Analysis on Bentonite Loss during Chalfont Saint Peter D-wall Excavation

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Revision	Author	Reviewed by	Approved by	Date approved	Reason for revision
C01	Xxxxxxxx xxxxxxxx	Xxxxxxxx xxxxxxxxx	Xxxxxxxxxx xxxxxxxxxxx	28/09/2020	First issue
C02	Xxxxxxxxx xxxxxxxxx	Xxxxxxxxx xxxxxxxxxx / xxxxxxxxxx xxxxxxxxx	Xxxxxxxxx xxxxxxxxx	07/10/2020	Revised following AfW comments
C03	Xxxxxxxxxx xxxxxxxxxx	Xxxxxxxxxx xxxxxxxxx	Xxxxxxxxx xxxxxxxxx	2/12/2020	Revised following EA and AfW comments and ongoing d-wall excavation

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Handling Instructions: none

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1 Introduction

1.1 Objective

1.1.1 The first two diaphragm wall panels at the Chalfont Saint Peter Ventilation Shaft that were excavated resulted in the loss of approximately 1,500m^3 of bentonite slurry into the ground. A campaign of ground treatment has been undertaken and remains ongoing to try to reduce the losses. Diaphragm wall excavation continues and bentonite slurry losses (post ground treatment) are being monitored along with groundwater levels and groundwater quality.

1.1.2 The objective of this technical note is to describe and explain the possible causes to the losses as well as to explain the mitigation measure that have been put in place and the lessons learnt for the oncoming works at the other shafts. The report is based on information received up to 25 November 2020.

1.2 Project Description

1.2.1 Chalfont Saint Peter (CSP) Ventilation Shaft is the first of five shafts that are being constructed. This shaft is for emergency access as well as tunnel ventilation. It is located just to the north of the village of Chalfont Saint Peter as can be seen on Figure 1.

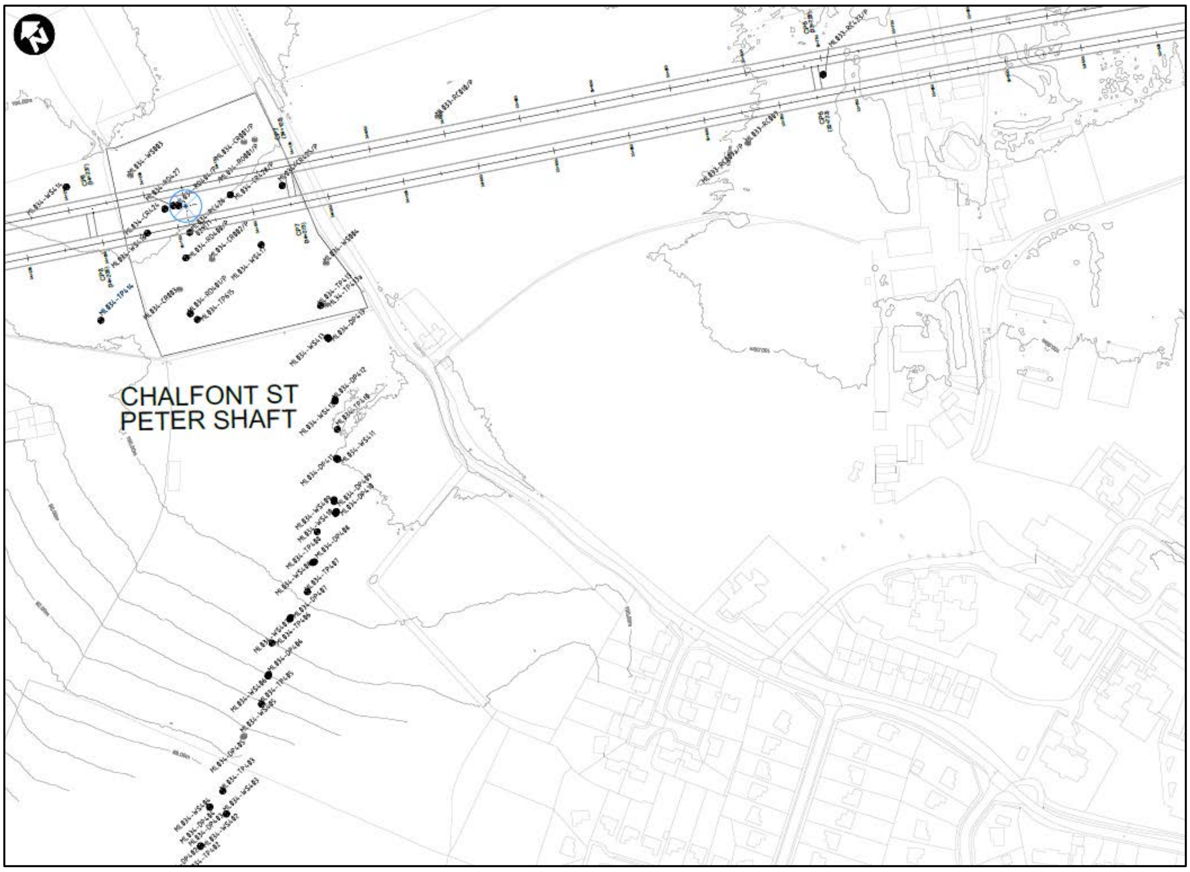

Figure 1 - Location of Chalfont Saint Peter Ventilation Shaft

1.3 Available Information

1.3.1 The available geological information is extracted from the ground investigations undertaken by HS2 as well as ALIGN between 2017 and 2019 and presented in the reports below:

- HS2, Ground investigation report for CSP is part of Work Package AAZ – 1G063-BAM-GT-REP-000-000001.
- ALIGN, Phase 1 Ground Investigation Report - 1MC05-ALJ_FES-GT-REP-C001-000001.
- ALIGN, Chalfont Saint Peter Pumping Test Report - 1MC05-ALJ_SWS_GT-REP-C001-000001.

1.3.2 The boreholes used for the analysis are shown in Table 1 and Figure 2 below.

Borehole ID	Type	OS Coordinates		Distance from Shaft centre
		Easting	Northing	
ML034-CR424	Rotary Coring	500047.7	193168.2	12.5
ML034-RD427	Rotary open hole	500053.2	193166.4	7.0
ML034-RD404	Rotary open hole	500055.9	193163.7	3.2
ML034-CR428	Rotary Coring	500085.7	193146.9	31.1
ML034-RD400	Rotary open hole	500036.8	193135.2	34.2
ML034-CR425	Rotary Coring	500115.1	193129	65.5
ML034-CR002	Rotary Coring	500049	193123.3	39.5
ML034-CR001	Rotary Coring	500115.1	193166.8	57.0
ML034-RD401	Rotary open hole	500015	193106.1	70.5
ML034-RC426	Rotary Coring	500049.7	193146	18.0
ML034-CR003	Cable percussive	500020.3	193122.6	54.6

Table 1: – Boreholes used for the Chalfont St Peters Shaft Geotechnical Analysis

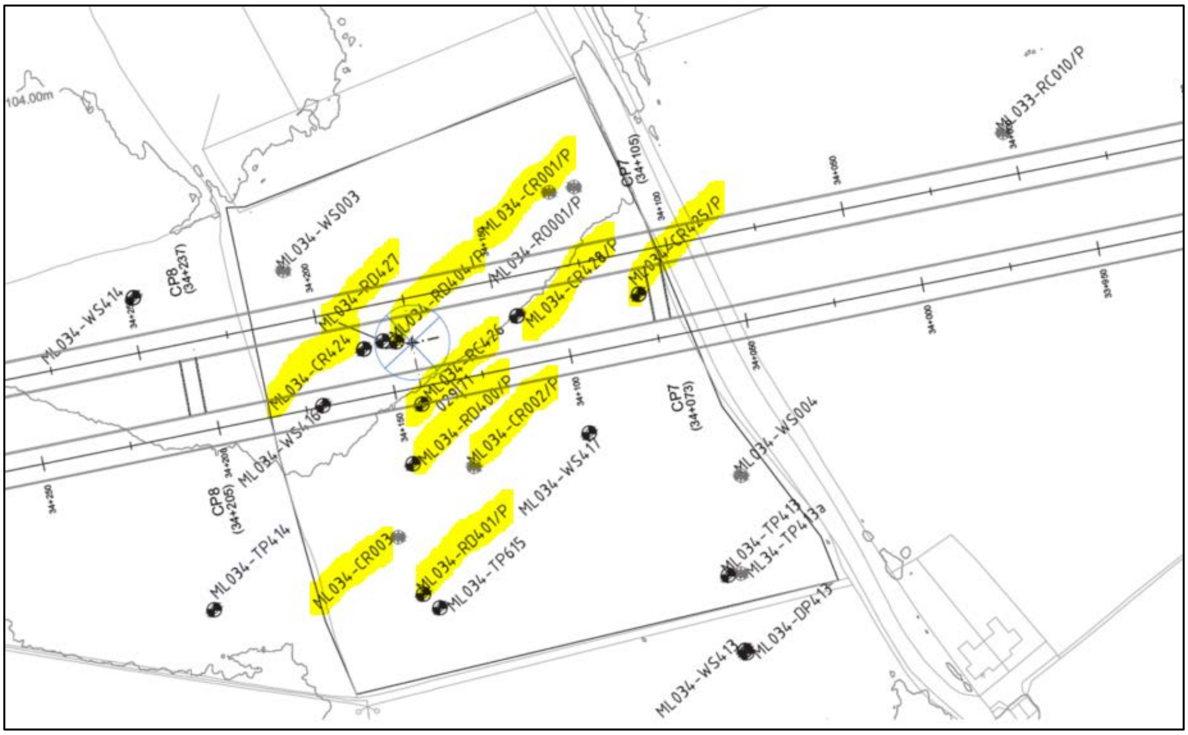

Figure 2 - Location of the GI boreholes

1.3.3 Cross hole Seismic tomography has been done between ML034-CR424 and ML034-RD427.

1.3.4 Below are presented the different reports where the GI information can be found.

- HS2, Ground investigation report for CSP is part of Work Package AAZ – 1G063-BAM-GT-REP-000-000001.
- ALIGN, Phase 1 Ground Investigation Report - 1MC05-ALJ_FES-GT-REP-C001-000001.
- ALIGN, Chalfont Saint Peter Pumping Test Report - 1MC05-ALJ_SWS_GT-REP-C001-000001.

2 Bentonite LossPlanned construction sequence

2.1.1 The diaphragm wall panel arrangements are shown in Figure 3. The original planned excavation sequence was: P1-P9-P3-P11-P2-P10-P15-P7-P16-P8-P5-P13-P4-P12-P6-P14. This was changed slightly during construction due to bentonite losses and ground treatment works.

2.1.2 As of 25 November 2020 the following panels have been excavated and concreted: P1, P9, P11, P15, P10 and P3. P16 is almost complete and work has commenced on excavating P7.

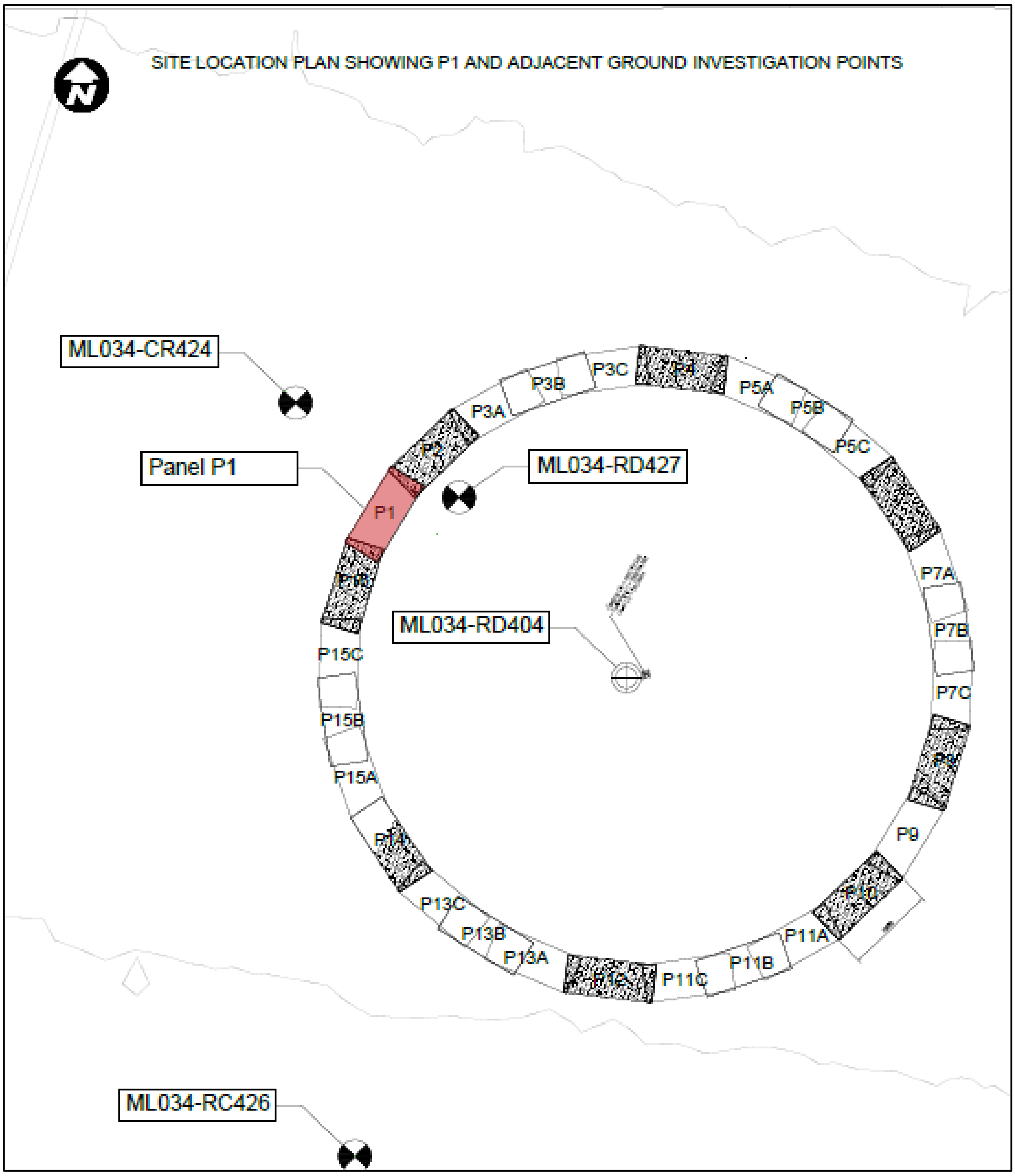

Figure 3 - Panel arrangement for CSP shaft

2.2 Bentonite Loss Description

2.2.1 The panel size and excavation sequence is provided in Table 2.

Panel No. / sequence	Size	Status
P1	Single bite	Completed on 3 Sep, no ground treatment
P9	Single bite	Completed on 17 Sep, no ground treatment
P11	Triple bite	Completed on 16 Oct after ground treatment
P15	Triple bite	Completed on 30 Oct after ground treatment

Panel No. / sequence	Size	Status
P10	Single bite	Completed on 5 Nov after ground treatment
P3	Triple bite	Completed on 13 Nov after ground treatment
P16	Single bite	Completed on 25 Nov after ground treatment
P7	Triple bite	Commenced on 23 Nov after ground treatment
P2	Single bite	Not started
P13	Triple bite	Not started
P8	Single bite	Not started
P5	Triple bite	Not started
P14	Single bite	Not started
P6	Single bite	Not started
P12	Single bite	Not started
P4	Single bite	Not started

Table 2: – Panel excavation sequence and status on 25 November 2020

2.2.2 Panel 1

2.2.2.1. During excavation of Panel 1, 744m^3 of bentonite was lost into the ground. Figure 4 shows the bentonite consumption vs. excavation depth and Figure 5 presents the excavation and bentonite volume vs. time, including the response measures put in place.

