated one further Amber trigger breach.
- By inspection, no Deflection Ratio triggers were breached.

4.5. Goslett Yard South





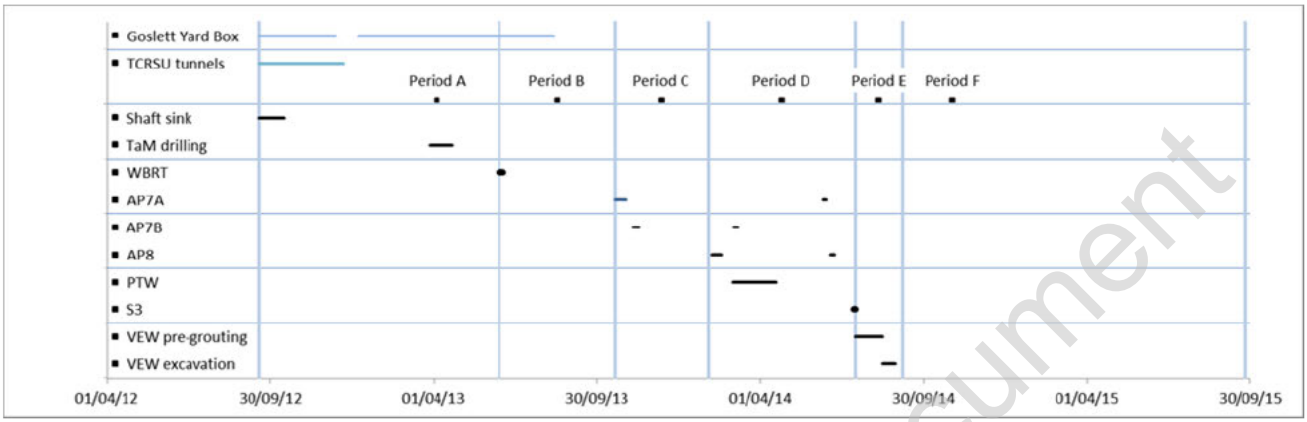


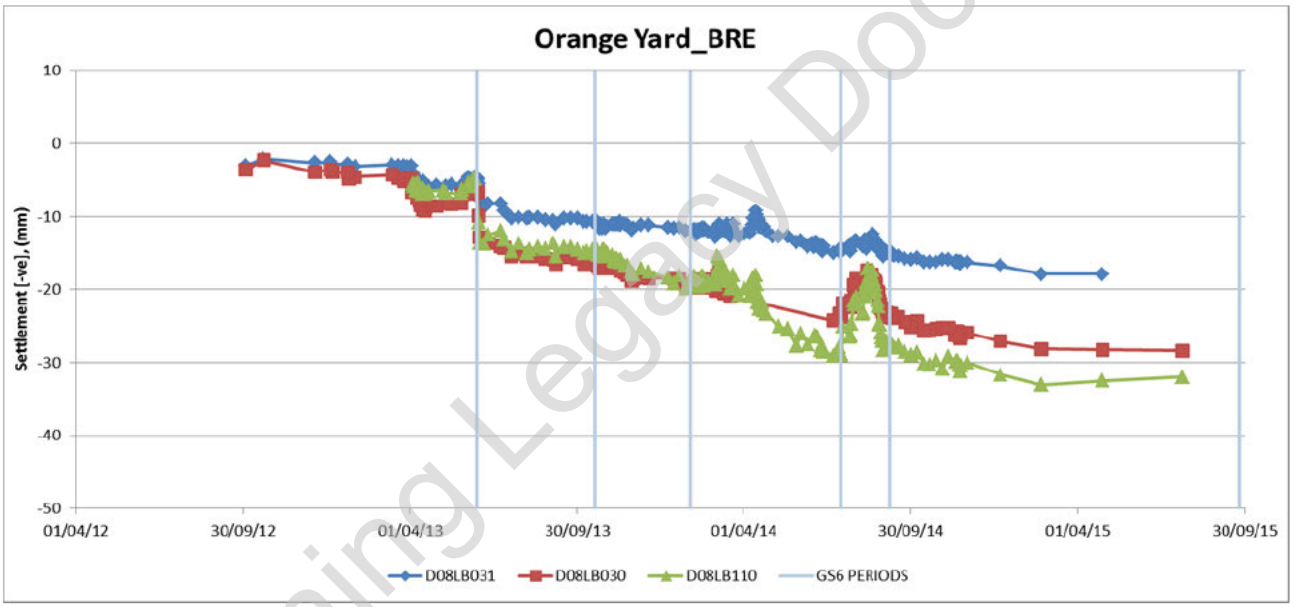


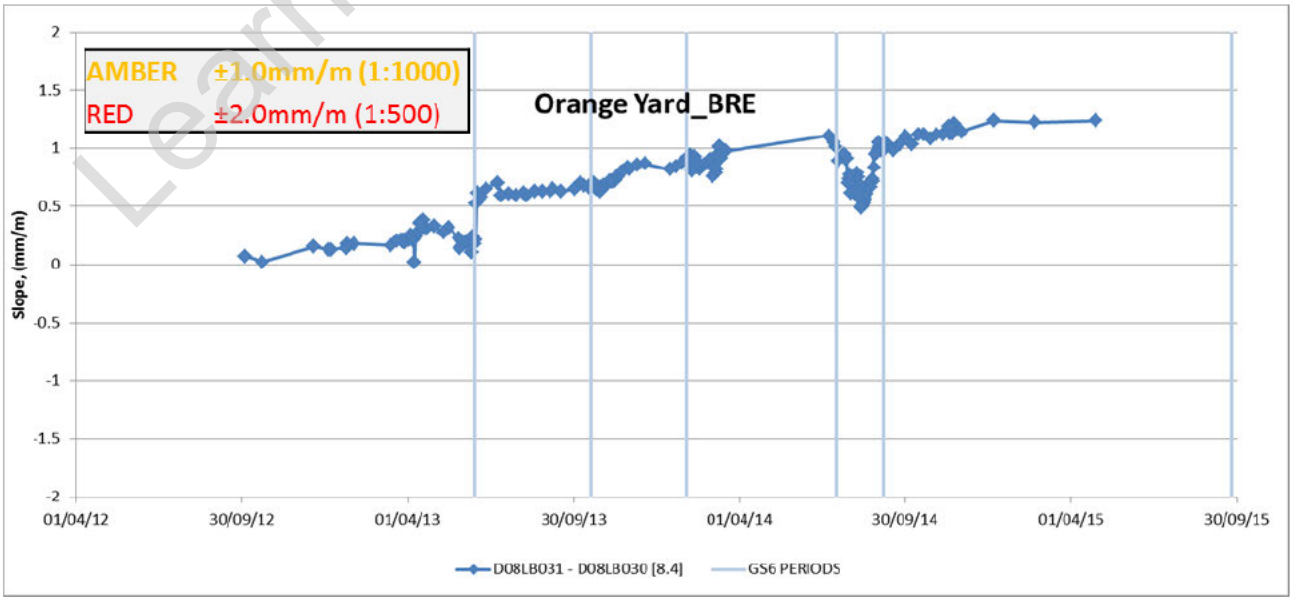
The following points are noted:

- Data is presented for the BRE located on the south facade of Goslett Yard, as shown on Figure 4.1.
- Overall settlement was ~25mm at the end of Period A, primarily as a result of TCRSU works. A small net increase (~3mm) is associated with TaM drilling and subsequent pre-treatment.
- The maximum settlement only increased slightly to 27mm in Period B, with no evidence of volume loss movement associated with the WBRT drive.
- Further increases in settlement are evident in Period C due to AP7B excavation, in Period D at the time of AP8 and PTW construction. Settlement also increased gradually between tunnel drives and reached about 35mm at the end of Period D. Uplift associated with grout jacking prior to VEW is shown in Period E, followed by settlement of almost the same magnitude, giving negligible net change in settlement over the Period.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing stable conditions, with a maximum settlement of ~40mm.
- It is noted that significant slopes existed prior to any BFK works as a result of movements generated by the TCRSU works. A maximum slope of ~0.9mm/m existed prior to the start of TaM drilling in a location where shaft sinking would have had no impact.
- No slope Amber trigger values were exceeded during construction or subsequently. Grout jacking prior to VEW construction in Period E had a temporary effect on slopes but this was reversed by the excavation of VEW.

4.6. Orange Yard







The following points are noted:

- Data is presented for the BRE located around the facades of Orange Yard as shown on Figure 4.1.
- Overall settlement was ~10mm or less at the end of Period A, primarily as a result of TCRSU works, although it appears that TaM drilling also caused some settlement of these points, albeit that most of this was reversed by pre-treatment.
- Settlement increased to a maximum of 17mm in Period B, associated with the WBRT excavation, without concurrent grouting, and subsequent consolidation.
- No significant increase in settlement is evident during construction of any of the tunnels constructed in Periods C, D or E as a result of concurrent grouting. Settlement increased gradually between and after the tunnel drives and reached about 29mm at the end of Period D. Uplift associated with grout jacking prior to VEW is shown in Period E, followed by settlement of almost the same magnitude, giving negligible net change in settlement over the Period.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions, with a maximum settlement of ~32mm.
- The slope between the two points on the east side of Orange Yard (D08LB030 and D08LB031) exceeded the Amber trigger due to consolidation settlement following PTw and AP8 construction in Period D, as detailed in Table 4.1. The construction of VEW in Period E had little net effect as the uplift generated prior to excavation was almost equal to the measured settlement. The slope continued to increase in Period F as a result of post-construction movement, but the final readings indicate that it has now stabilised.
- By inspection, no Deflection Ratio triggers were breached.

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. By inspection, no Deflection Ratio triggers have been exceeded. A larger version of Figure 5.1 is included in Appendix D. Details are given in Table 5.1.