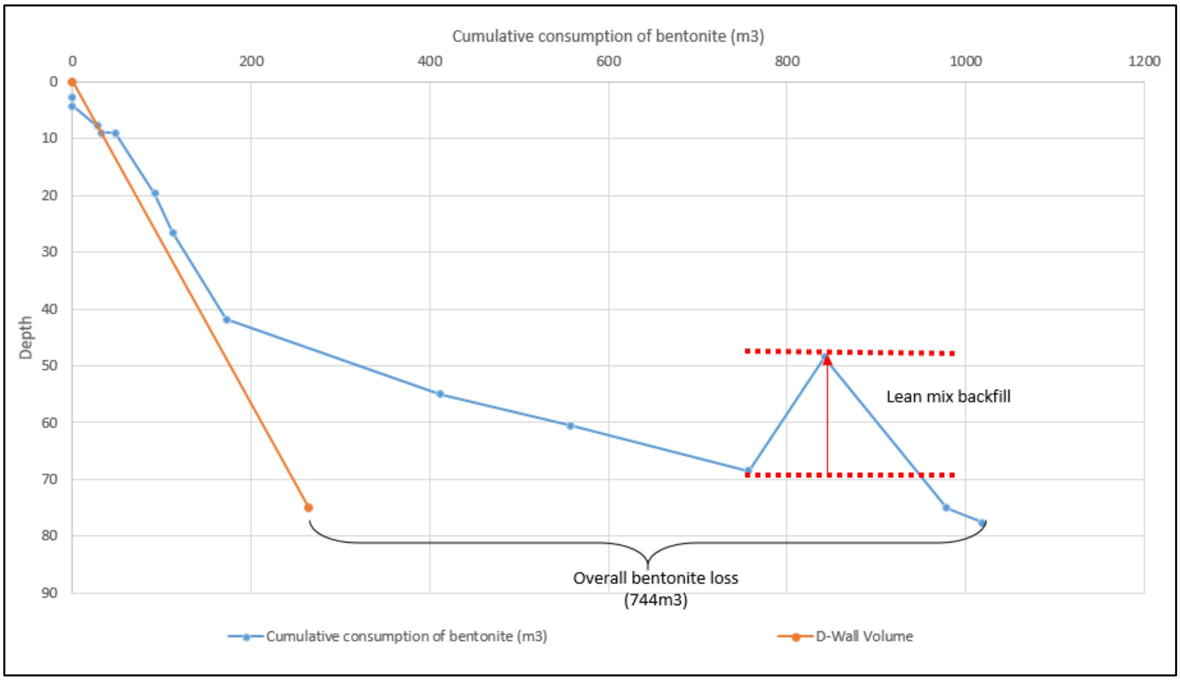

Figure 4 - Cumulative consumption of bentonite vs. depth for Panel 1

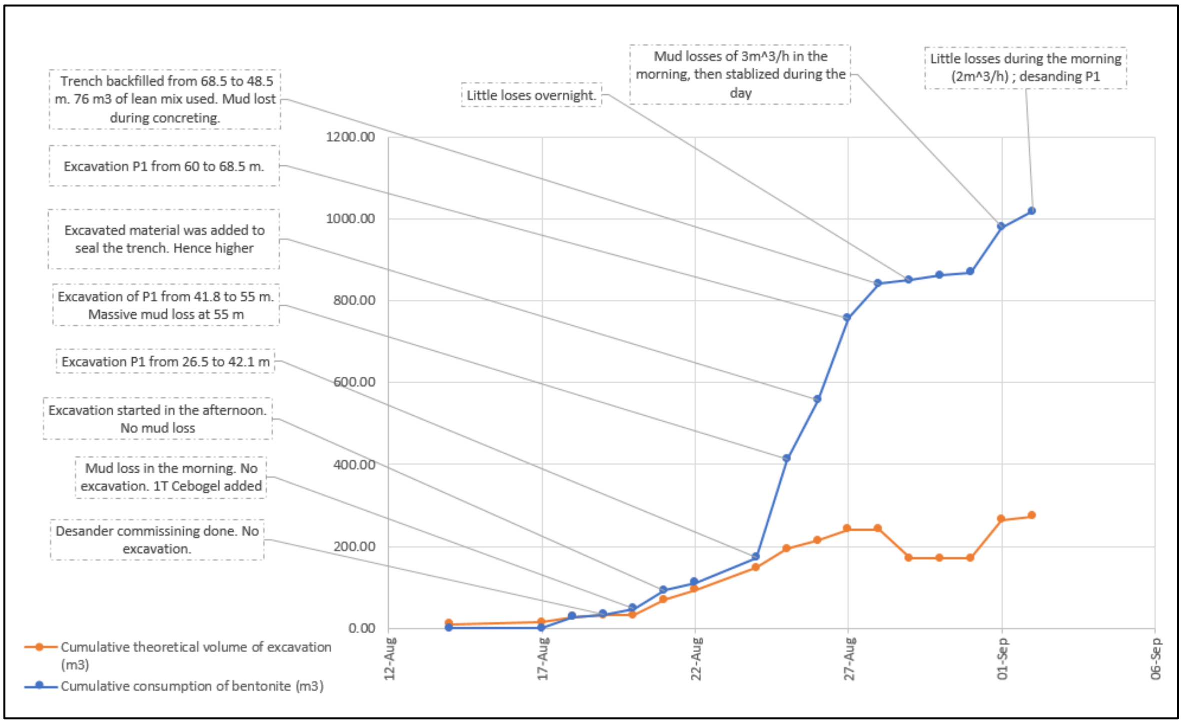

Figure 5 - Cumulative consumption of bentonite vs. time for Panel 1

2.2.2.2. For the first six days, until 42mbgl, the fluid loss was minimal (<0.18m^3/h). This nominal loss can be explained by some small open fissures, and as the panel excavation does not form a uniform rectangle such that the theoretical volume is not the same as the as cut volume.

2.2.2.3. At 42mbgl (59.5mAOD), a sudden bentonite loss occurred. This loss was steady and continuous and indicates a network of well interconnected fractures forming a preferential fluid path. To prevent bentonite loss over the bank holiday weekend (29th to 31st of August), the panel was backfilled to 48.5mbgl with a concrete lean mix and slurry loss was reduced to 0.35m^3/h. When excavation resumed to finish the panel, the losses were still steady and minimal (<1m^3/h), with a slight increase in the losses during the desanding of the panel.

2.2.2.4. The concrete at Panel 1 was finally poured with 285m^3 for a theoretical volume of 274m^3. This limited difference between the volumes show that the remediation measures put in place managed to plug the fissures and prevented the concrete from flowing out of the excavation.

2.2.3 <u>Panel 9</u>

2.2.3.1. During the excavation of Panel 9, 860m^3 of bentonite was lost to the ground. Figure 6 shows the bentonite consumption vs. excavation depth and Figure 7 presents the excavation and bentonite volume vs. time, including the response measures put in place.

2.2.3.2. In P9, the first loss of bentonite occurred at 30mbgl. After reaching 40mbgl, a decision to backfill to 20mbgl with concrete lean mix was made to allow excavation to resume with less bentonite loss. Successive backfills (from 45 to 30mbgl and from 71.5 to 63mbgl) were attempted to reduce the bentonite losses with little success. The trend of this curve tends to indicate fractured ground with a well-connected network rather than isolated voiding (which would have been shown by a sudden major loss followed by a reduction of the loss rate). Completion and pouring of Panel 9 was achieved and the final concrete volume poured (277m^3) is very close to the theoretical one (276m^3). This could be explained by the facts that:

- Fractures, even though being opened, have a rather small aperture, which prevents the concrete from flowing into them.
- The successive backfills, sand and cebogel pellets put in place have sealed the main fractures.

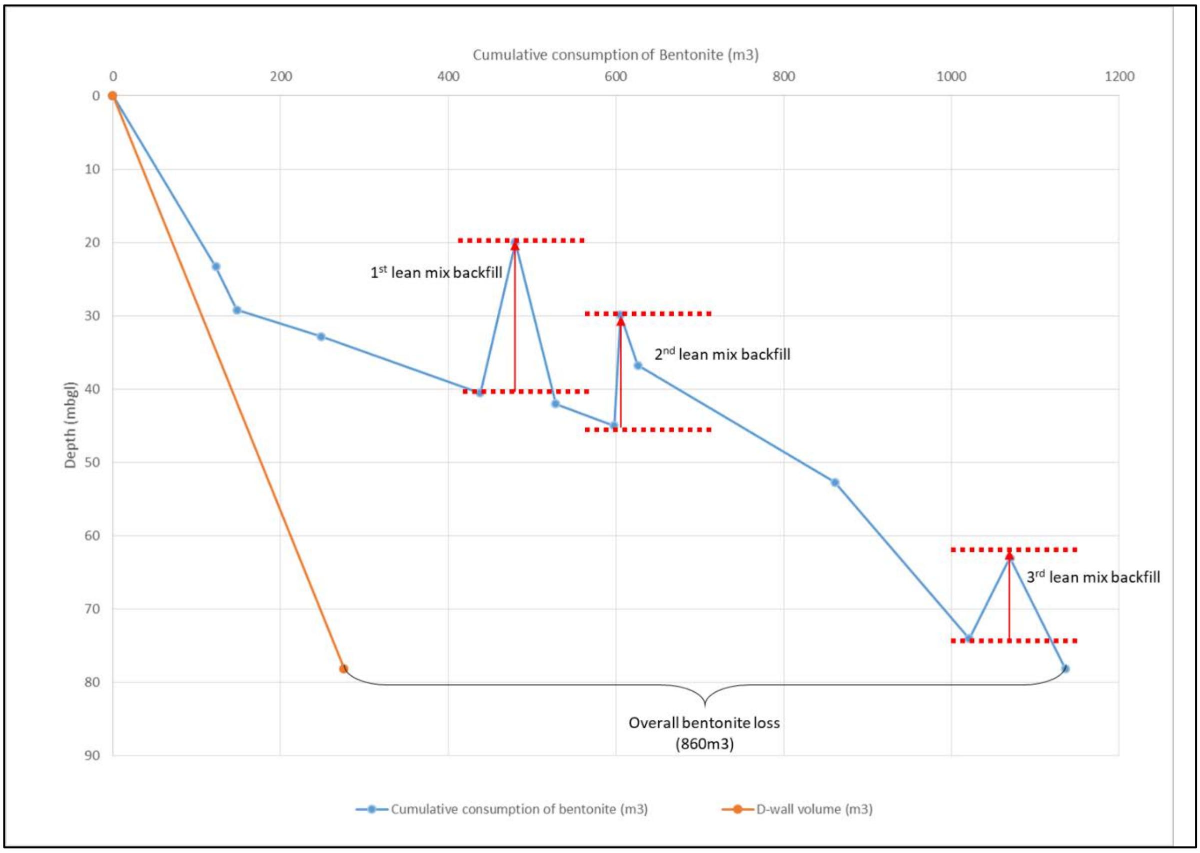

Figure 6 - Cumulative consumption of bentonite vs. depth for Panel 9

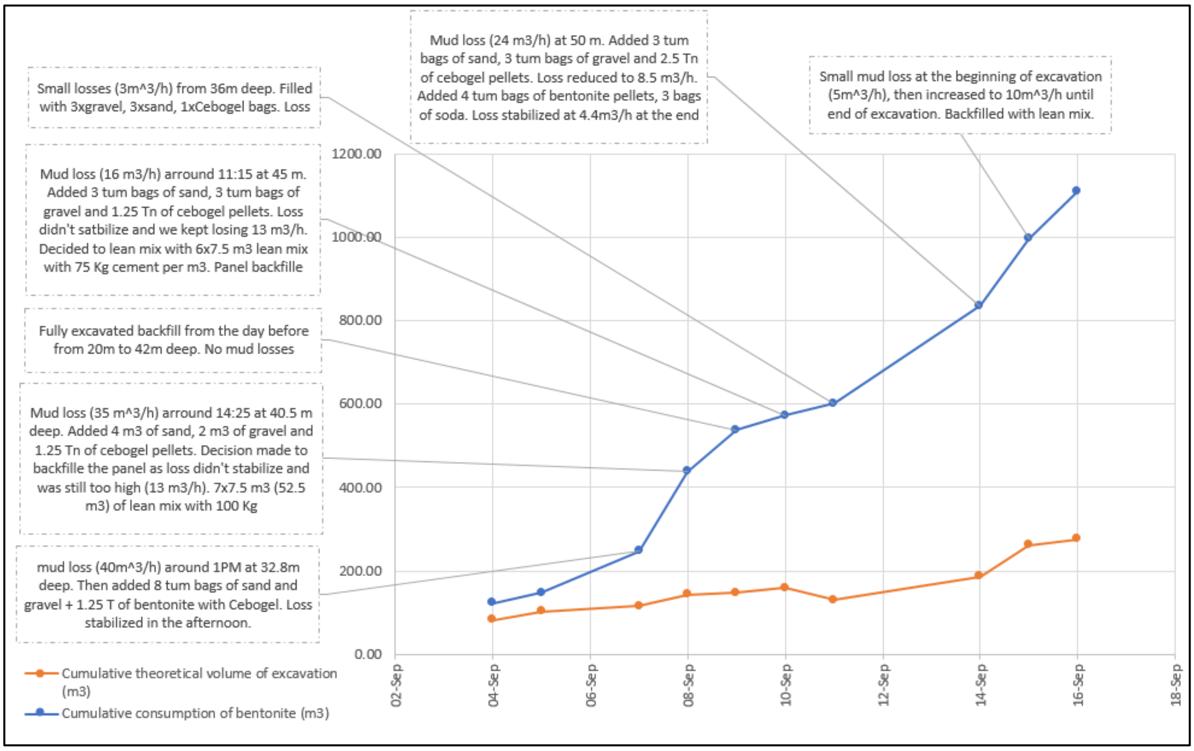

Figure 7 Cumulative consumption of bentonite vs. time for Panel 9

2.2.4 **Panel 11**

2.2.4.1. Panel 11, which is a three bite panel, was the first panel completed after ground treatment. The treatment included drilling 3 grout holes along the centre line of the d-wall (Figure 8) prior to starting d-wall excavation. Figure 9 shows the bentonite consumption vs. excavation depth for bites 11a and 11c and Figure 10 presents the excavation and total bentonite volume vs. time, including the response measures put in place.

2.2.4.2. During the excavation of all three bites of Panel 11, 327m^3 of bentonite was lost to the ground, substantially less than for Panels 1 and 9 even though Panel 11 was a three bite panel and the other two were single bite panels. The most significant bentonite losses occurred between depths of 48 and 63mbgl whilst digging bite 11a which was the first panel bite excavated and which was left open over the weekend with losses of c.125m^3. There was no bentonite loss when bites 11b and 11c were excavated with the result that bite 11b was completed in one day. This can be seen on Figure 8 (for clarity bite 11b is not shown) as the actual and theoretical bentonite consumption lines lie on top of one another.