Slope triggers are as follows:

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

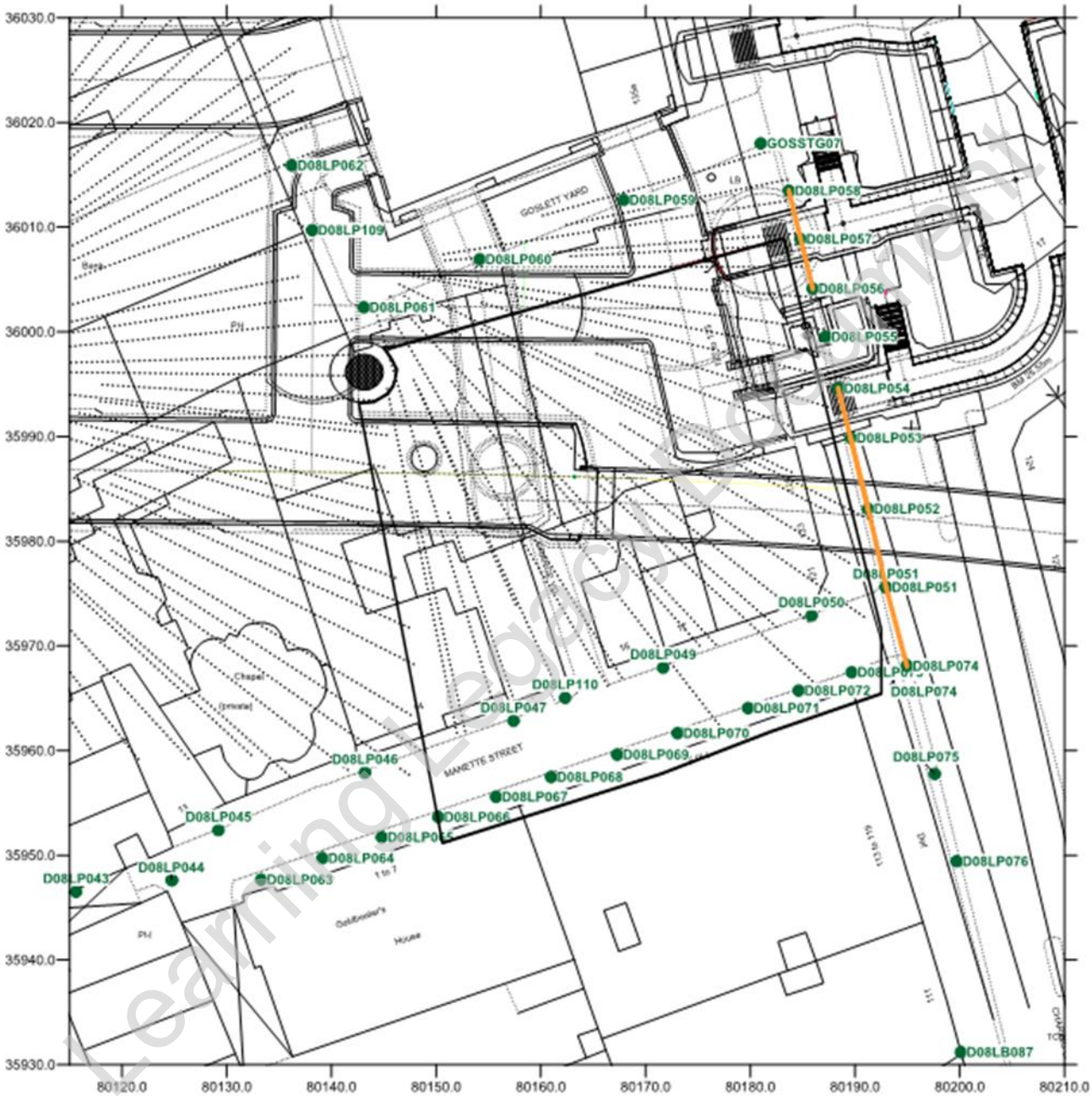
PLP monitoring data from the kerb lines within the footprint of GS6 are presented in the following sections, namely Manette Street north and south, Charing Cross Road west and Goslett Yard south. The plots presented for each comprise, as appropriate:

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

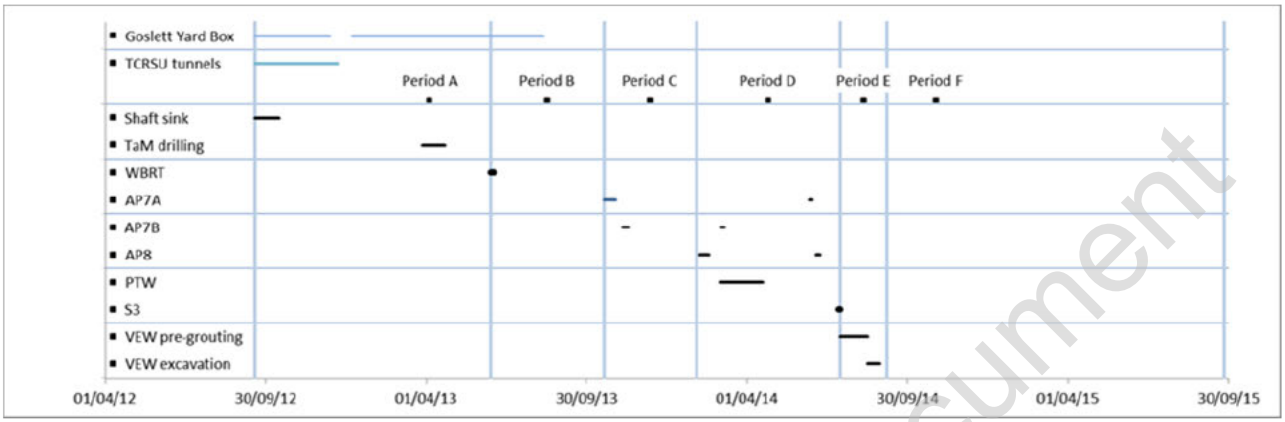
Table 5.1 Details of Amber trigger breaches on PLP

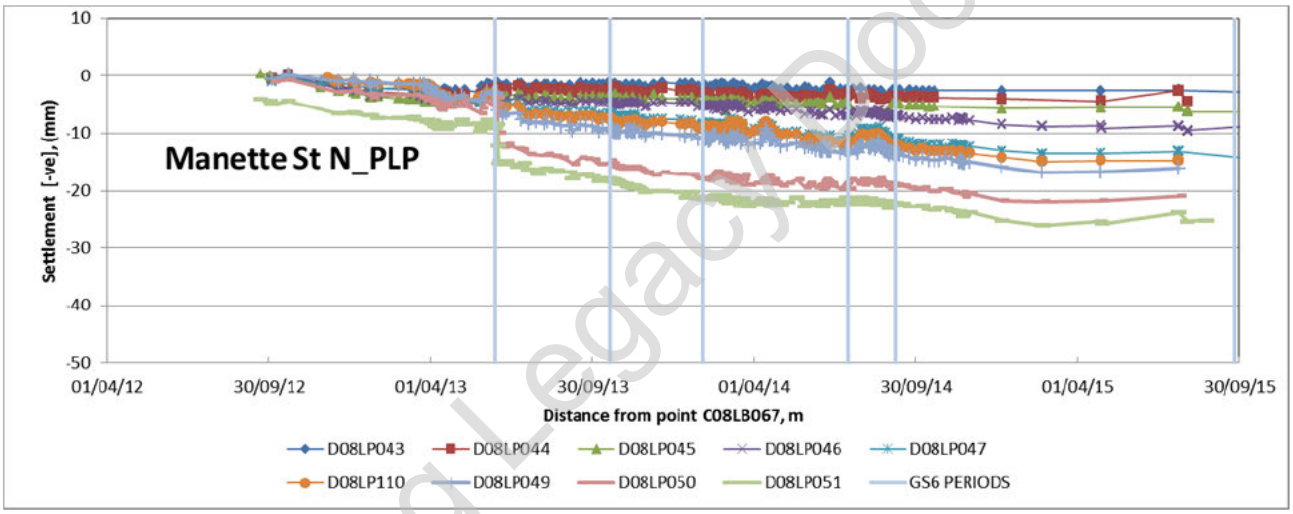
Kerb Line		Comment	Date exceeded	Maximum (mm/m)	Final (mm/m)
Manette Street – North: NONE					
Manette Street - South: NONE					
Charing Cross Road - West:					
D08LP052 – D08LP053	Amber	Trigger due to TCRSU prior to BFK works – reduced below threshold by WBRT settlement 15/06/13	04/10/12	1.44	0.53
D08LP052 – D08LP054	Amber	Trigger due to TCRSU prior to BFK works – reduced below threshold by WBRT settlement 15/06/13	18/12/12	1.24	0.60
D08LP074 – D08LP051	Amber	Post WBRT movement in Period B – gradual increase thereafter	08/09/13	1.46	1.41
D08LP051 – D08LP052	Amber	WBRT volume loss settlement – approximately constant thereafter	16/06/13	1.22	1.19
D08LP056 – D08LP058	Amber	Several isolated values >1.0mm/m during construction. Exceeded Amber post construction	18/11/14	1.13	1.06
Goslett Yard - South: NONE					

Figure 5.1 Location of PLP Amber slope triggers

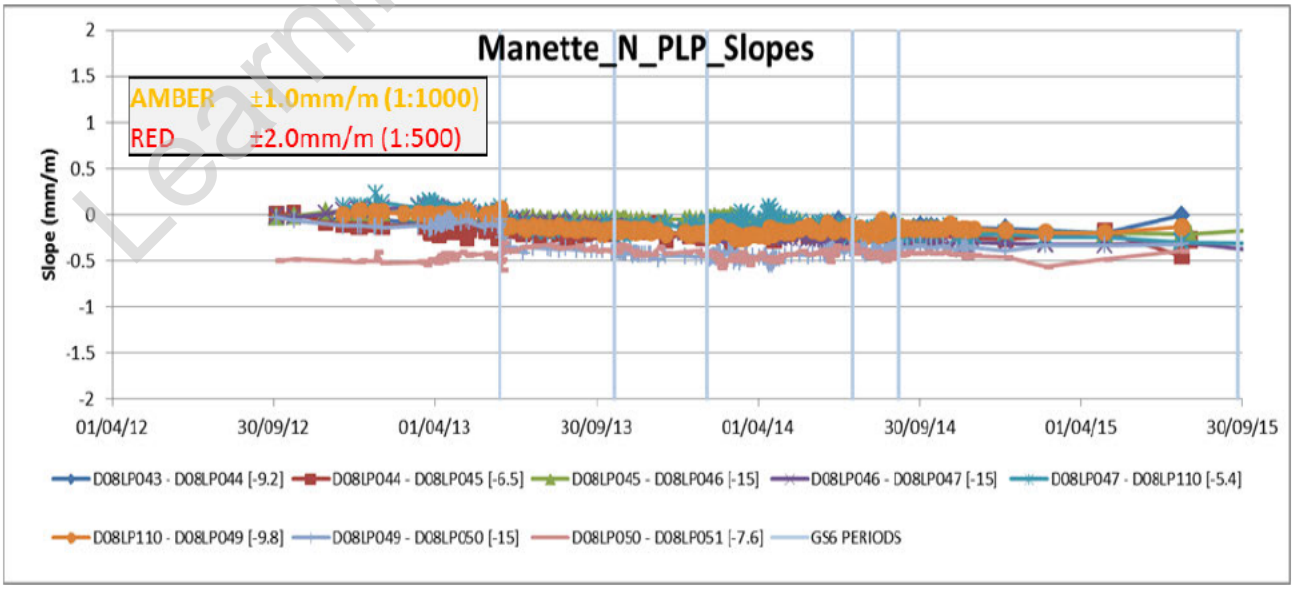


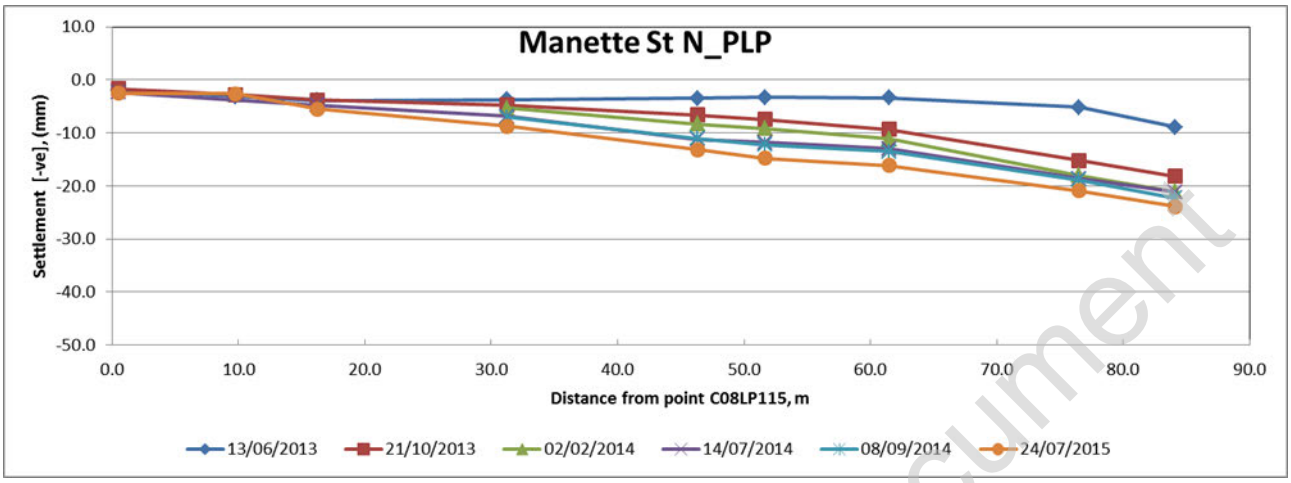
5.2. Manette Street - north





NB. Monitoring continued beyond Sept 2015 for points in GS5 area – refer GS5 report (C300-BFK-C4-RGN-CRT00_ST005-51229)

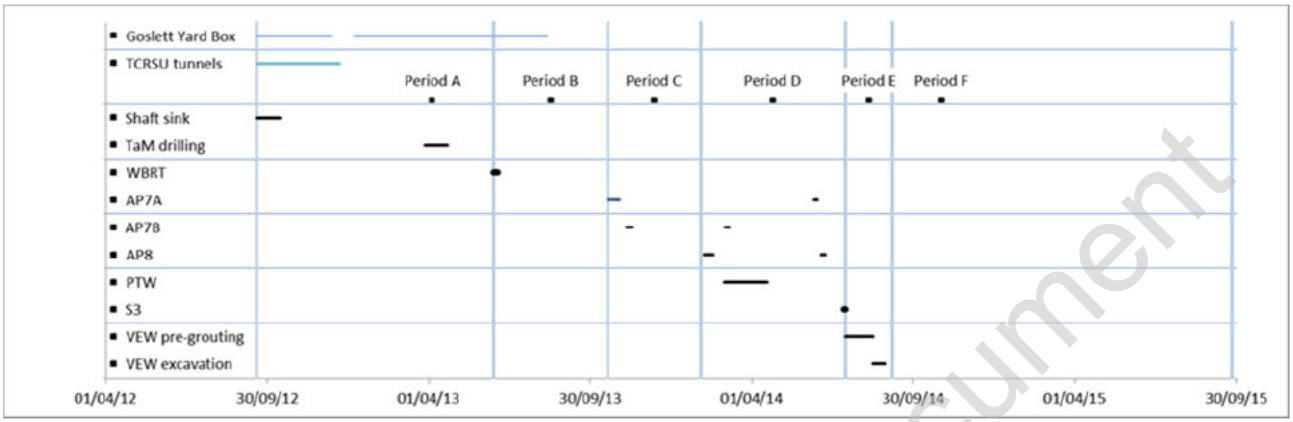


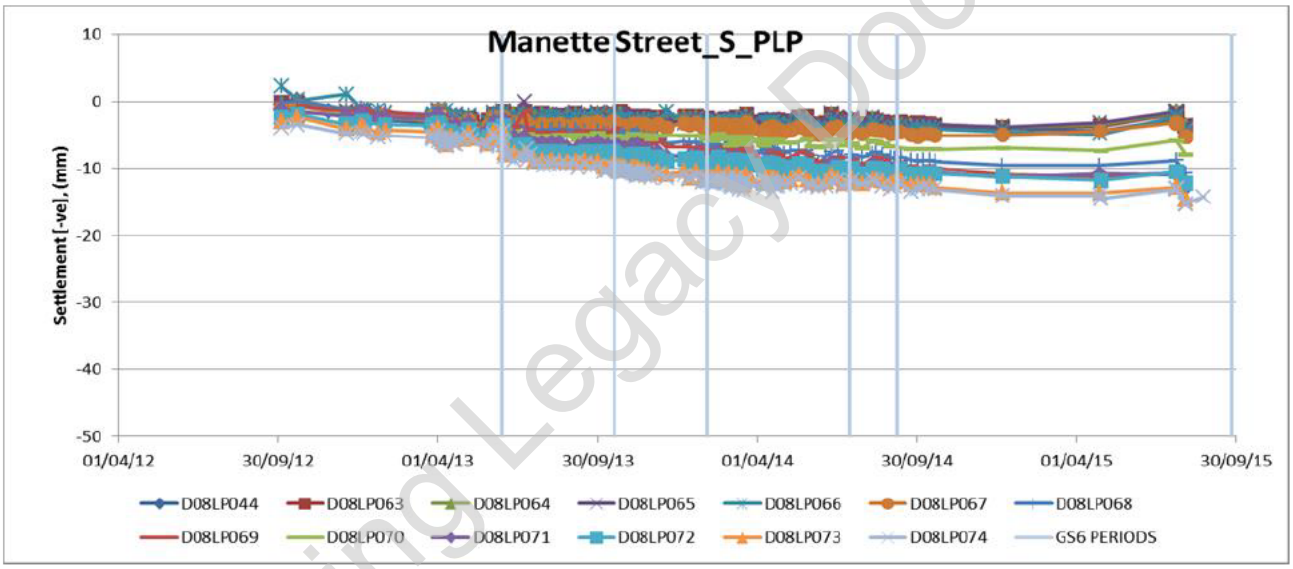


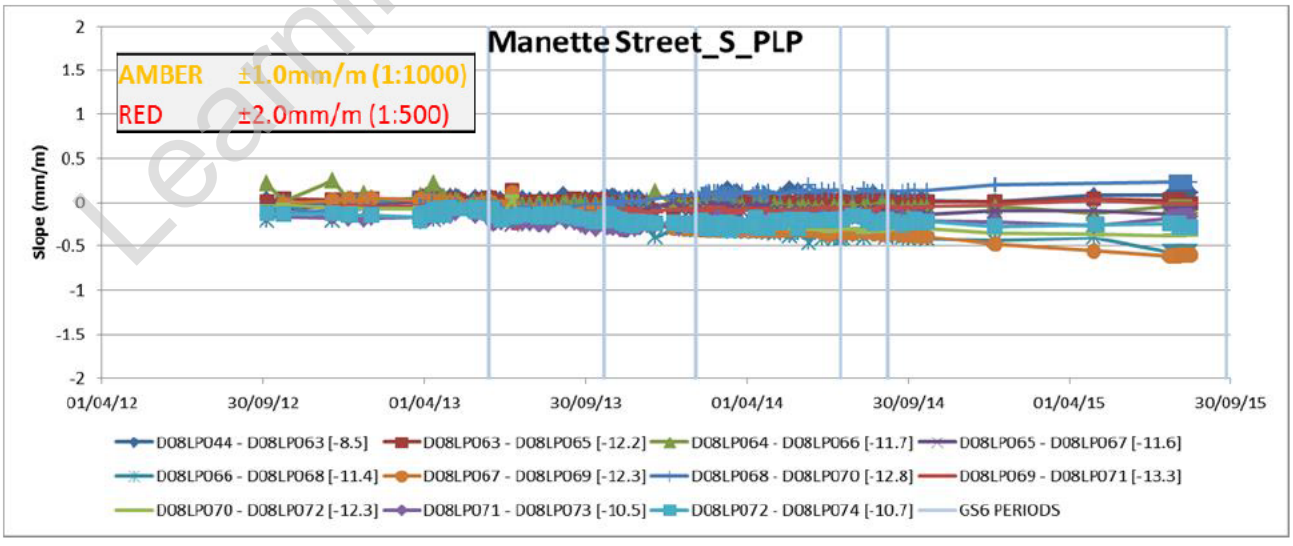
The following points are noted:

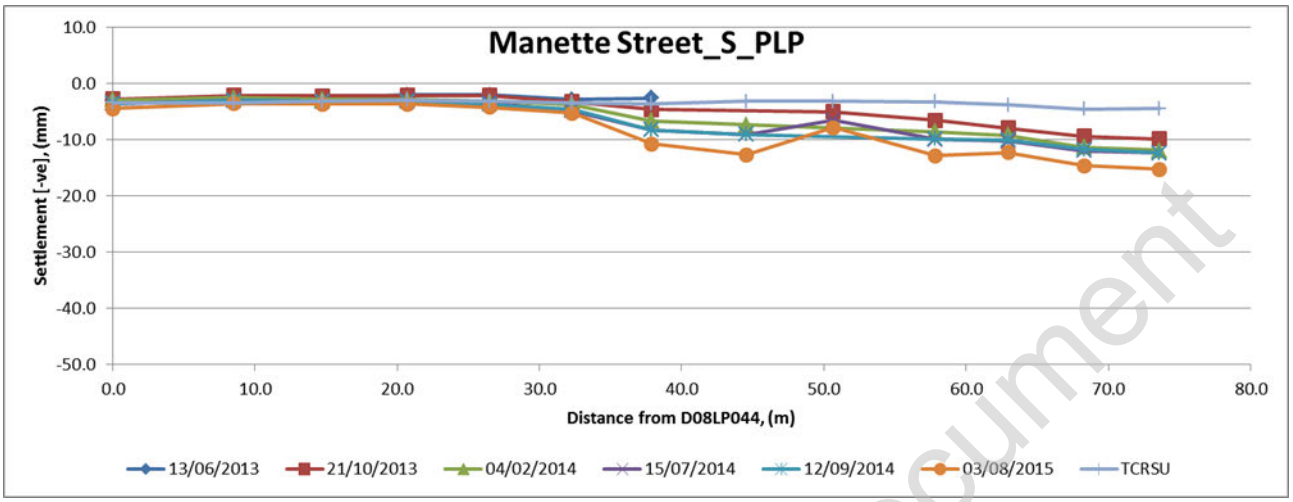
- Data is presented for the PLP located on the north kerb line of Manette Street as shown on Figure 5.1.
- Overall settlement was ~9mm or less at the end of Period A, primarily as a result of TCRSU works. A small net increase (~3mm) is associated with TaM drilling and subsequent pre-treatment.
- Settlement increased to a maximum of 19mm in Period B, associated with the WBRT excavation, without concurrent grouting, and subsequent consolidation.
- No significant increase in settlement is evident as a result of any of the tunnels constructed in Periods C, D or E as a result of concurrent grouting. Settlement increased gradually between tunnel drives and reached about 22mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions, with a maximum of ~26mm.
- It is noted that a significant slope (~0.5mm/m) existed between D08LP050 and D08LP051 prior to any BFK works as a result of movements generated by the TCRSU works.
- No slope Amber trigger values were exceeded during construction or subsequently.