2.2.4.3. The concrete pour for P11 was 645m^3 which is only slightly greater than the theoretical volume of 630m^3.

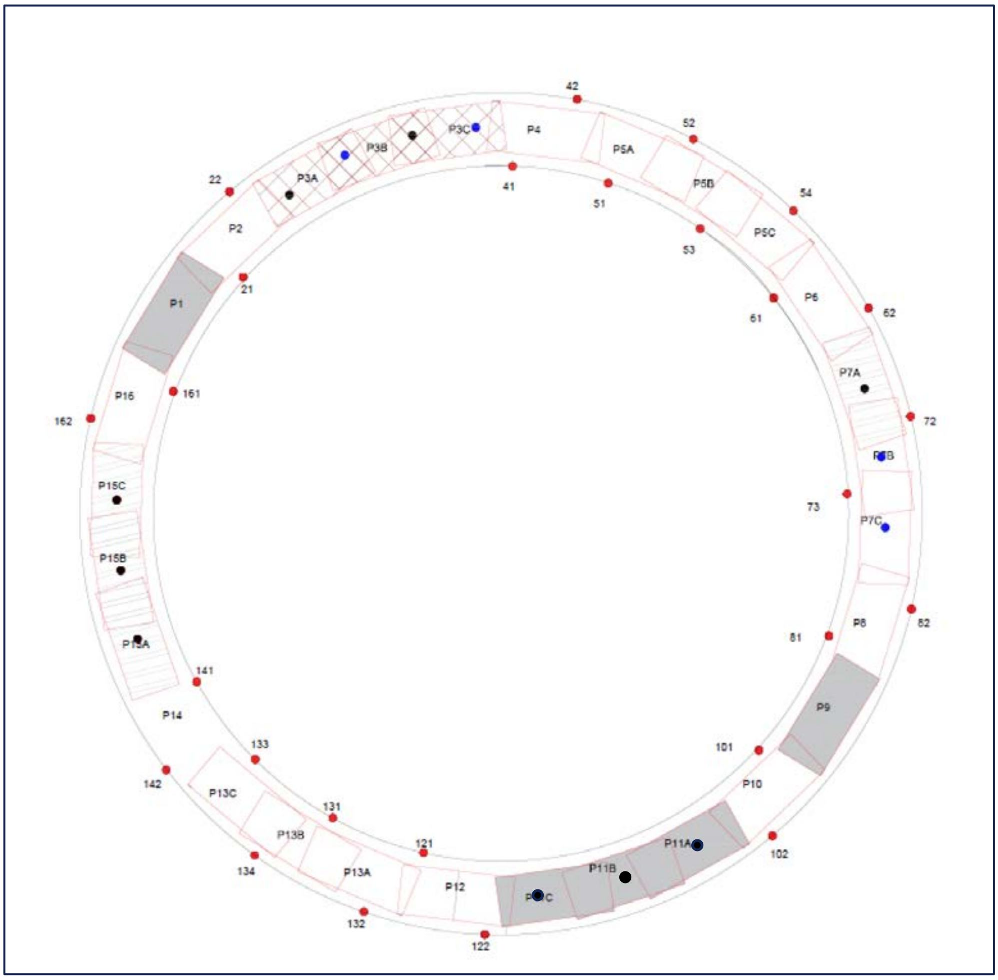

Figure 8 Location of ground treatment holes at each panel

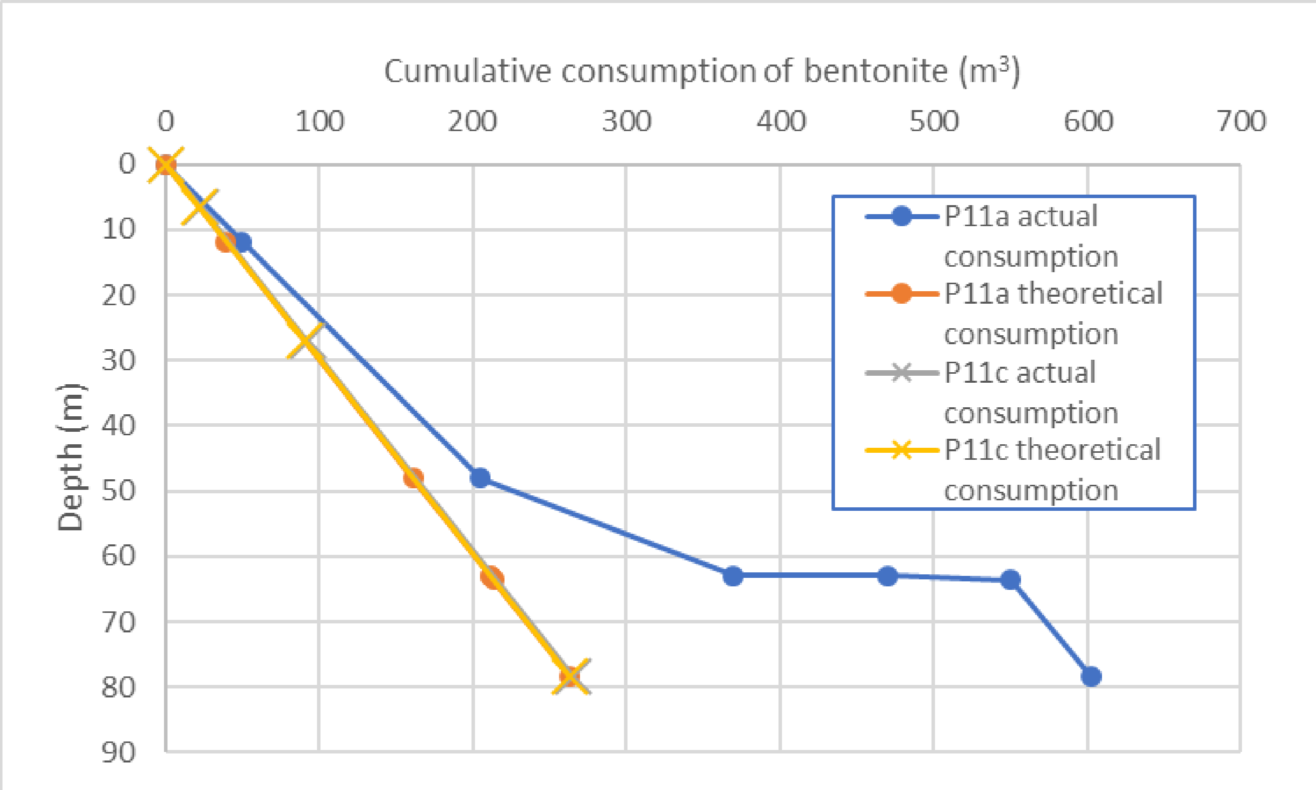

Figure 9 Cumulative consumption of bentonite vs. depth for Panels 11a and 11c

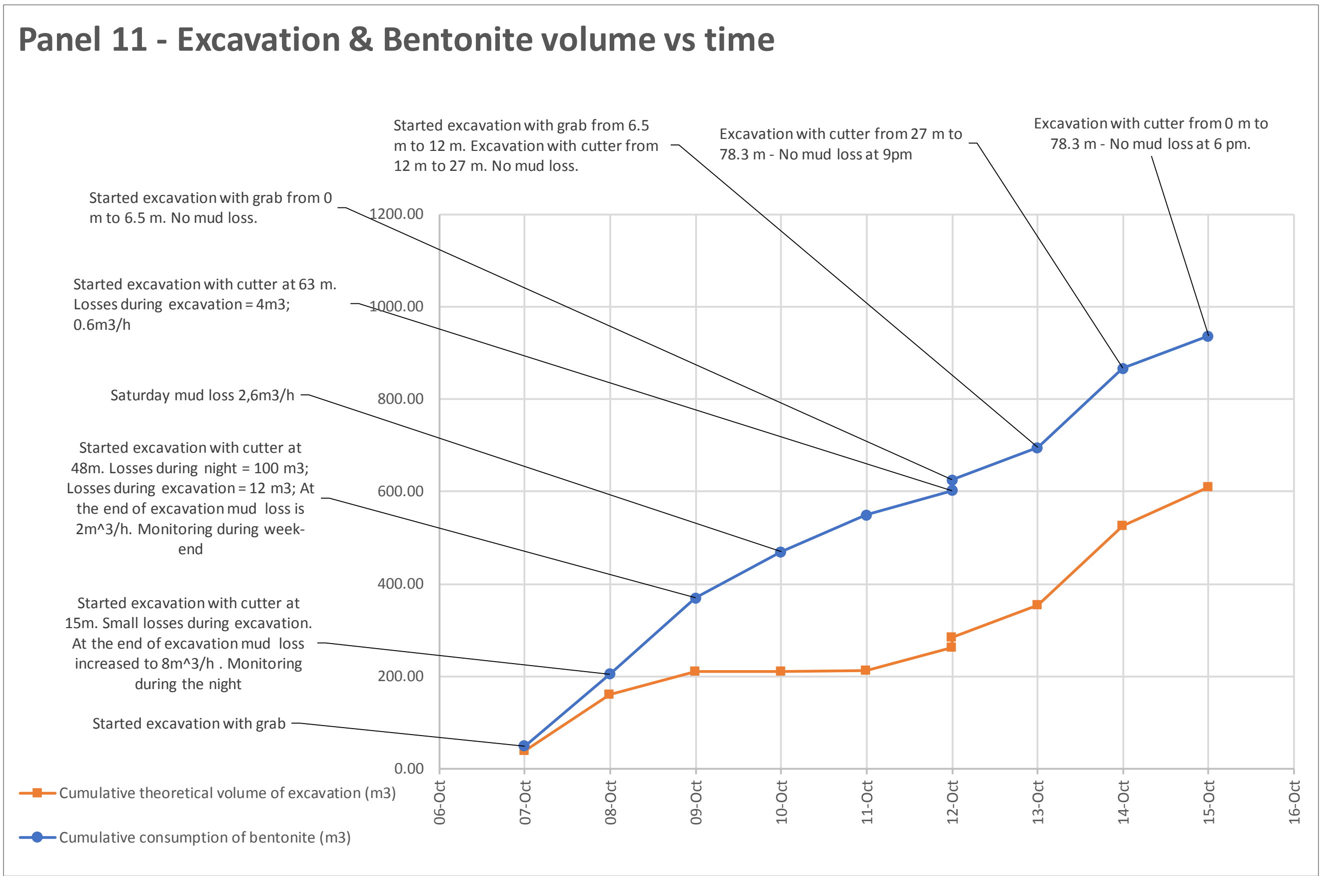

Figure 10 Cumulative consumption of bentonite vs. time for Panel 11

2.2.5 Panel 15

2.2.5.1. Panel 15, which is a three bite panel, was completed after ground treatment. The treatment included drilling 3 grout holes within the d-wall alignment (Figure 8) prior to starting d-wall excavation. Figure 11 shows the bentonite consumption vs. excavation depth for bites 15a and 15c and Figure 12 presents the excavation and bentonite volume vs. time, including the response measures put in place, for all three bites of Panel 15.

2.2.5.2. During the excavation of Panel 15, 279m^3 of bentonite was lost to the ground. The most significant bentonite losses occurred from bite 15a (the second bite excavated) when it was at full depth (78m) and remained open over the weekend (losses of c.100m^3 of bentonite). There was no significant bentonite loss during excavation of bite 15b the majority of which was completed in one day. bite 15b is therefore not shown on Figure 10.

2.2.5.3. The concrete pour for P15 was 620m^3 which is slightly less than the theoretical volume of 630m^3.

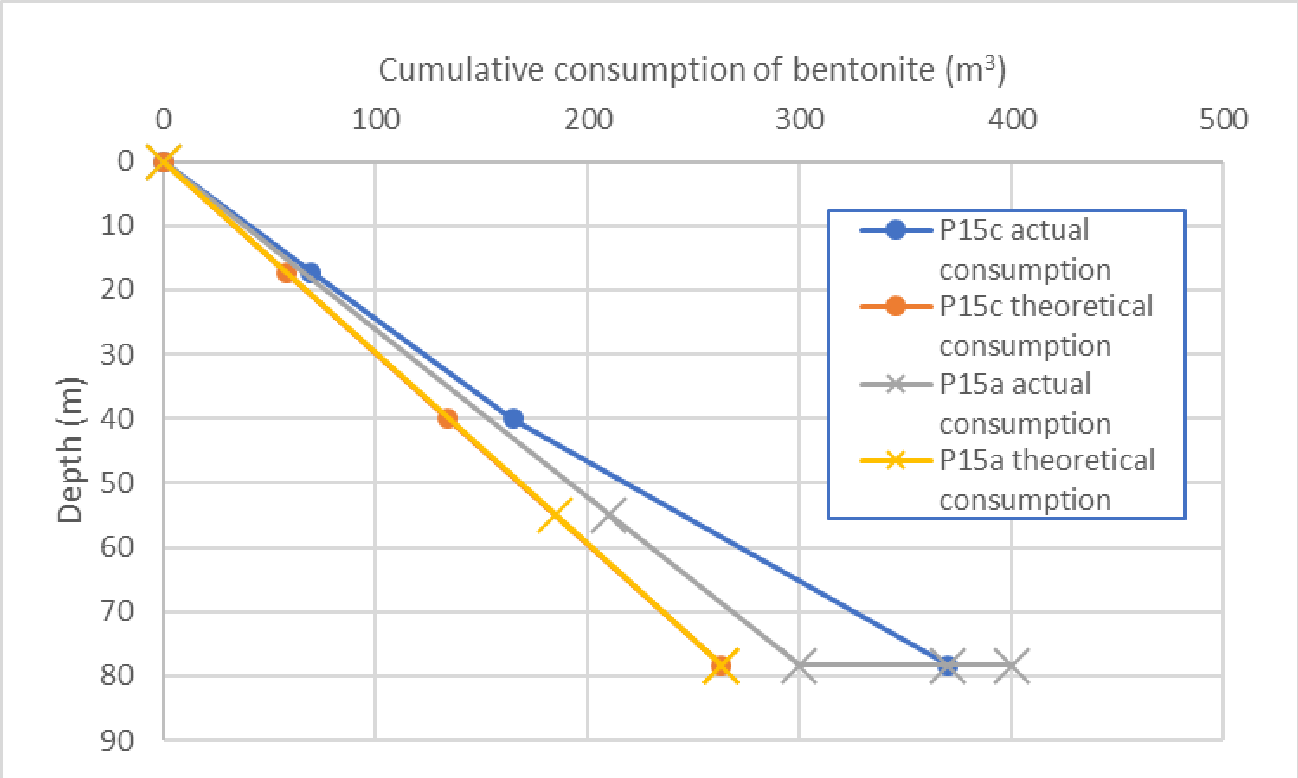

Figure 11 Cumulative consumption of bentonite vs. depth for bites 15a and 15c

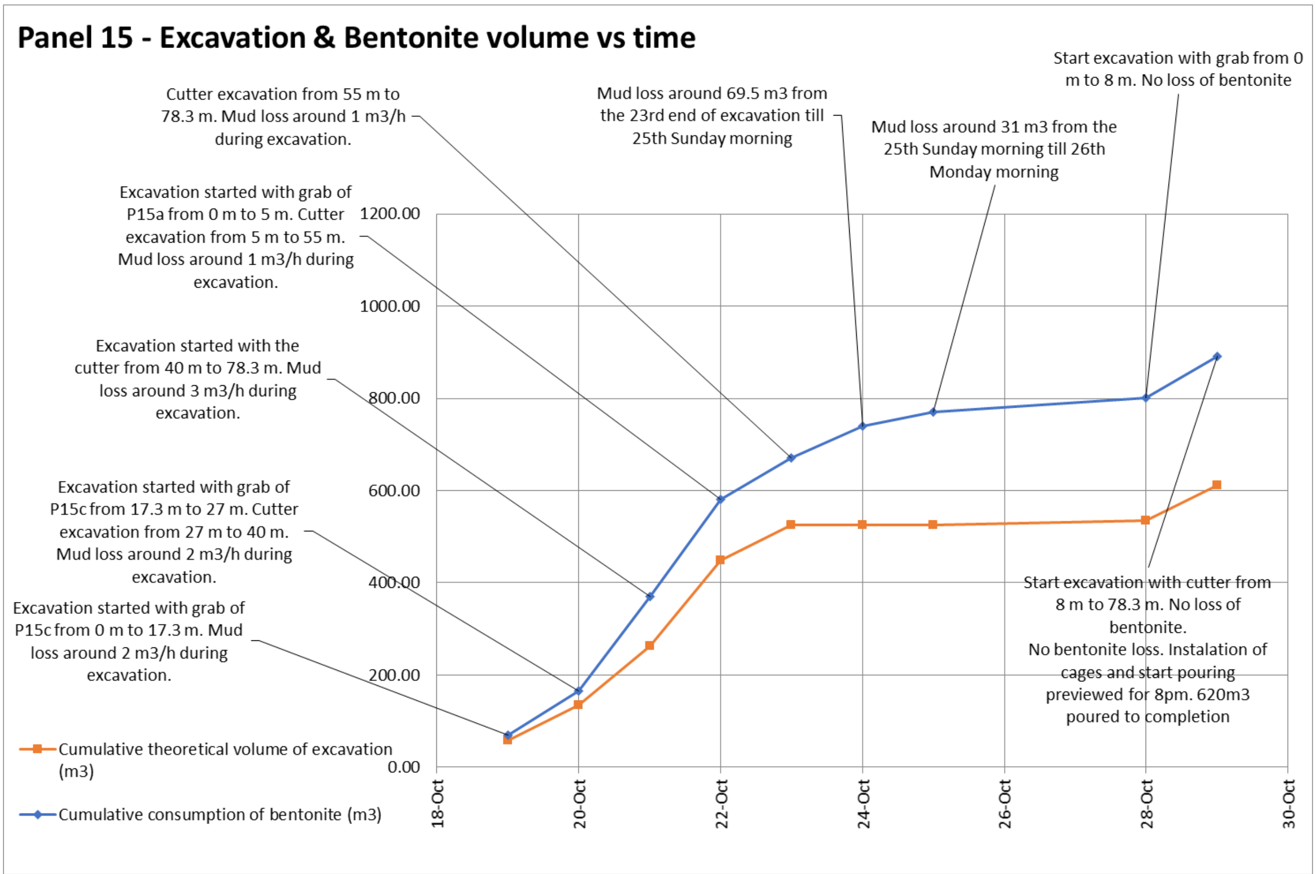

Figure 12 Cumulative consumption of bentonite vs. time for Panel 15

2.2.6 Panel 10

2.2.6.1. Panel 10, which is a one bite panel, was completed after ground treatment. The treatment included drilling 2 grout holes adjacent to the d-wall (Figure 8) prior to starting d-wall excavation. Figure 13 shows the bentonite consumption vs. excavation depth and Figure 14 presents the excavation and bentonite volume vs. time, including the response measures put in place.

2.2.6.2. During the excavation of Panel 10, only 51m^3 of bentonite was lost to the ground which is a significant reduction over previous three bite panels, albeit that Panels 11b, 11c and 15b were all excavated with no bentonite loss. The low bentonite loss may be partly due to the fact that P10 is a closing panel. Treatment and concreting of adjacent panels P9 and P11 would bring a benefit in reducing bentonite loss as there is less surface area and there will be some grout and concrete sealing the fissures around P10.

2.2.6.3. The concrete pour for P10 was 288m^3 which is only slightly greater than the theoretical volume of 260m^3.

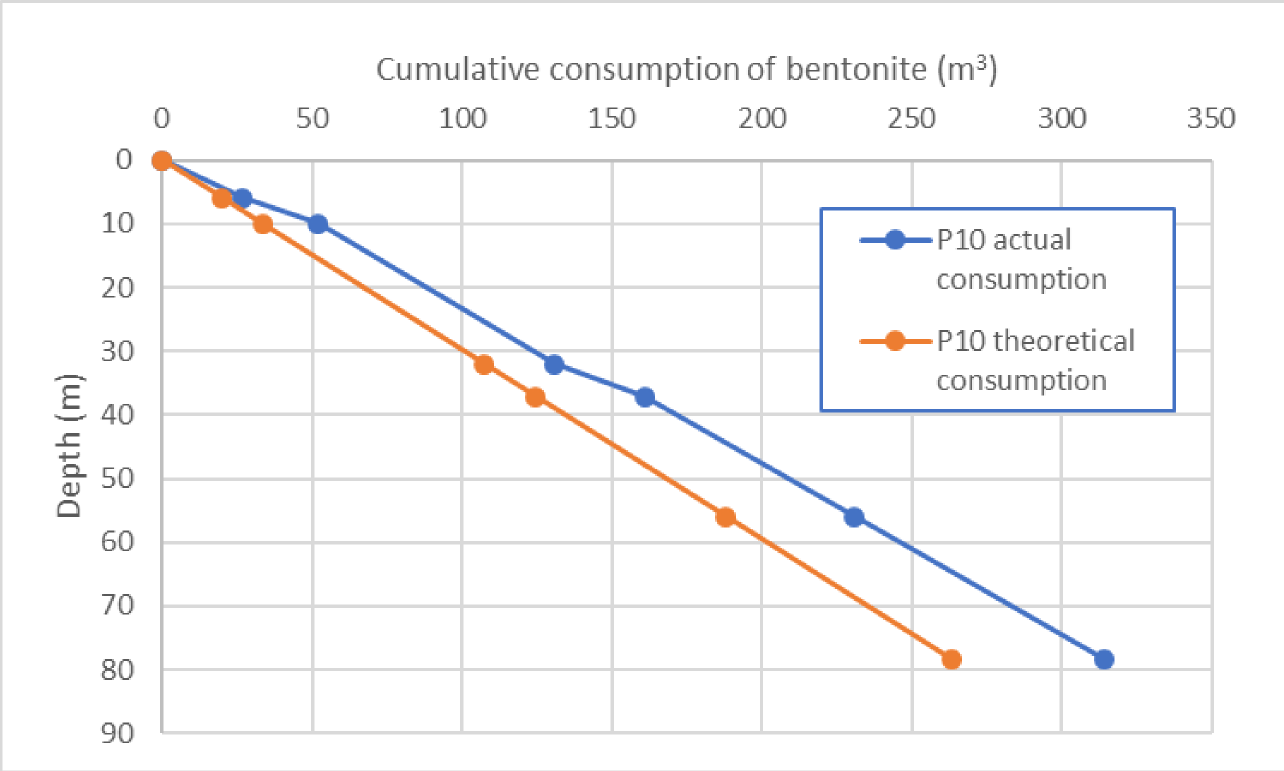

Figure 13 Cumulative consumption of bentonite vs. depth for Panel 10

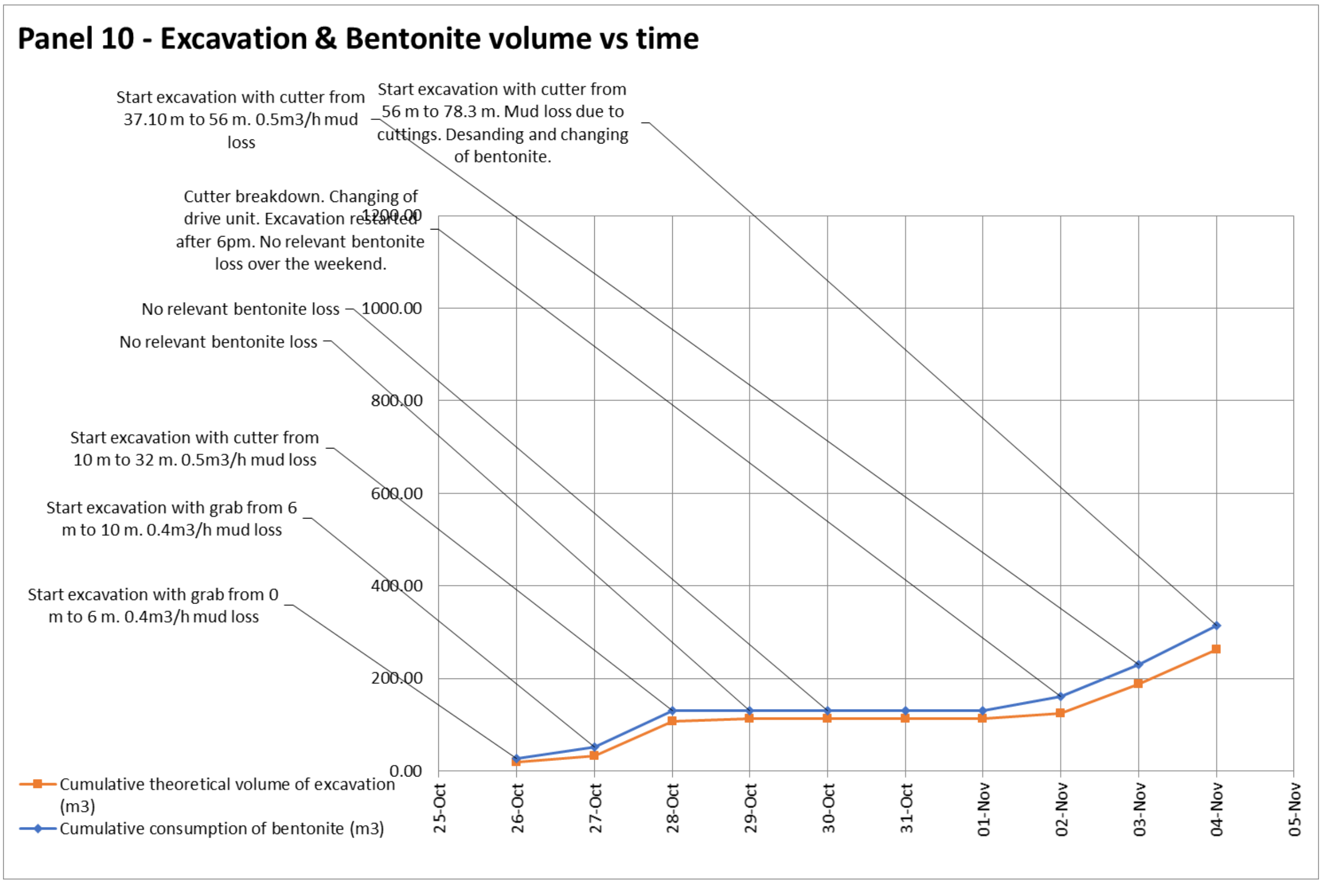

Figure 14 Cumulative consumption of bentonite vs. time for Panel 10

2.2.7 Panel 3

2.2.7.1. Work on Panel 3, which is a three bite panel, started on 22 September after Panel 9 was complete. Two ground treatment boreholes were successfully drilled within the alignment of the d-wall panel (Figure 8). However, during grouting of a third borehole on 28 September the casing became stuck and work halted until the casing could be removed in late October. For this reason the grouting method was reviewed and eventually revised (following changes to the consent documentation) such that ground treatment boreholes were subsequently drilled adjacent to the d-wall alignment rather than within it (as shown on Figure 8). A fourth ground treatment hole was drilled within Panel 3 on 23 October.

2.2.7.2. Figure 15 shows the bentonite consumption vs. excavation depth for bites 3a and 3c and Figure 16 presents the excavation and bentonite volume vs. time, including the response measures put in place, for all three bites of Panel 3. Panel 3 was completed to depth on 13 November with the concrete pour completed on 14 November. A total of 177m^3 of bentonite was lost to ground. The most significant bentonite losses were below 60m depth, although this effect is exaggerated for bite 3c as the bite remained open over the weekend and bentonite topping up was required (c. 100m^3). The final bite (3b) was excavated with only limited bentonite loss.

2.2.7.3. The concrete pour for P3 was 623m^3 which is only slightly less than the theoretical volume of 630m^3.

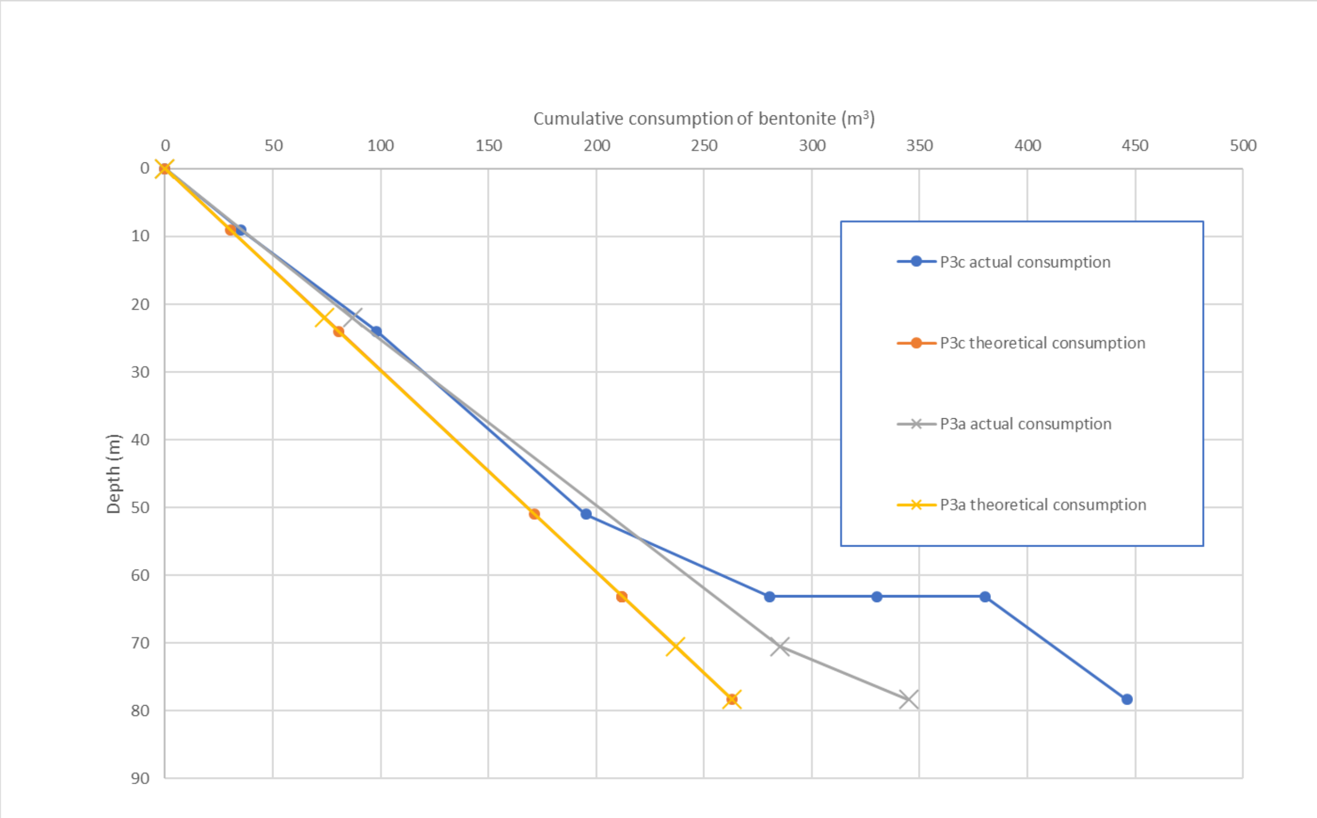

Figure 15 Cumulative consumption of bentonite vs. depth for bites 3a and 3c

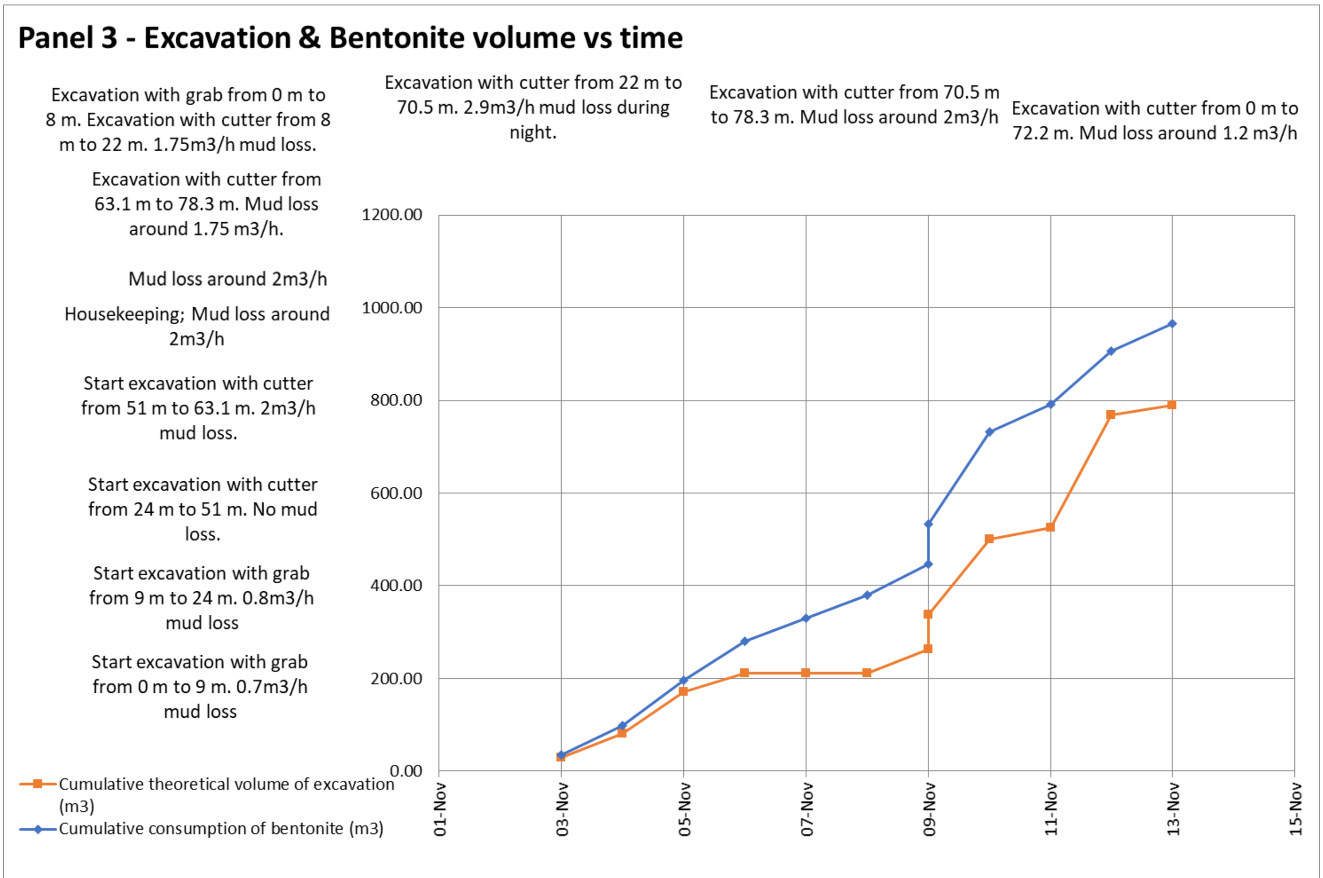

Figure 16 Cumulative consumption of bentonite vs. time for Panel 3

Summary

2.2.8 The monitoring of bentonite losses during d-wall excavations indicates that:

- Bentonite losses are most significant below 30m depth.
- Ground treatment markedly reduces bentonite losses. Before treatment the loss at a single bite panel (Panels 1 and 9) was typically c.800m^3, reducing to 50m^3 (Panel 10) post treatment, albeit that Panel 10 was a closing panel and so lower losses would be expected.
- Significant losses can occur over weekends when work is not being undertaken and bentonite slurry has to be kept topped up.
- Concrete losses are minimal.