5.3. Manette Street - South





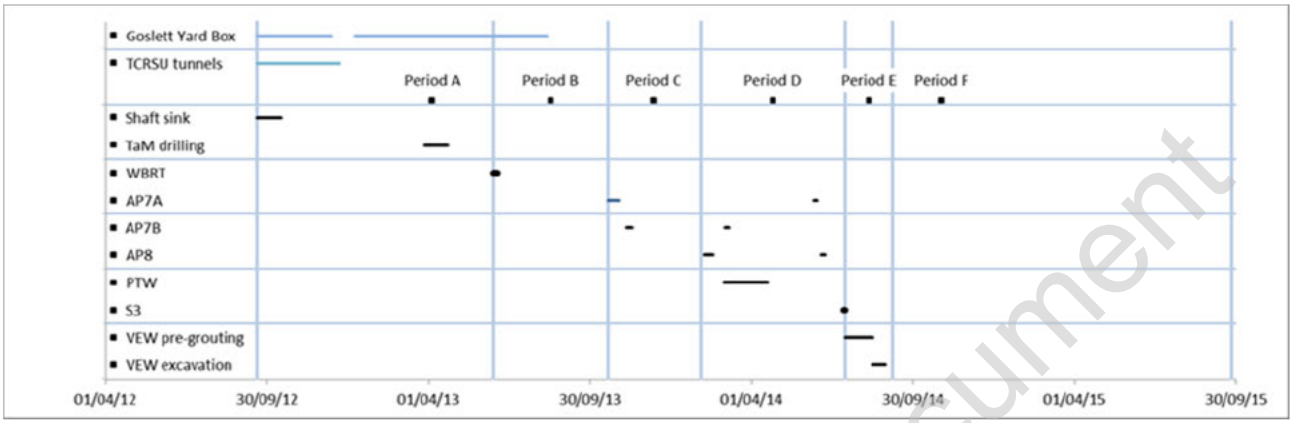


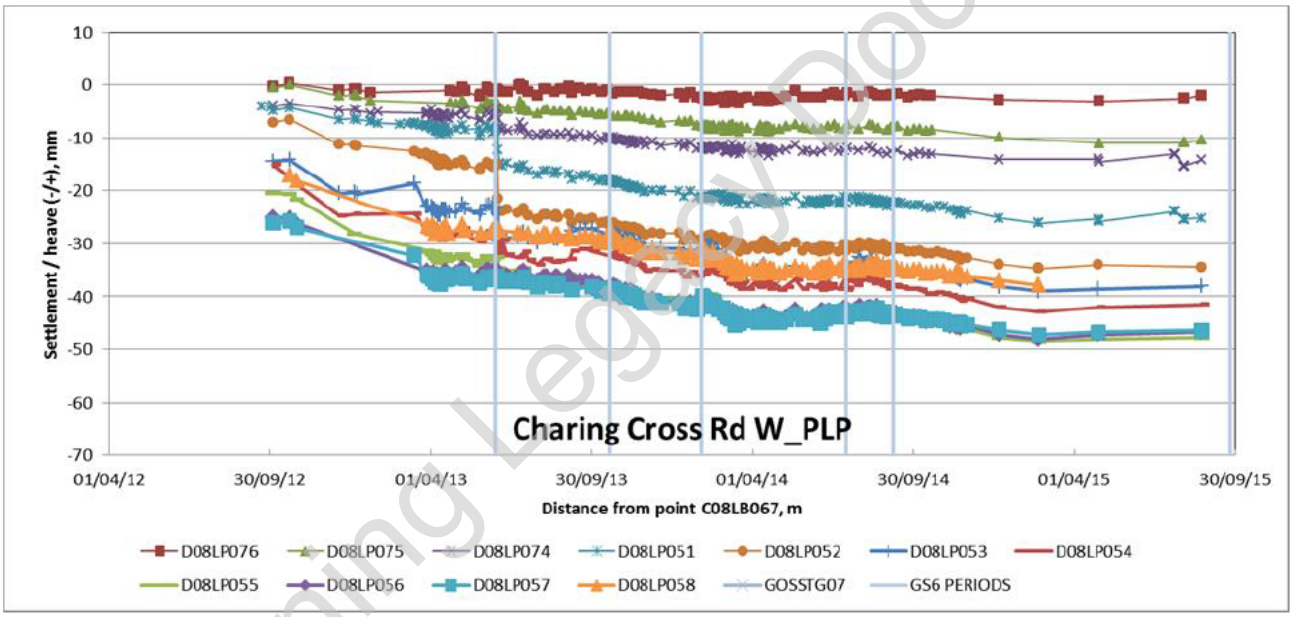


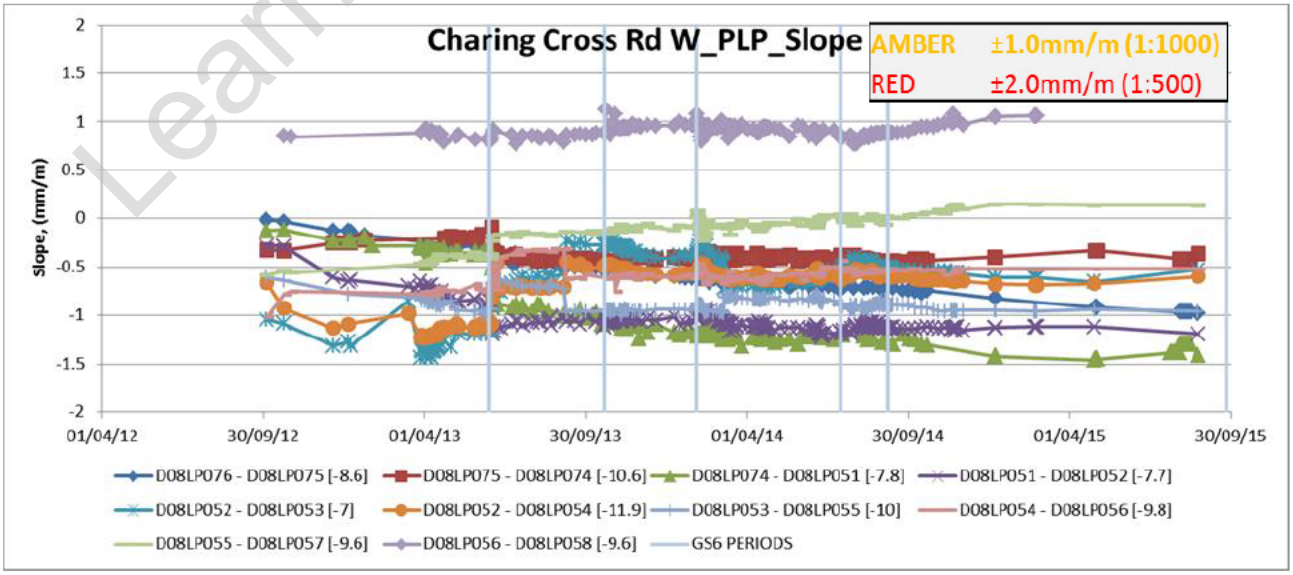
The following points are noted:

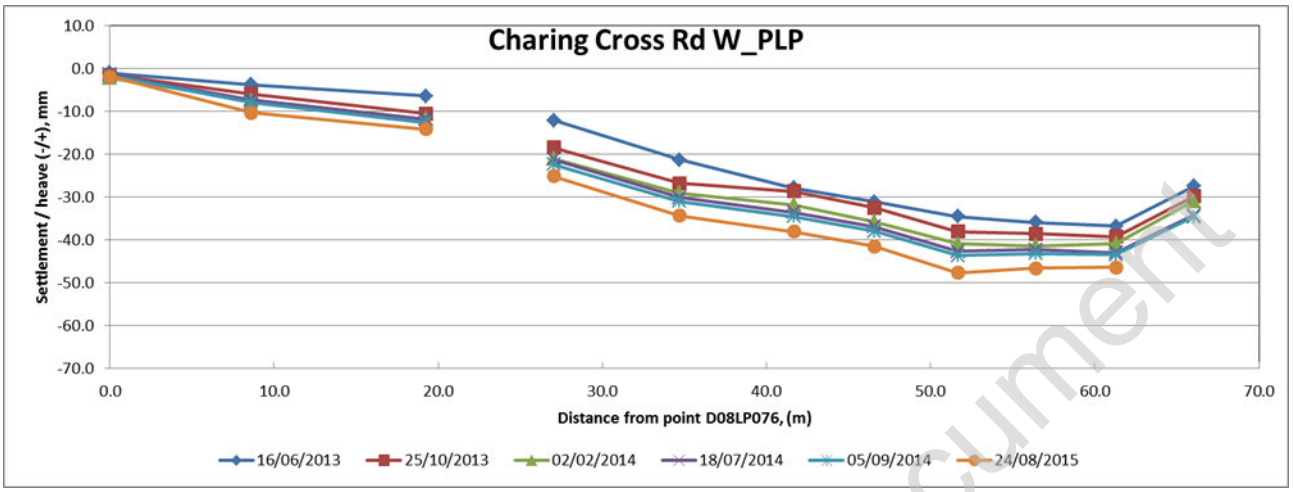
- Data is presented for the PLP located on the south kerb line of Manette Street. None of the points are within the extent of the GS6 arrays, as shown on Figure 5.1. It is noted that the Compensation Grouting area was amended from the centre of Manette Street to the façade on the north side of the road due to an obstruction encountered during drilling for TaM installation.
- Overall settlement was ~5mm or less at the end of Period A, primarily as a result of TCRSU works. No net effect is evident from TaM drilling and subsequent pre-treatment.
- Settlement increased to a maximum of 10mm at the east end of the façade in Period B, associated with the WBRT excavation, without concurrent grouting.
- No significant increase in settlement is evident as a result of any of the tunnels constructed in Periods C, D or E as a result of concurrent grouting. Settlement increased gradually between tunnel drives and reached about 12mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing near stable conditions, with a maximum settlement of ~15mm.
- No slope Amber trigger values were exceeded during construction or subsequently.