2.3 *In situ* Groundwater quality monitoring

2.3.1 Groundwater quality data (three times daily, Mon-Fri) are available for monitoring boreholes ML034-CR001, ML034-RO408 and ML034-RO407 and have already been provided to Affinity Water and the EA and so are not repeated here. The data are assessed below for Panels 1 and 9 which were completed without pre-treatment and then for Panels 11, 15, 10 and 3 which were completed with pre-treatment. Panels 1, 9 and 10 were one bite panels whilst Panels 11, 15 and 3 were three bite panels.

Panels 1 and 9

2.3.2 Water quality variations measured by well head parameters are shown in Figures 17 to 20. The turbidity and pH data provide the best indication of any bentonite losses and are shown in Figures 17 and 18 for the each of the three monitoring boreholes with the borehole locations shown on Figure 21.

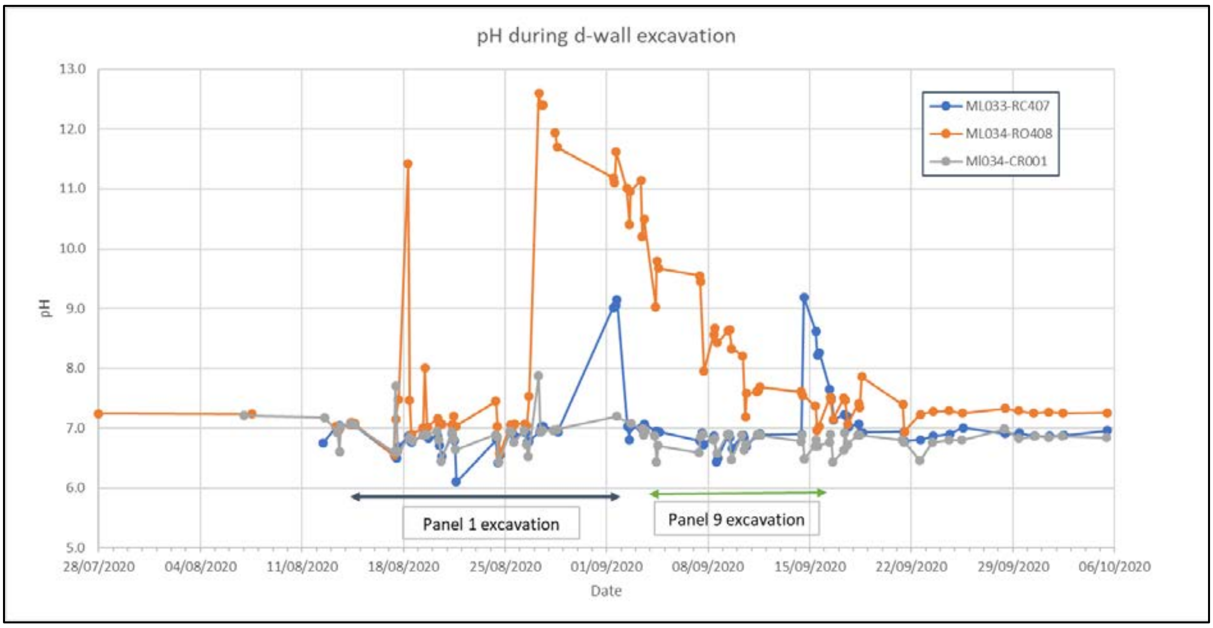

Figure 17 – pH during d-wall excavation of Panels 1 and 9

2.3.3 The pH results show a significant change in boreholes RO407 and RO408 but there is no significant change in CR001 that can unequivocally be related to d-wall excavation and bentonite loss (there are some minor changes during excavation of Panel 1 but these are not thought to be due to panel excavation). Boreholes RO407 and RO408 are across the hydraulic gradient from the shaft whilst CR001 is more down gradient, although not completely (see water table maps in Figures 9 and 10 in Construction of Chalfont St Peter Ventilation Shaft Water Environment Assessment, Document no: 1MC05-ALJ-EV-REP-CS02_CL04-000030).

2.3.4 There is a noticeable difference in the degree and timing of changes in pH between boreholes RO407 and RO408, with the greatest impact from Panel 1 being identified in RO408 with a much higher pH and a longer duration of effect than in borehole RO407. The effect in RO408 is also noted much earlier than in RO407, although the elevated pH on 18 August is likely due to the drilling trials which were completed in borehole P02 on 18 August.

2.3.5 No significant effect is noted in RO408 from Panel 9 excavation, with the possible exception of a minor change after the excavation is complete. However, in RO407 an effect is observed from both panels, albeit that the maximum pH is less than measured in borehole RO408. It is not clear why a very high pH (>12) was measured in RO408 on 27 August as this was prior to the use of lean mix cement on 28 August (Figure 5).

2.3.6 The turbidity results in Figure 18 show a similar response to the pH variations in Figure 17 with a significant effect from both panels observed in borehole RO407 but in borehole RO408 the only substantial effect was from Panel 1 (there was much smaller spike from Panel 9). In both boreholes the magnitude of effect from Panel 1 was similar at around 7500 NTU, whilst the effect from Panel 9 in RC407 was slightly greater at 8600 NTU. No effect of d-wall construction was identified in borehole CR001, with the early elevated data possibly due to particles remaining from drilling which were gradually cleared during purging and sampling.

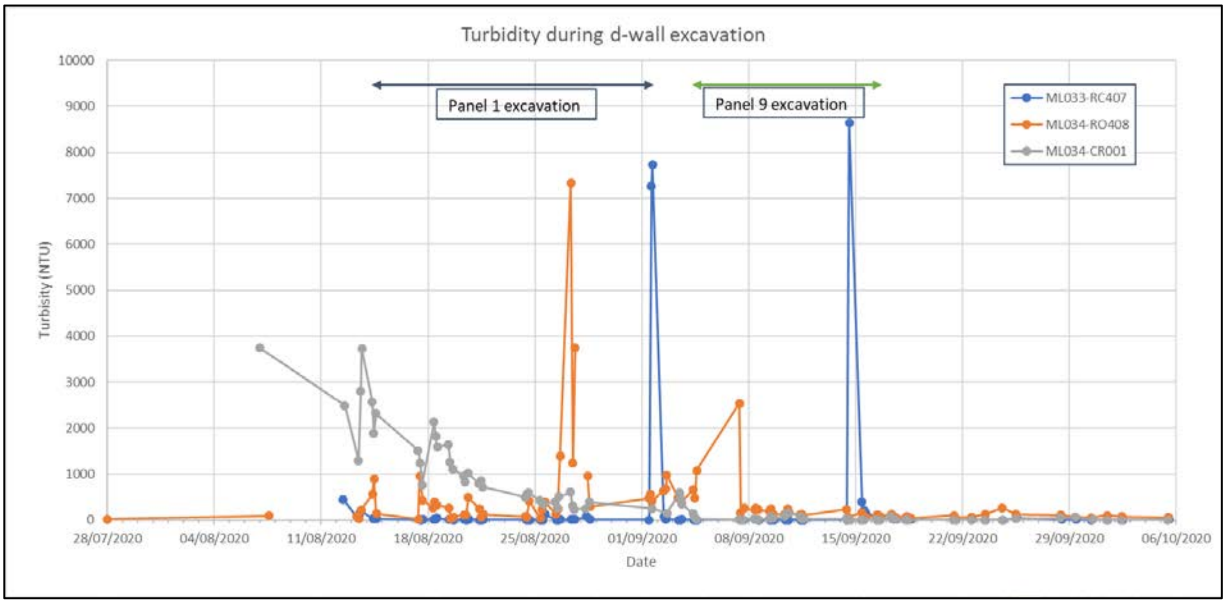

Figure 18 – turbidity during d-wall excavation

2.3.7 Redox during excavation of Panels 1 and 9 is shown in Figure 19. This shows some significant variations between boreholes and with time. There is a significant drop in redox in RO408 from over 200mV on 26 August part way through Panel 1 excavation to -15mV on 27 August followed by a gradual rise through Panel 9 excavation peaking again at over 200mV on 23 September. This appears to correlate well with the sudden increase in pH to 12.5 (Figure 17) followed by a gradual decline and a turbidity spike (Figure 18) and could be related to a sudden bentonite loss. There is also a significant peak in redox in RO407 at the end of Panel 1 excavation but then a drop of over 200mV in 3 hours. This correlates well with a turbidity spike and an increase in pH.

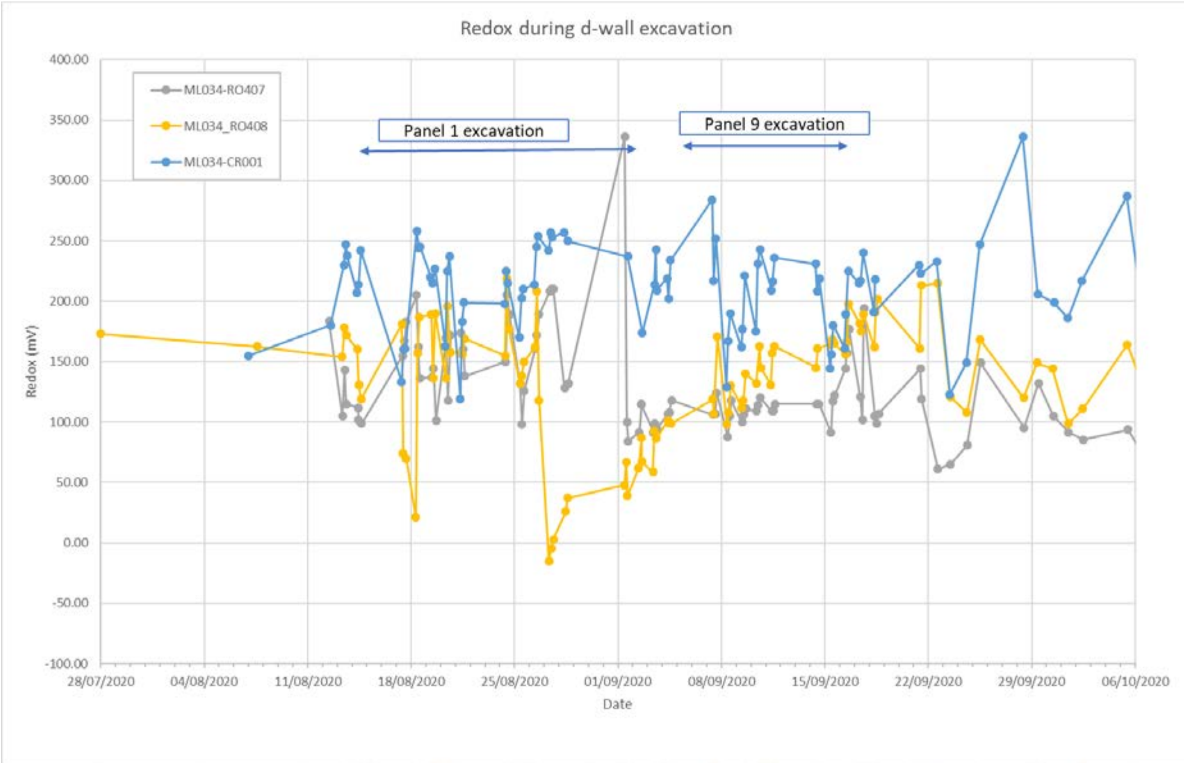

Figure 19 – Redox during d-wall excavation

2.3.8 Electrical conductivity values are shown in Figure 20. The values in RO407 and CR001 are generally (but not always) very similar to one another throughout the monitoring. However, values in RO408 are quite different with a significant spike to over 2400µS/cm on 27 August followed by a rapid decline and then gradual recovery. This correlates with the changes in pH, turbidity and redox.

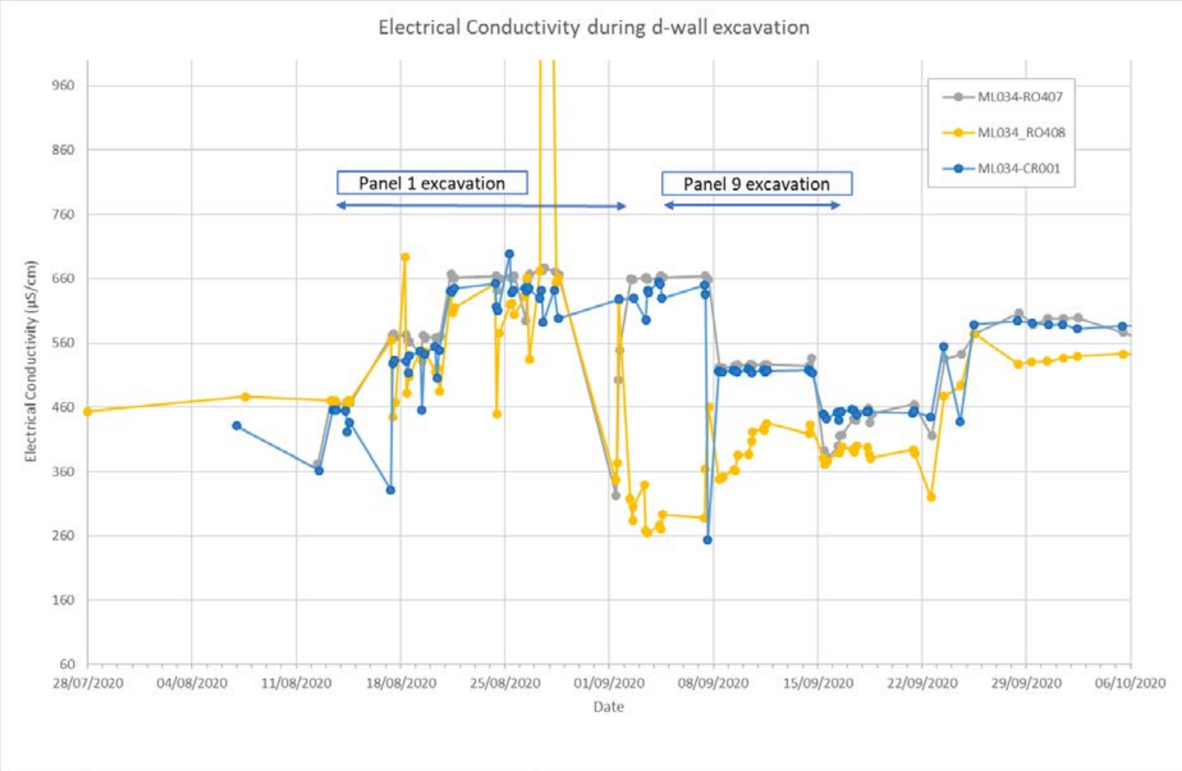

Figure 20 – Electrical conductivity during d-wall excavation

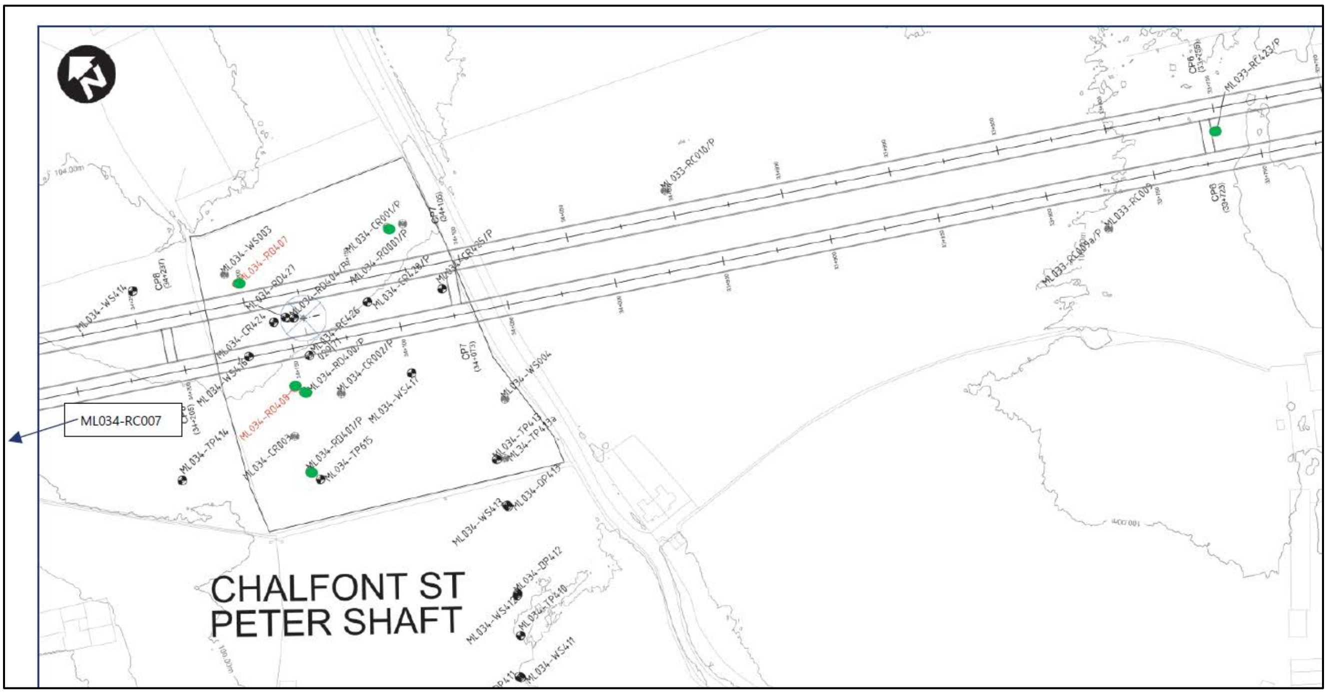

Figure 21 - Location of the water monitoring location (green dots)

Panels 11, 15, 10 and 3

2.3.9 All four of these panels were excavated following ground treatment. The work included ground treatment along the centre line of the d-wall at all locations except Panel 10 as follows:

- Panel 11 – three boreholes for ground treatment
- Panel 15 - three boreholes for ground treatment
- Panel 10 – two boreholes for ground treatment
- Panel 3 – four boreholes for ground treatment

2.3.10 Water quality variations during piling are shown on Figures 22 to 26. The pH during excavation of the four panels, which is shown on Figure 22, shows very little change (there is a very slight upward trend) during d-walling in comparison to that during Panels 1 and 9 (Figure 17) with all values neutral and typically varying by between 0.5 and 1 pH unit. Assessment of baseline pH monitoring from the nearest Priority Monitoring borehole, ML035-CR003, shows a natural variation of just under 1 pH unit (Figure 23), albeit that the time period is over two years and so incorporates seasonal variations that would not occur during the 5 week d-walling period shown in Figure 22.

2.3.11 The pH changes have been examined in detail to determine if there are any apparent minor changes that could be related to d-wall excavation. The largest amount of bentonite lost was at Panel 11 where 327m^3 was lost, mostly from bite 11a between 48 and 63mbgl over the period 9 to 12 Oct (a weekend). Borehole RO408 is the closest to Panel 11 (see Figures 2 and 3) and so might be expected to show the greatest change in pH, however, at all three boreholes the pH changed less 0.1 unit in all cases between 9 and 12 Oct and similarly less than 0.1 pH from 9 to 19 Oct. There was pH increase in all three boreholes at the end of Panel 11 excavation but this was only 0.2 pH units.

2.3.12 A similar situation pertains during excavation of Panels 15, 10 and 3 when the bentonite losses were significantly less than at Panel 11. This does suggest that if there are pH changes due to d-wall installation they are very minor unless there are significant losses of bentonite slurry.

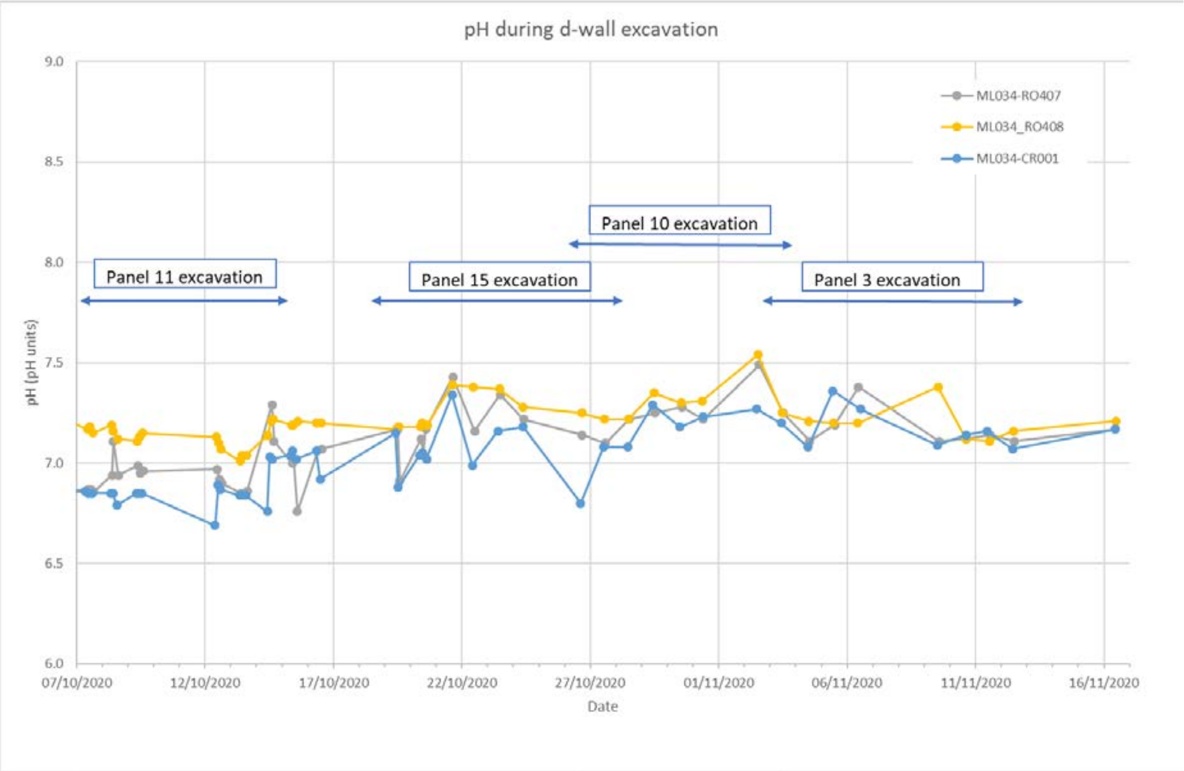

Figure 22 – pH during d-wall excavation of Panels 11 to 3

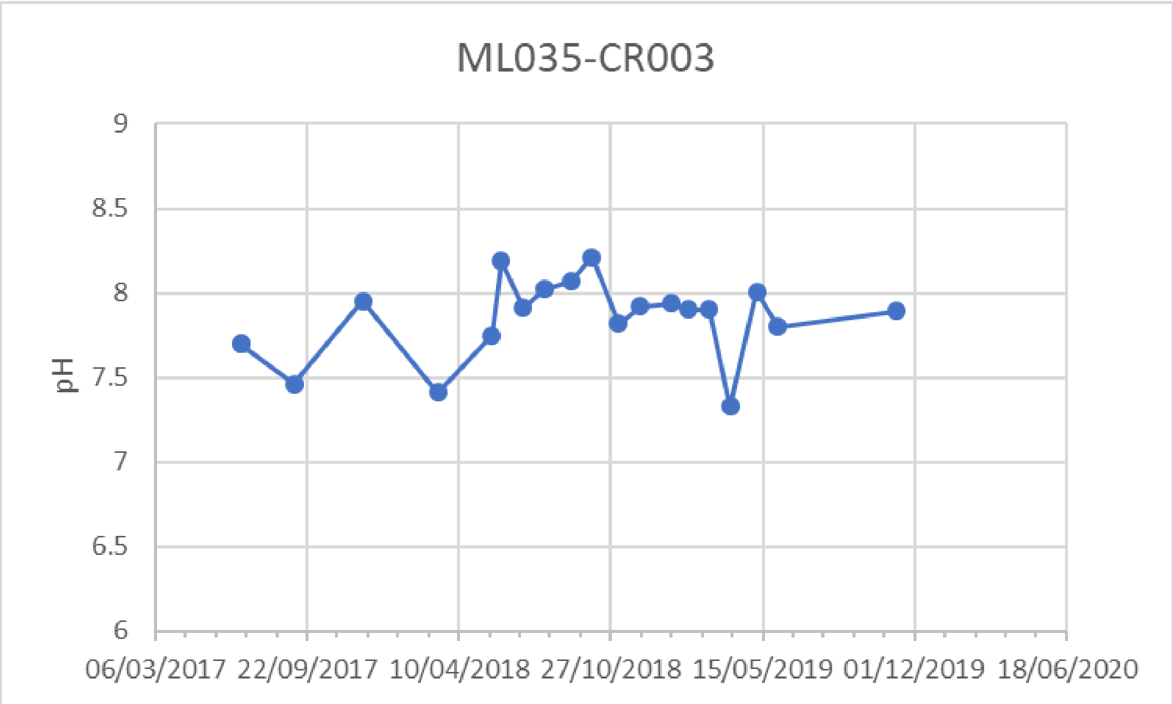

Figure 23 – baseline pH in ML035-CR003, the nearest priority monitoring borehole to CSP shaft

2.3.13 The turbidity results, which are shown in Figure 24 do show some variations with d-wall installation with distinct peaks in turbidity in both RO407 and RO408. During Panel 11 excavation there is a significant peak in turbidity on 8 October at 09:20 although turbidity then rapidly declined through the day and only small bentonite losses were recorded from the d-wall. The most significant bentonite losses occurred on 9 October but turbidity remained low in RO407. However, turbidity did increase on 9 October in RO408 and remained elevated during Panel 11 excavation only declining at the end of excavation of this panel. RO408 is the closest borehole to Panel 11 and suggests that there was a short lived impact on turbidity.

2.3.14 During excavation of Panel 15 some 279m^3 of bentonite was lost with the largest losses being over the weekend of 24 / 25 Oct when the panel was open but not being worked. The turbidity in RO408 peaked at 495 NTU on 26 October, with a similar peak in RO407 following on 28 October. Borehole RO408 is slightly closer to Panel 15 than RO407. This indicates an impact on turbidity from d-wall excavation.

2.3.15 During excavation of Panel 10, a single bite panel, losses were very low at 51m^3 and no significant peaks in bentonite concentration were identified although there was a general rise in concentration in RO407 and CR001.

2.3.16 The most significant turbidity spikes measured during the excavation of Panels 11 to 3 were in RO407 during the excavation of Panel 3 which is the closest monitoring point to Panel 3. Two peaks were measured with turbidity in excess of 1300 NTU on both occasions, dropping to 0 NTU in between, albeit that this low value was measured on a Monday morning after no weekend working and only limited bentonite loss over the weekend (c.2m^3/hr).

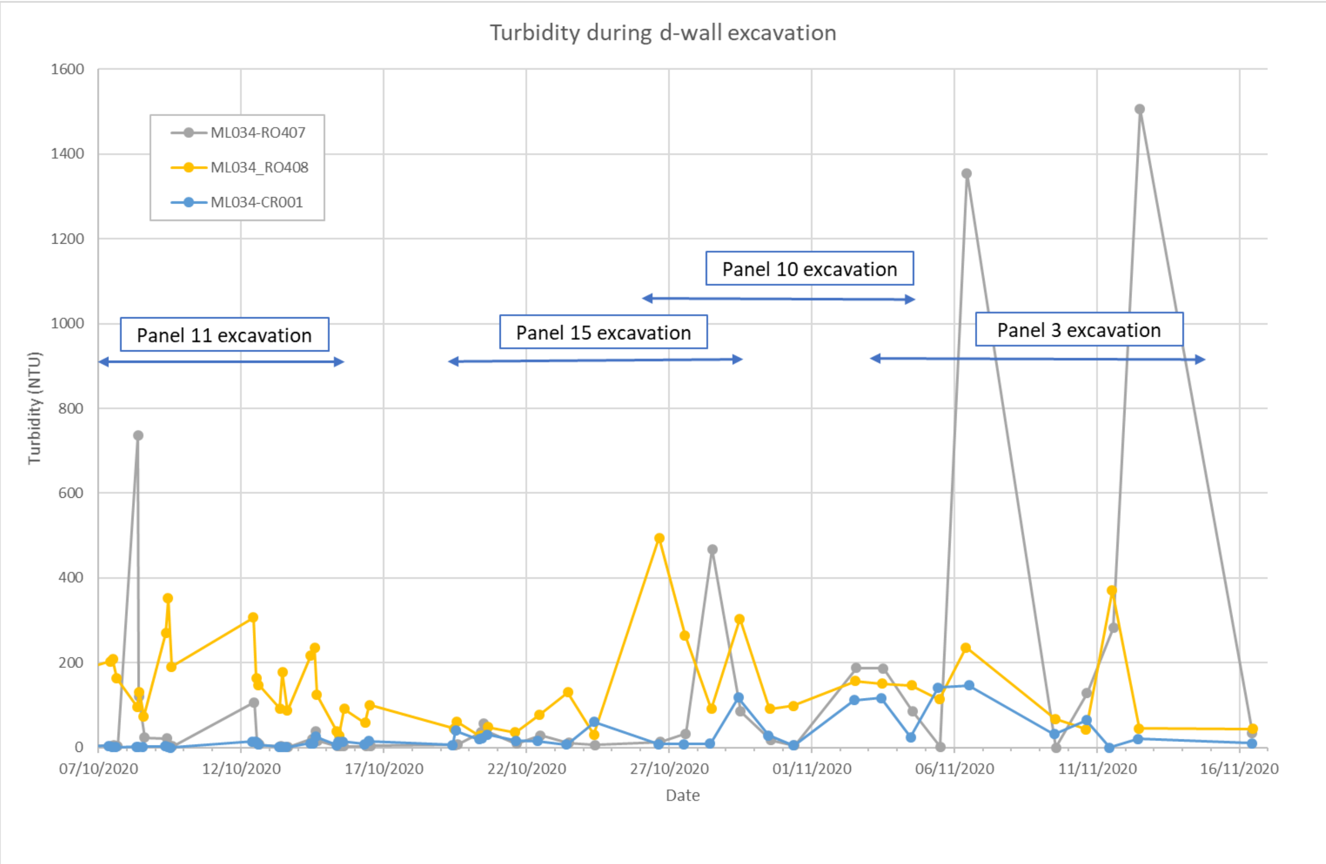

Figure 24 – Turbidity during excavation of Panels 11 to 3

2.3.17 Electrical conductivity variations during d-wall activity are shown in Figure 25. Although there are variations in conductivity during d-wall excavation no significant variations that can be directly linked to d-wall excavation have been identified. The largest changes are during the excavation of Panel 3 when there are some significant changes at all three boreholes with a low on 10 November. This broadly corresponds with the trough in turbidity in RO407 and RO408.