5.4. Charing Cross Road - West





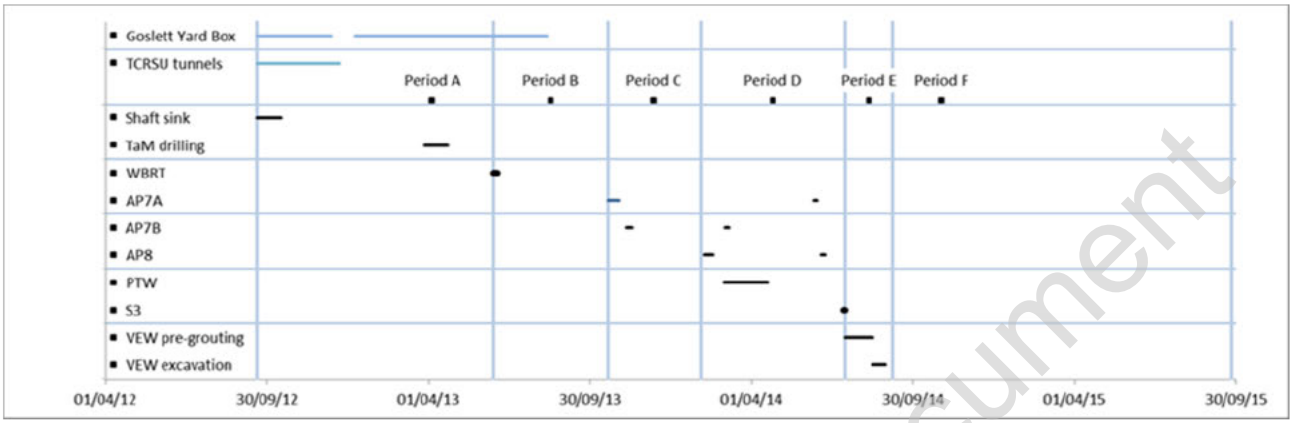


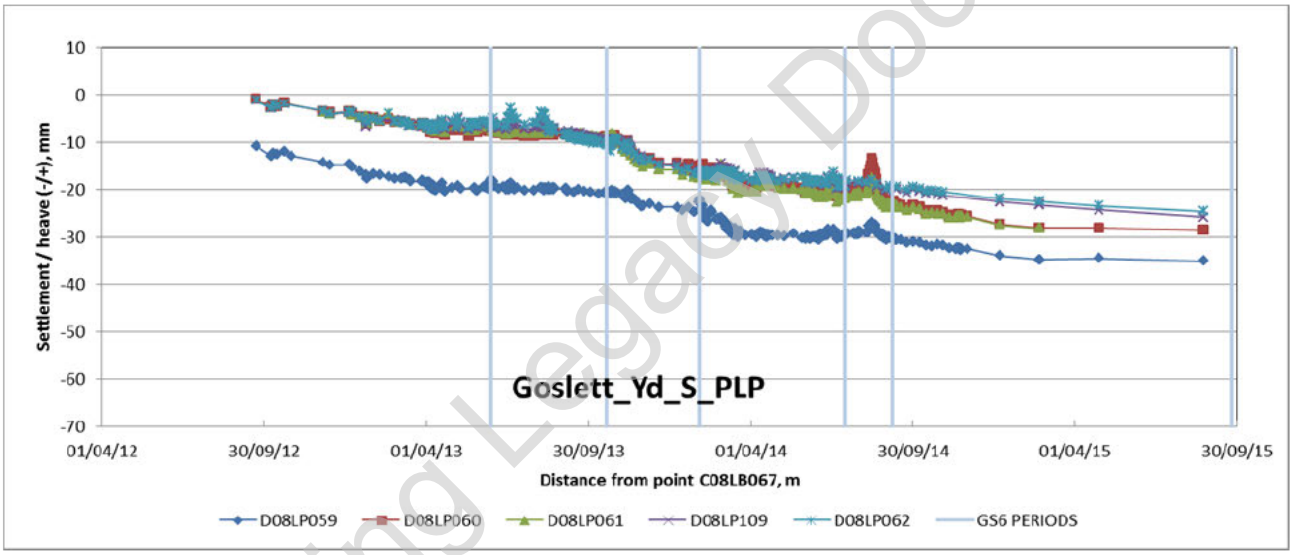


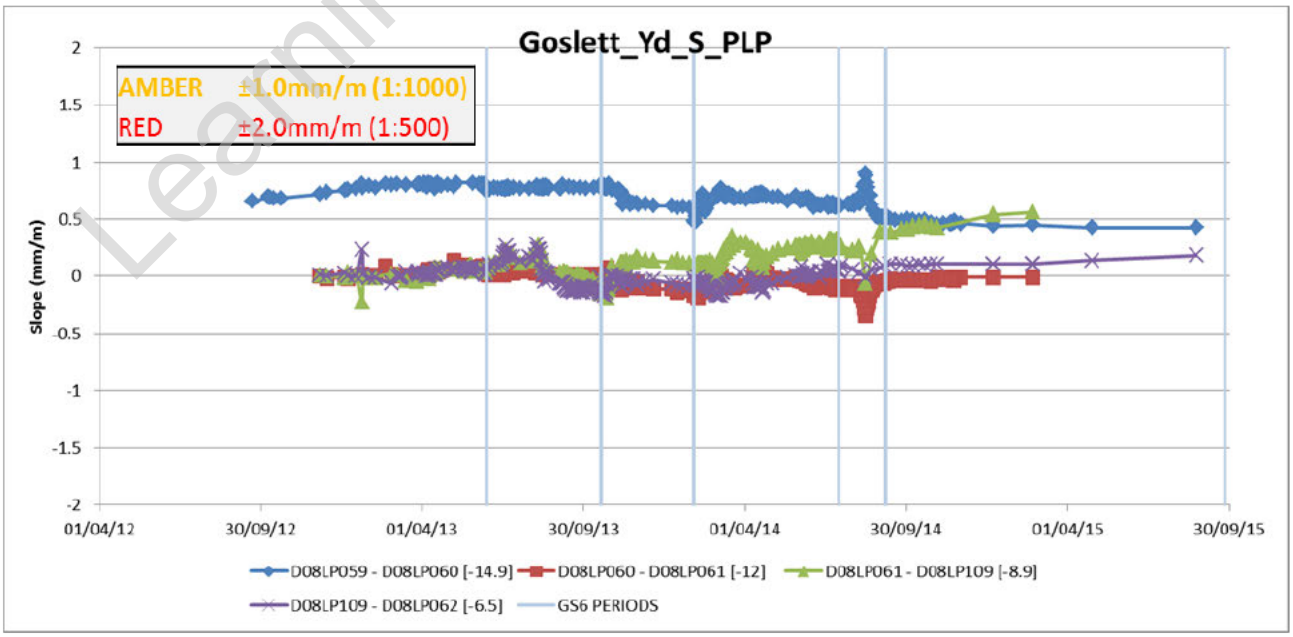
The following points are noted:

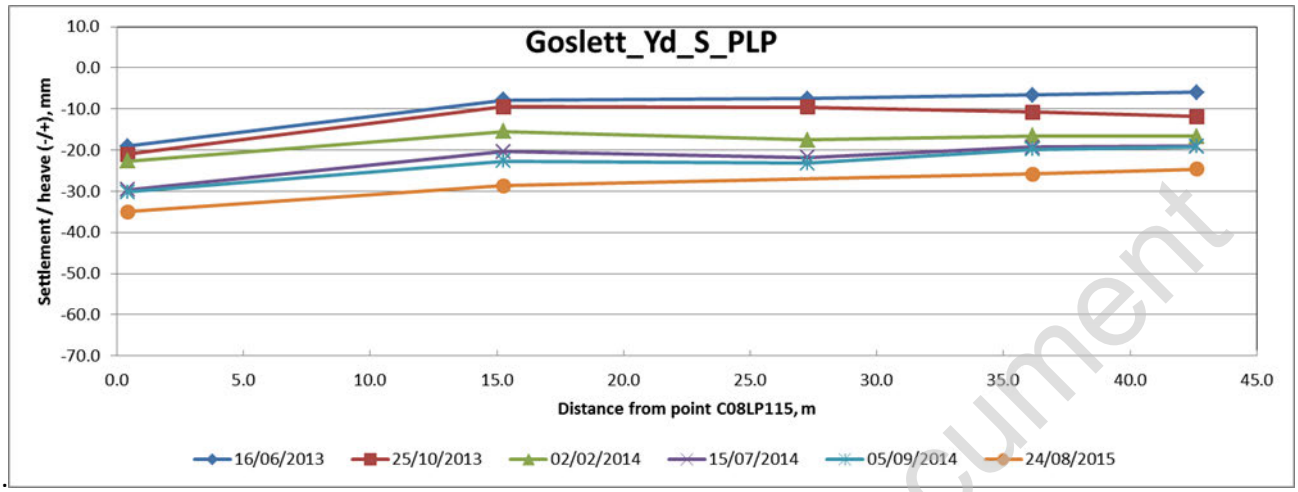
- Data is presented for the PLP located on the west kerb line of Charing Cross Road. Only the points north of Manette Street are within the extent of the GS6 arrays, as shown on Figure 5.1.
- Overall settlement was ~38mm at the end of Period A, primarily as a result of TCRSU works. A small (~3mm) net effect is evident from TaM drilling and subsequent pre-treatment.
- The maximum settlement only increased slightly to 40mm in Period B, although settlement increased by up to 8mm on the point at the corner of Manette Street (D08LP051), associated with the WBRT drive without concurrent grouting.
- Further increases in settlement are evident in Period D at the time of AP8 and PTW construction. Settlement also increased gradually between tunnel drives and reached about 43mm at the end of Period E.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing stable conditions, with a maximum settlement of ~48mm.
- It is noted that significant slopes existed prior to any BFK works as a result of movements generated by the TCRSU works.
- Slopes exceeded the Amber trigger value at 2 locations prior to the start of BFK works: these slopes were reduced by the construction of the WBRT and thereafter remained below the threshold for the remainder of the construction period and subsequently. However, 2 further slope triggers were exceeded during construction and post construction movements generated one further trigger. Details are given in Table 5.1.
- By inspection, no Deflection Ratio triggers were breached.

5.5. Goslett Yard - South









The following points are noted:

- Data is presented for the PLP located on the south kerb line of Goslett Yard, as shown on Figure 5.1.
- Overall settlement was ~20mm at the end of Period A, primarily as a result of TCRSU works. A small net increase (~3mm) is associated with TaM drilling and subsequent pre-treatment.
- The maximum settlement did not increase in Period B, with no evidence of volume loss movement associated with the WBRT drive.
- Further increases in settlement are evident in Period D at the time of AP8 and PTW construction. Settlement also increased gradually between tunnel drives and reached about 30mm at the end of Period D. Uplift associated with grout jacking prior to VEW is shown in Period E, followed by settlement of almost the same magnitude, giving negligible net change in settlement over the Period.
- The rate of post construction settlement in Period F has reduced continually with the final readings showing stable conditions, with a maximum settlement of ~36mm.
- It is noted that significant slopes existed prior to any BFK works as a result of movements generated by the TCRSU works.
- No slope Amber trigger values were exceeded during construction or subsequently.

6. DISCUSSION

The preceding presentation of settlement monitoring data shows that the Compensation Grouting Performance Criteria (CGPC) on slope has been exceeded at a number of locations within the footprint of the arrays installed from Grout Shaft 6.

It is noted that there were significant constraints on the grouting that could be undertaken from Grout Shaft 6. Firstly, significant settlement and slopes had been generated by TCRSU works prior to the commencement of tunnelling. Secondly, the ventilation tunnel (VEW) connecting the Westbound Platform Tunnel (PTW) to the Goslett Yard Box was at a higher elevation than the other tunnels and the TaMs were at about the level of the crown of the tunnel. This not only precluded concurrent compensation grouting during excavation but also made any grout jacking following excavation impractical. An extensive grout jacking operation was undertaken immediately prior to VEW excavation which successfully limited the net change in settlement to a few millimeters.

There were 4 Amber slope trigger breaches on building facades during construction and a further 2 due to post construction settlement. Of the four Amber slope triggers, the two on Charing Cross Road had initial slopes of >0.65mm/m due to TCRSU works and the other 2 were only marginally greater than the specified limit of 1:1000. There were no Red slope triggers or Deflection Ratio triggers breached on buildings.

There were 5 Amber slope trigger breaches on PLP, all of which were along Charing Cross Road in the area where large settlements were generated by TCRSU works prior to tunnelling. Two of these slopes reduced below the Amber limit due to the construction of the WBRT without concurrent grouting, but another 2 were generated. The 5th was marginal and only exceeded the Amber value in the post construction period. There were no Red slope triggers or Deflection Ratio triggers breached on ground monitoring.

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

7. CONCLUSION

It was concluded that no further grouting from TCR GS6 would be required based on an abridged version of this report submitted in August 2014: Grout Shaft 6 was subsequently decommissioned.

The key factor which lead to this conclusion was that the construction of VEW precluded any further grouting. Grout jacking to achieve an agreed target uplift was undertaken prior to its construction to control the risk of damage as far as practicable. This was successfully achieved and consequently, it was concluded that the grout shaft could be decommissioned.

Manual monitoring within the GS6 area was terminated under C300-PMI-01858, and consequently this report comprises a Final and Close Out report.

Appendix A

Assumptions used to produce contour plots of grout intensity

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

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

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

Or, rearranging:

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

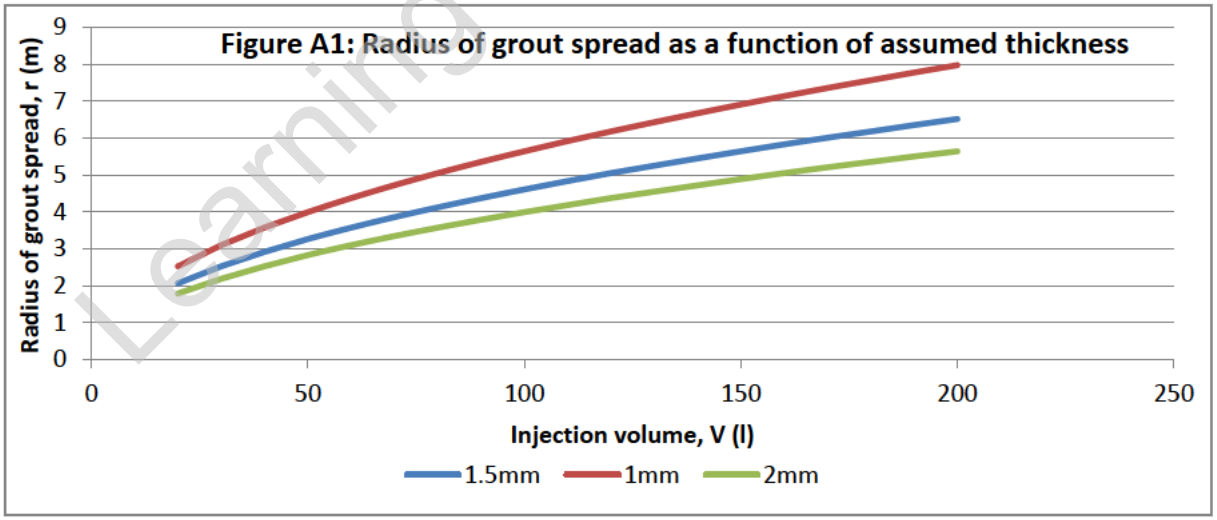


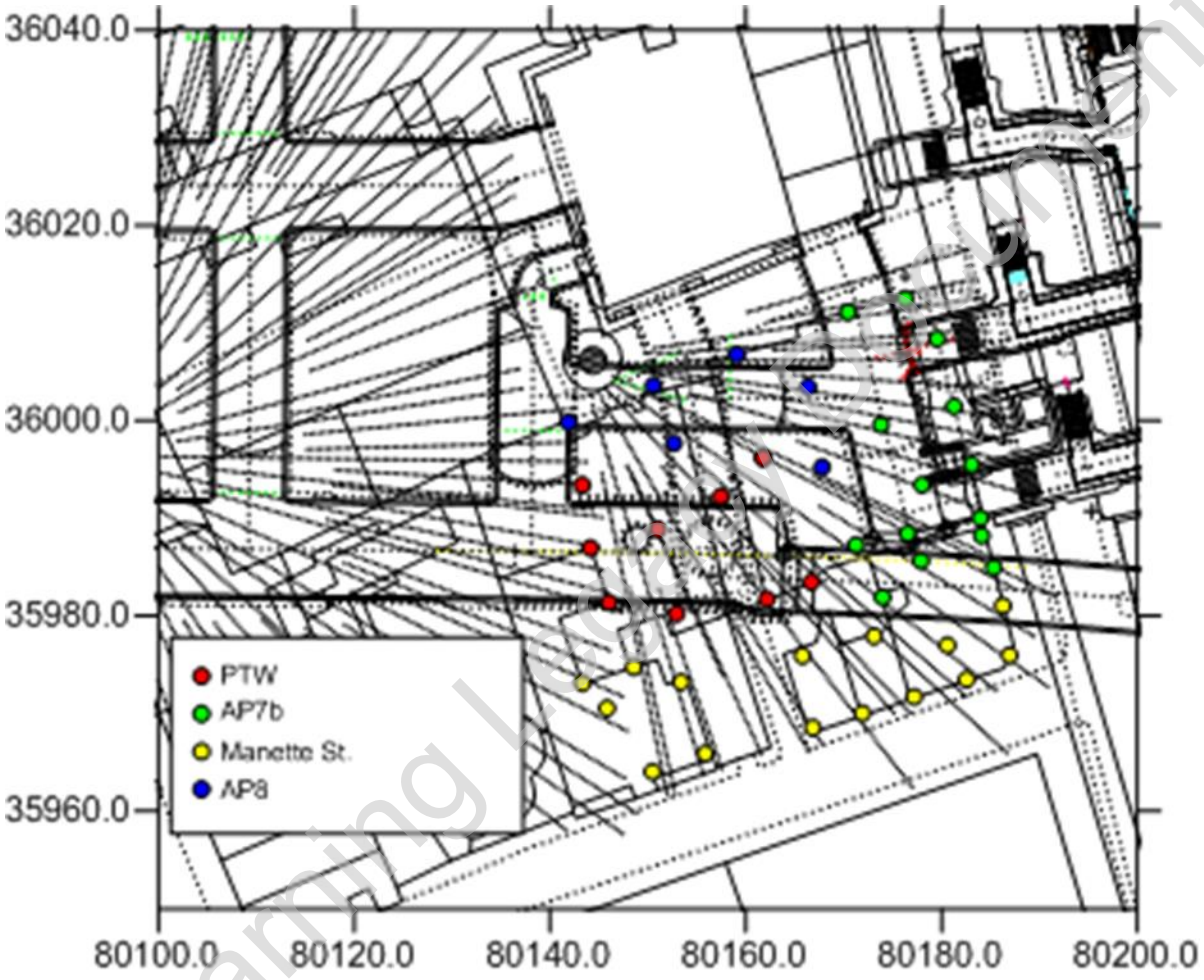
Figure A1: Radius of grout spread as a function of assumed thickness

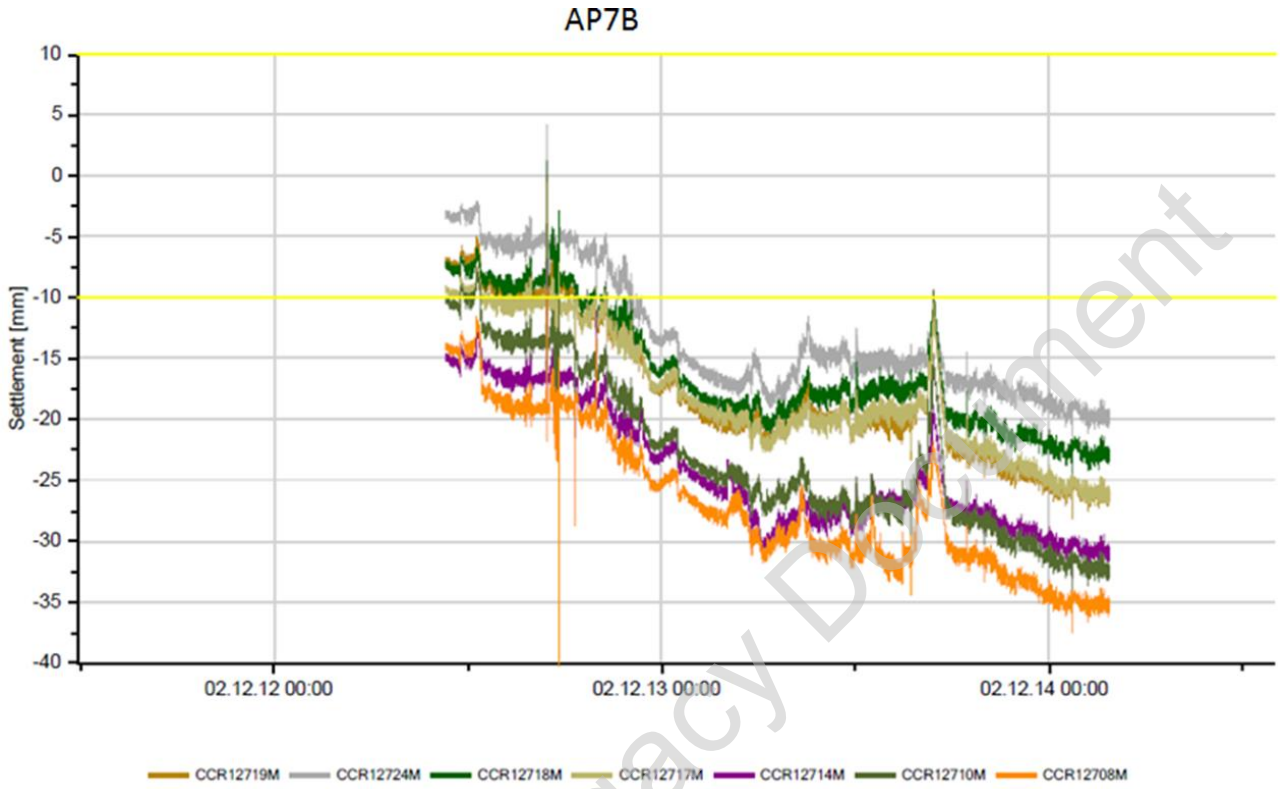
Observations of grout in the ground suggests that a thickness of 1 – 2mm is predominantly achieved. All of the plots included in this report are based on an assumed thickness of 1.5mm. Figure A1 shows the variation in radius for thicknesses of 1.0, 1.5 and 2.0mm.