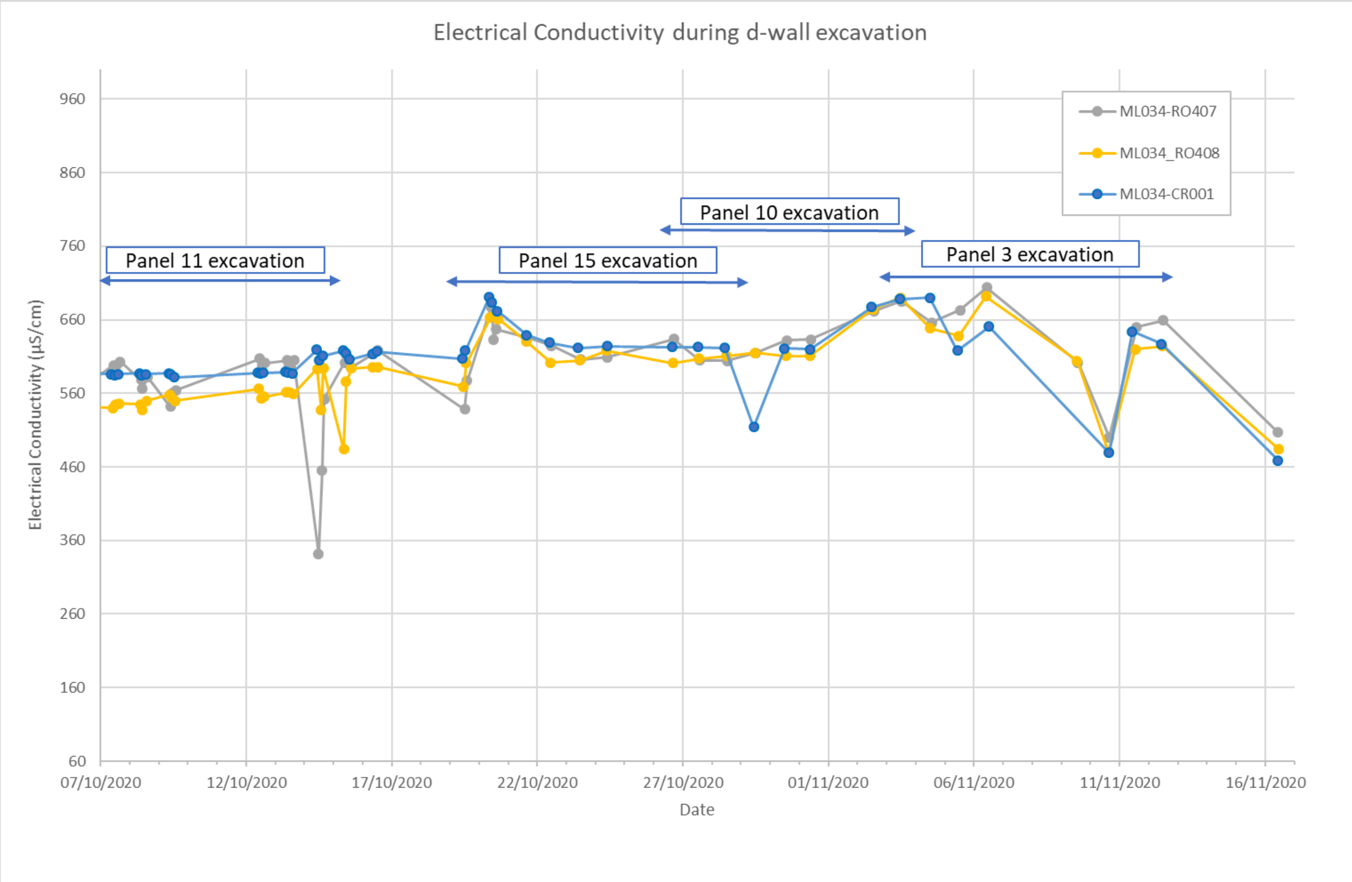

Figure 25 – Electrical conductivity during excavation of Panels 11 to 3

2.3.18 Redox varies quite significantly with time and on occasions between each of the boreholes as shown in Figure 26. However, there are no clear correlations between d-wall panel excavation and redox values. As an example, at the start of Panel 15 values are probably around their average for the period with RO408 for example being around 160mV. The values then decline markedly to just below zero on 21 October before climbing steeply to just over 250mV on 23 October and then fluctuating at between 80 and 190mV at the end of Panel 15. There may be a relationship with d-wall excavation but it is not clear or obvious and other parameters provide a more reliable method of assessing the effects of d-wall excavation.

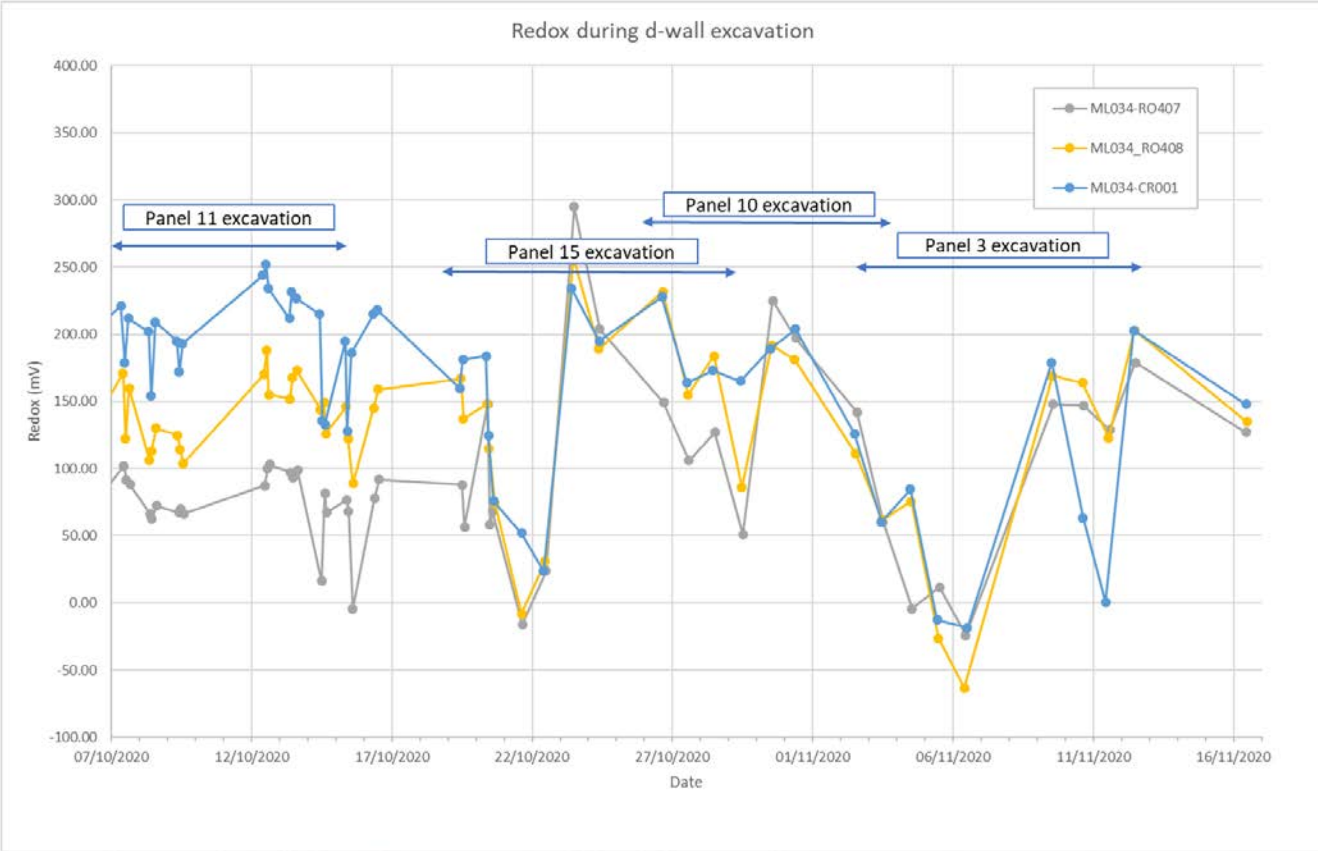

Figure 26 – Redox during excavation of Panels 11 to 3

Summary

2.3.19 Monitoring of *in situ* water quality parameters indicates:

- Small losses of bentonite are not readily detected at the monitoring locations likely due to a combination of distance and direction to the boreholes and screened elevation relative to the panels being excavated.
- pH, turbidity, electrical conductivity and redox all show some changes but the clearest and most significant changes are with regard to pH and turbidity.
- Following ground treatment any changes in water quality that are detected generally tend to be lower, though not always, and appear to be much shorter lived and more spikey in terms of response.
- No effects on water quality due to ground treatment have been identified although it may not be possible to differentiate such effects from those of d-wall construction as ground treatment and construction were taking place at the same time.

2.4 Changes in aluminium concentrations

2.4.1 Following the losses of bentonite during excavation of Panels 1 and 9 monitoring of dissolved and total aluminium was commenced, the results of which are shown in Figures 27 and 28. The dissolved concentrations of aluminium in RO407 and RO408 at the start of monitoring were both greater (RO408 particularly so) than the total aluminium reported by the laboratory and so the results for one or other are likely to be in error. It is therefore not possible to interpret these results with any certainty and they are assessed as anomalous. With the exception of the early (anomalous) data all results are significantly less than the drinking water standard of 0.2mg/l.

2.4.2 Ignoring these early data the dissolved aluminium concentrations do not show a correlation with d-wall activity with all results being at or close to the limit of detection, although the data set is limited. The dissolved aluminium concentrations in RO408 show a very slight increase during d-walling, but not RO407 or CR001.

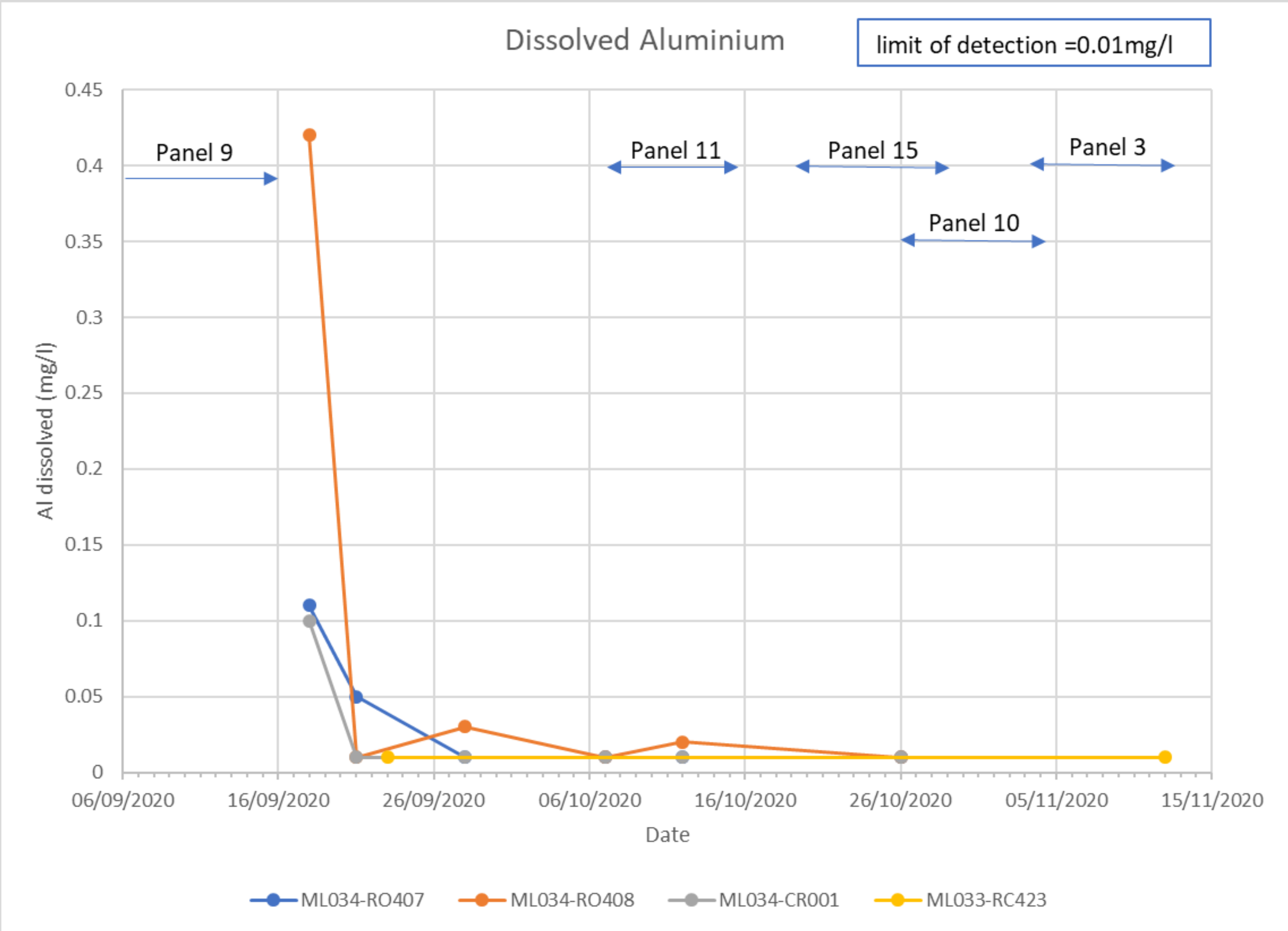

Figure 27 – Dissolved aluminium concentrations during d-walling

2.4.3 The total aluminium concentration is shown in Figure 28. This includes the dissolved aluminium in addition to any aluminium in suspension in the water. The results indicate changeable and elevated results in RO408 and slightly elevated concentrations in RO407 and CR001 in comparison to background concentrations in RC423 which is over 300m from the shaft. The results do suggest that there is some increase in total aluminium in groundwater associated with shaft construction in the area around the shaft.

2.4.4 There is poor correlation between total aluminium and turbidity in RO407 and RO408 but a very good correlation in CR001 (Figures 29 to 31). This is likely due to the greater variability (in terms of spikeyness, absolute value and short term changes in concentration) of effects of bentonite losses measured at RO407 and RO408 compared to CR001. As total aluminium concentration is driven by suspended solids concentration in groundwater, turbidity variations away from the shaft give a broad indication of likely total aluminium variations (though not the absolute aluminium concentration).