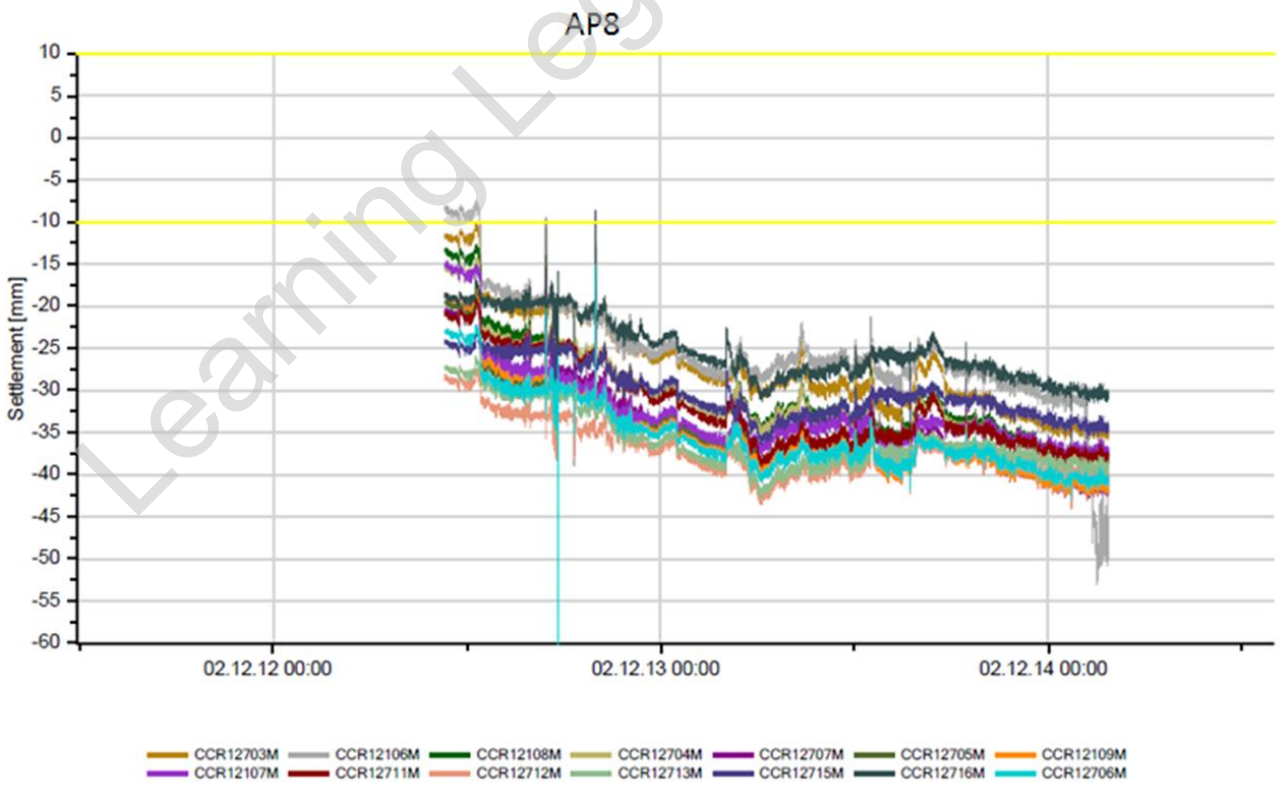
The contribution of each injection within a specified data set are summed at each node within a grid. This grid file is then contoured within Surfer.

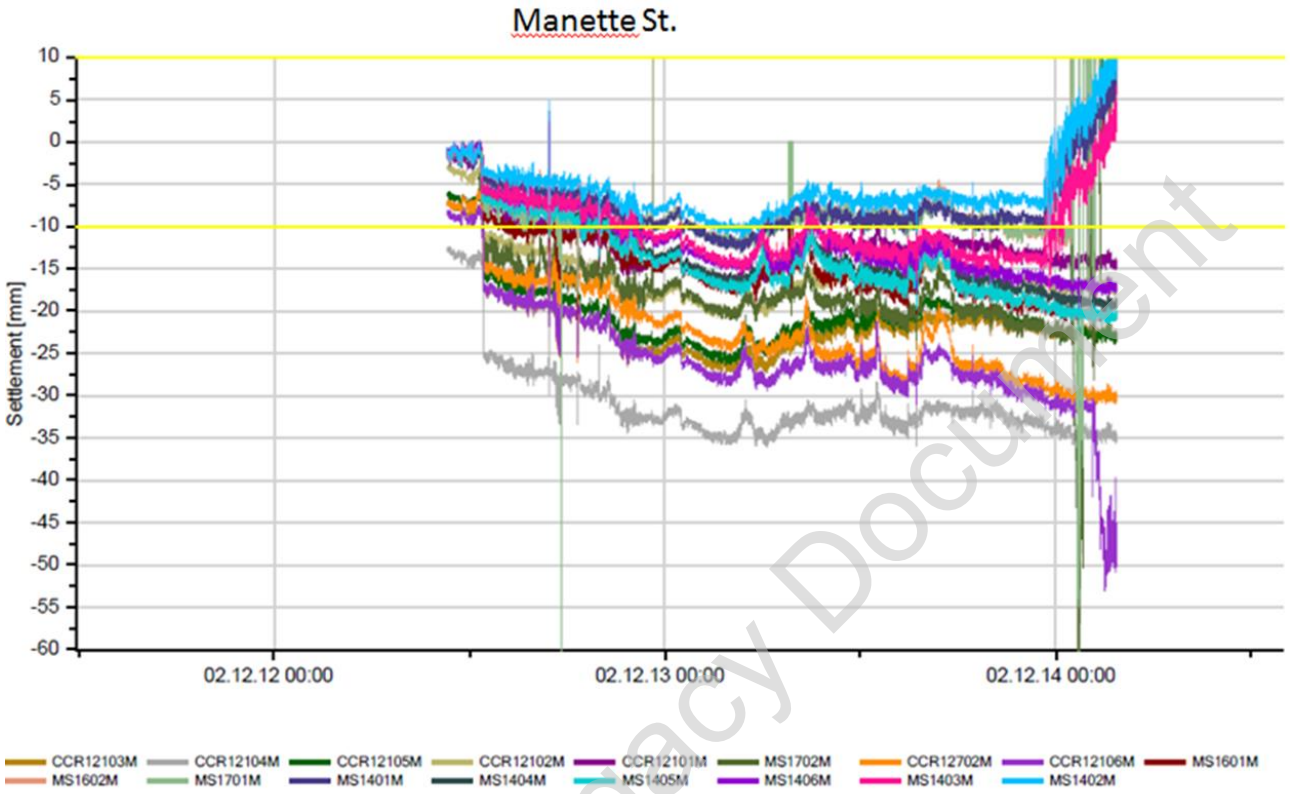
Appendix B

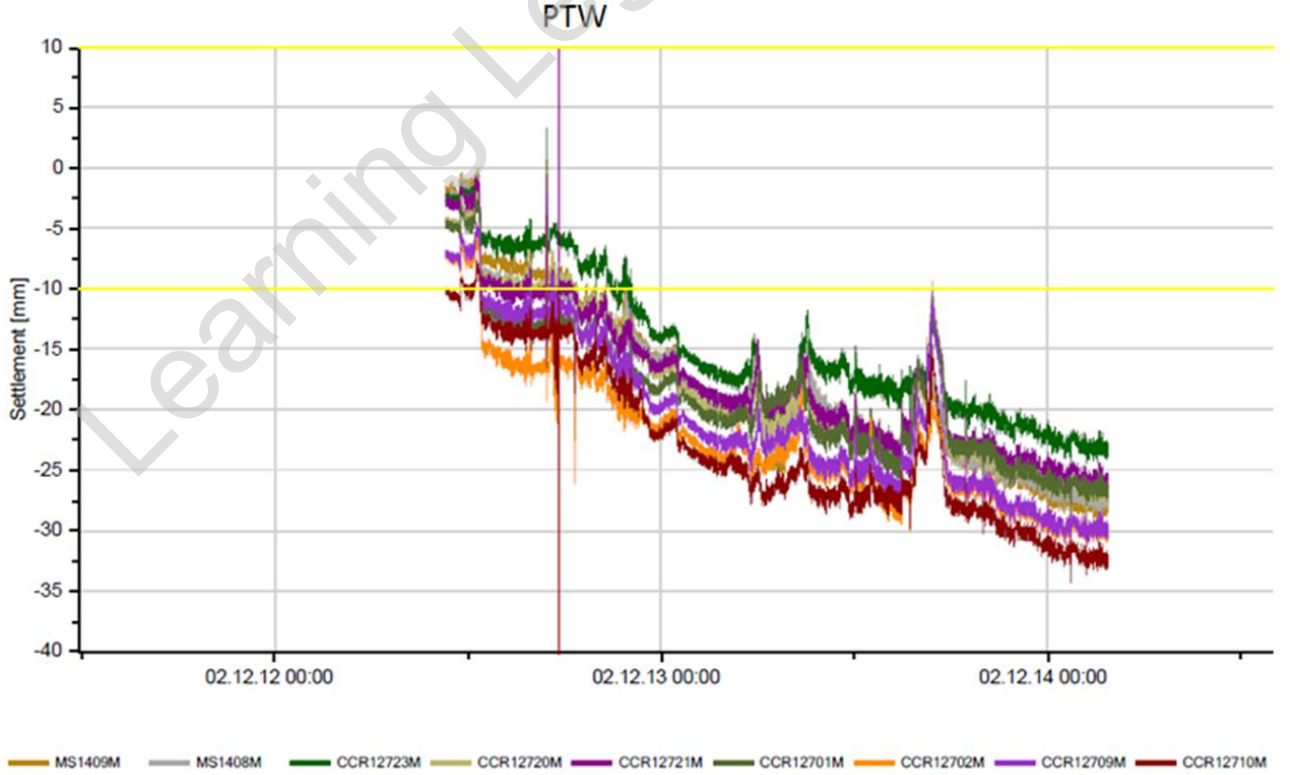
Example plots of HLC data



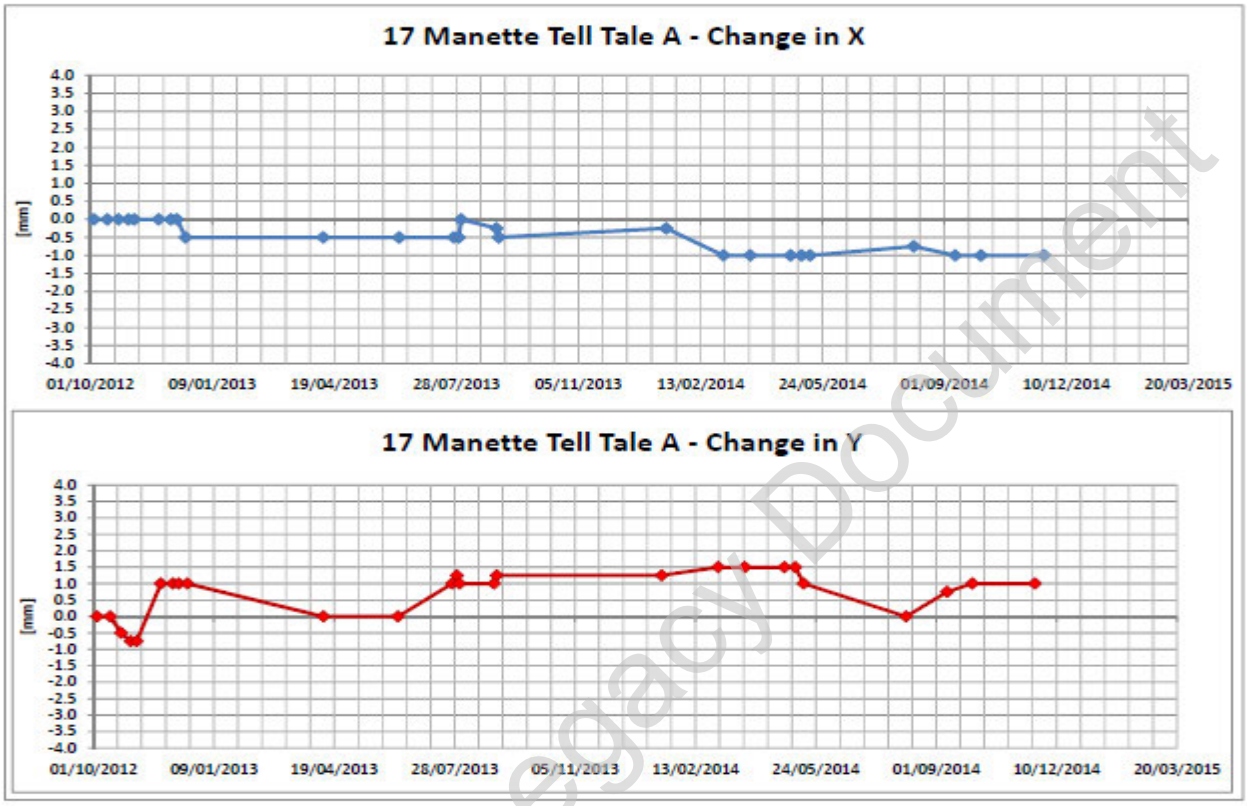


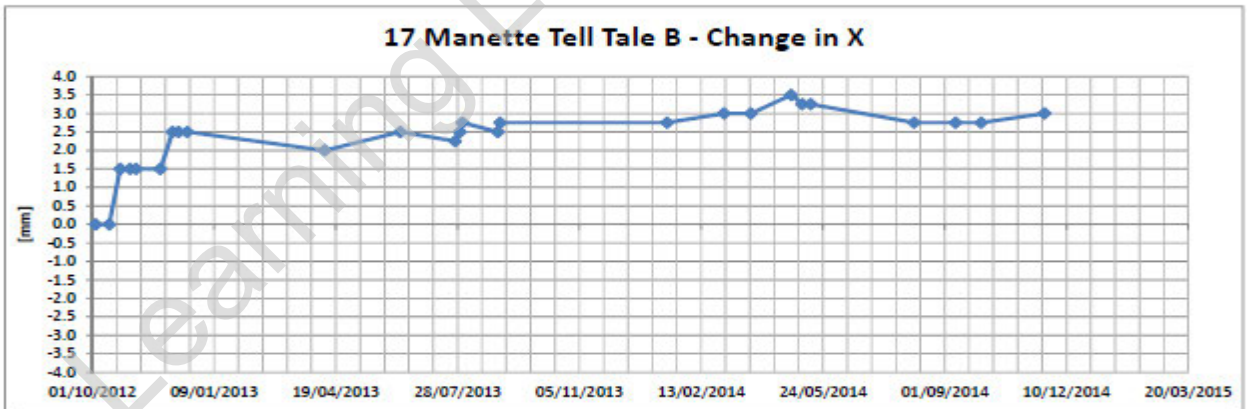


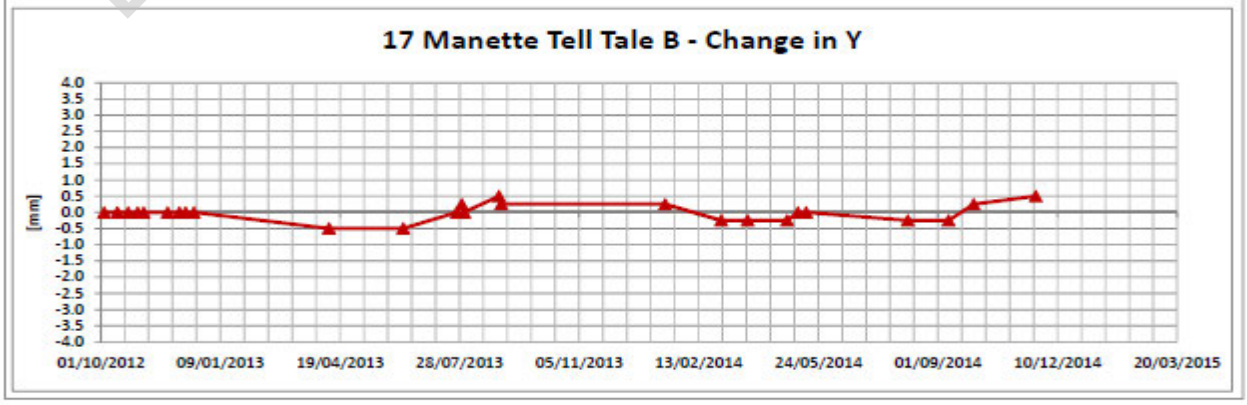




Plots of Crackmeter readings: 17 Manette Street







Appendix C

Summary of TCRSU construction dates (Provided by C122)

Table 1: Surface excavation

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

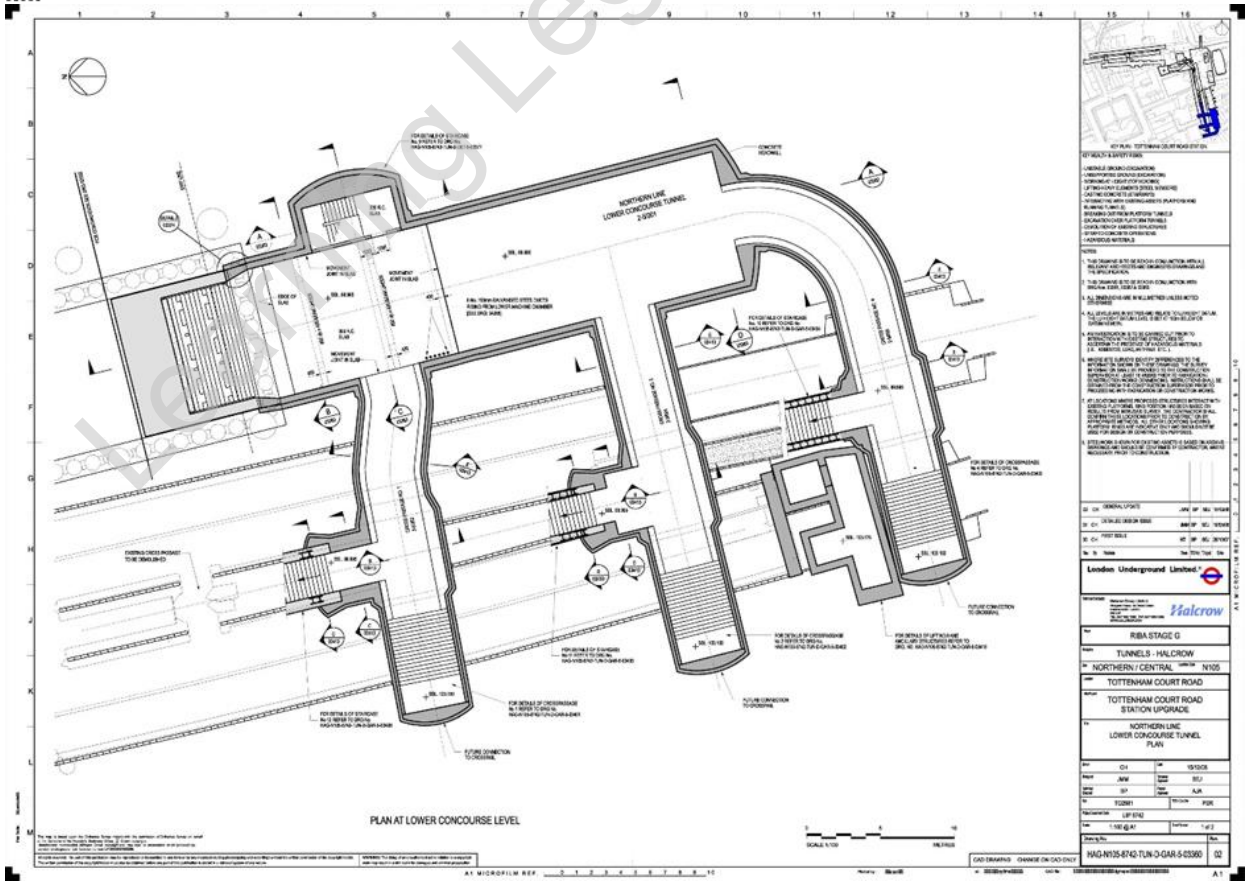
Table 2: Goslett Yard Detailed Excavation Dates

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

Layout of TCRSU works



Appendix D

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