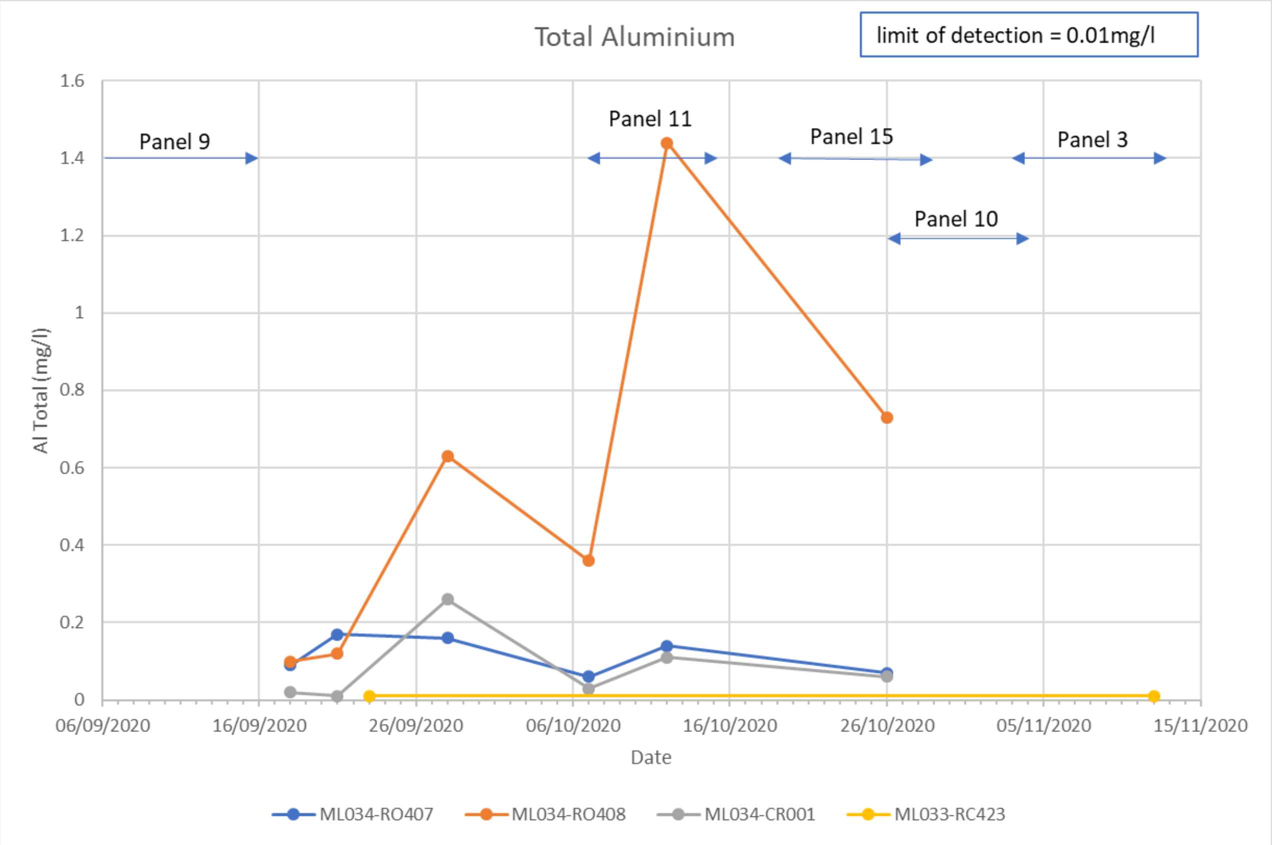

Figure 28 – Total aluminium concentrations during d-walling

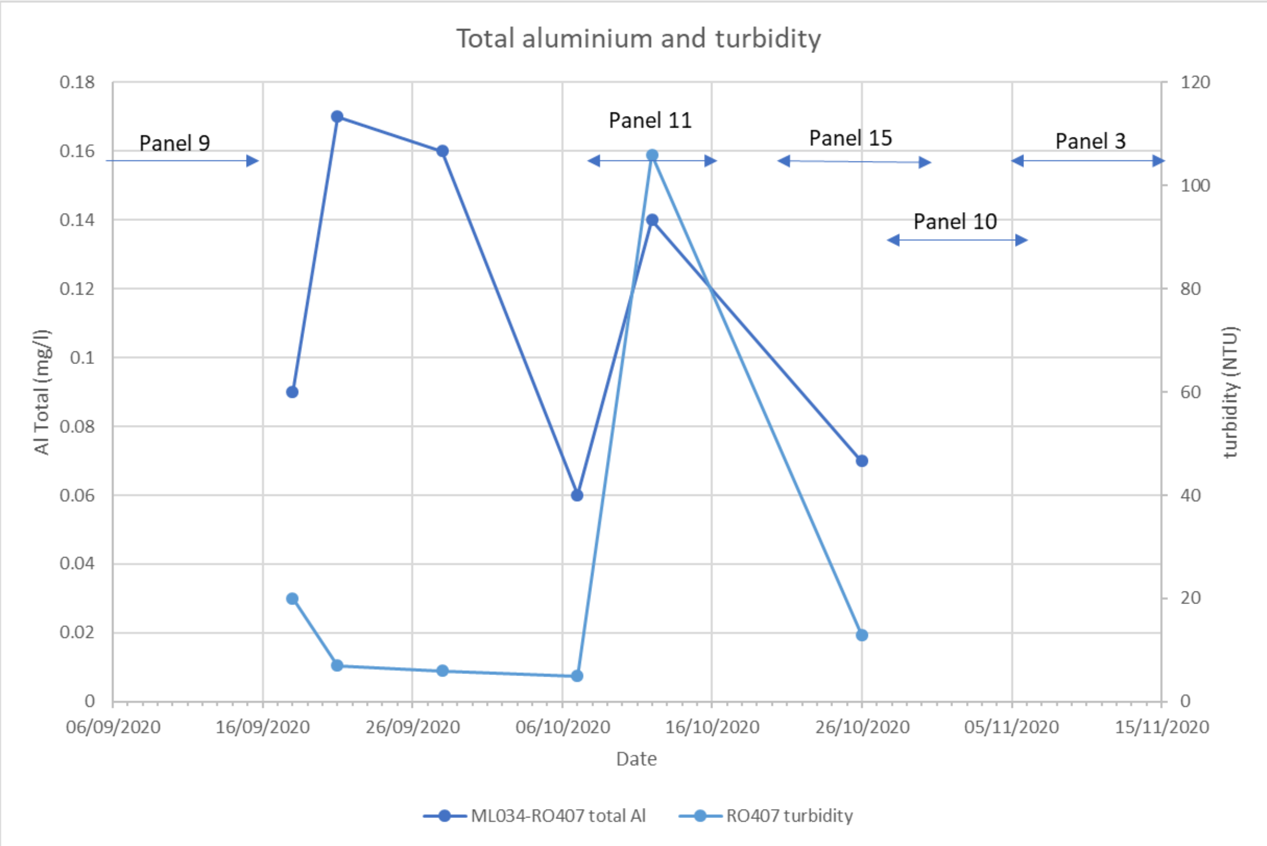

Figure 29 – Total aluminium versus turbidity at RO407

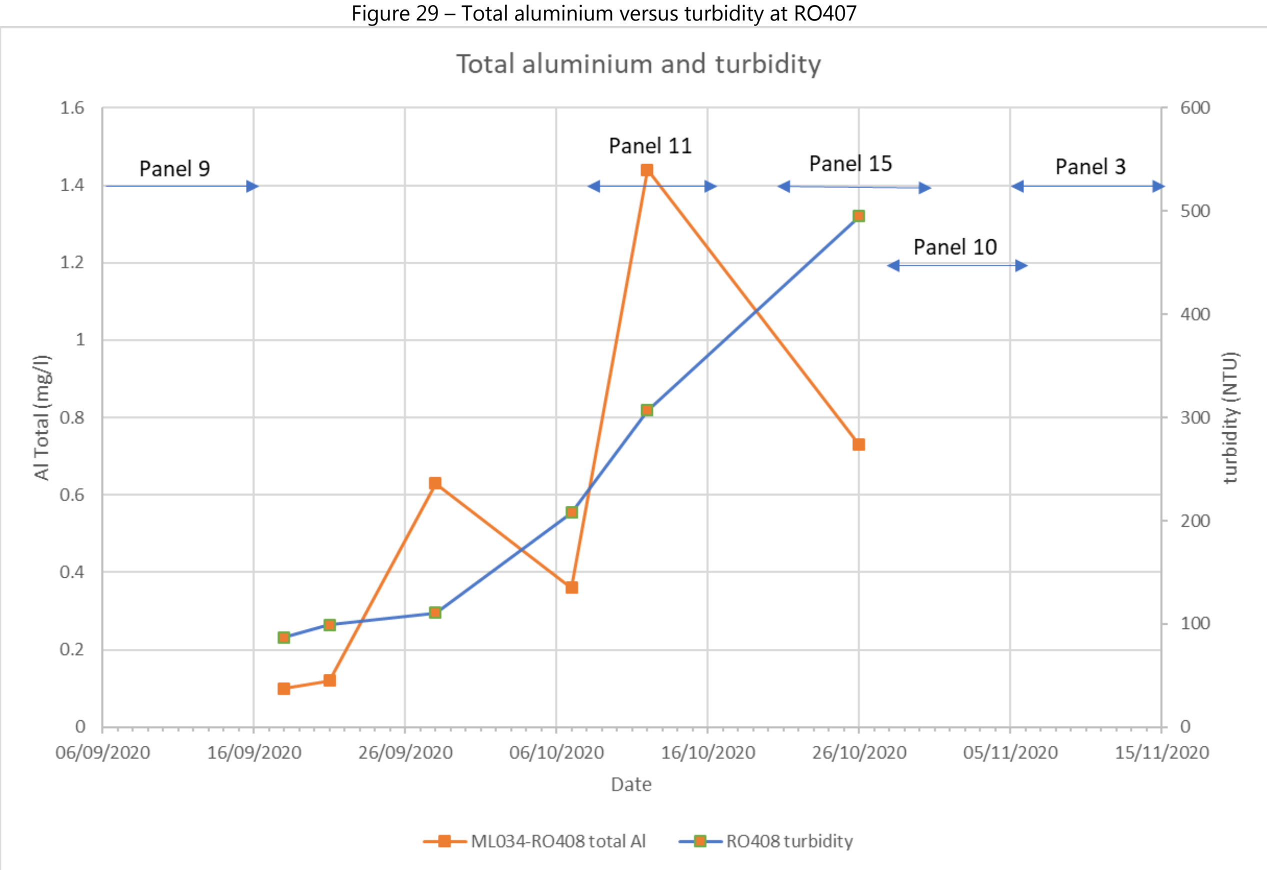

Figure 30 – Total aluminium versus turbidity at RO408

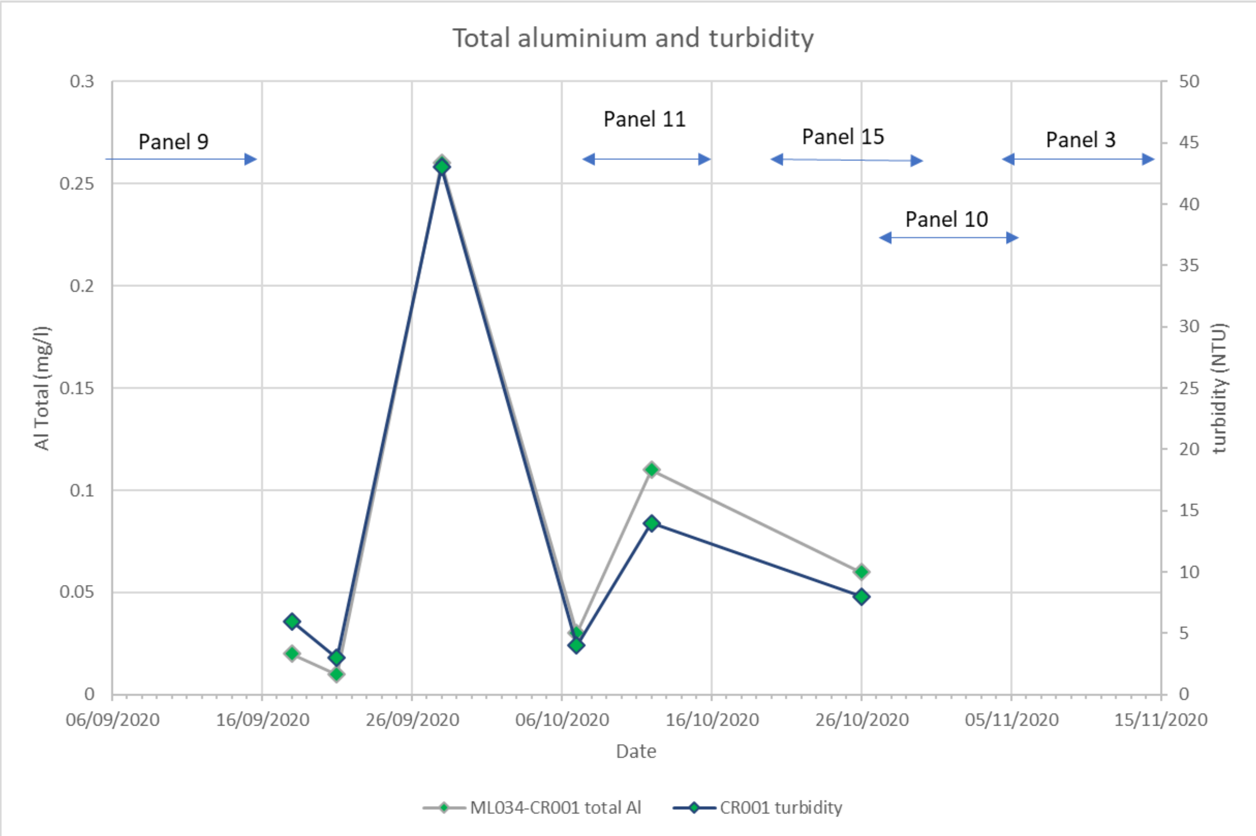

Figure 31 – Total aluminium versus turbidity at CR001

2.4.5 In summary, loss of bentonite has a very slight effect on dissolved aluminium concentrations in groundwater but this is not significant in comparison to drinking water standards. There is a significant effect on total aluminium concentrations which will be directly linked to suspended solids concentrations as indicated by turbidity. Close to the shaft where the effects of excavation are greatest the concentration of aluminium varies most widely and is probably a result of the turbidity being a mixture of chalk particles and bentonite particles with the latter having high aluminium concentrations.

2.5 Water level monitoring

2.5.1 The results of the water level manual dips are shown in Figure 32, with ML033-RC423 plotted on the right hand axis to allow the water levels in the remaining boreholes to be shown at a better resolution. The data show the end of the summer recession with water levels declining until the start of October when levels begin to recover.

2.5.2 The results clearly show fluctuations in water levels in monitoring boreholes RO407, RO408 and CR001 that are likely to be associated with d-walling activity during excavation of Panels 1 and 9. The results are greatest in RO408 with up to 0.5m water level change seen during one day whilst in RO407 and CR001, 0.3m change is the maximum. The changes tend to be associated with short term water levels increases (spikes).

2.5.3 The water level fluctuations during excavation of Panels 1 and 9 appear to be short term spikes associated with daily excavation operations, but the trend through the data is always downwards with the slope of the trend line for CR001 and RO408 very similar to RC423 which is some 400m (Figure 10) away from the shaft and very unlikely to be affected by the d-wall. The exception to this downward trend is borehole RO407 where an overall increase in water levels has been observed of around 0.2m. This may be due to a direct effect on the borehole by the d-wall construction, or potentially an effect on fracture systems that pass through the borehole and both panels 1 and 9 of the d-wall.

2.5.4 The water levels during excavation of Panels 11 to 3, which were all completed after ground treatment, show a different response in that the water level variations are not as spikey, although some of this is due to a reduced frequency of monitoring. In RO408 there are some short term water level increases during Panel 11 and at the start of Panel 15, but not for the remainder of the panels. In RO407 there are no sudden increases in water level but there are several sharp drops. In CR001, with the exception of a sudden short drop in water level towards the end of Panel 3 excavation there are no significant changes in water level.

2.5.5 Overall the results show that significant bentonite losses impact water levels close to the shaft but these are only short term. The ground treatment appears to have reduced the effect of d-wall construction on water levels which suggests that the water level changes during Panels 1 and 9 were associated with bentonite losses rather than panel construction *per se*. The water level response in the boreholes during Panels 11 to 3 shows a recovery that is similar to boreholes at distance from the shaft indicating that this is due to the onset of autumn recharge. It could be that the reduced water level spikes seen during construction of Panels 11 to 3 is in part due to groundwater recovery with recharge masking any construction effects.

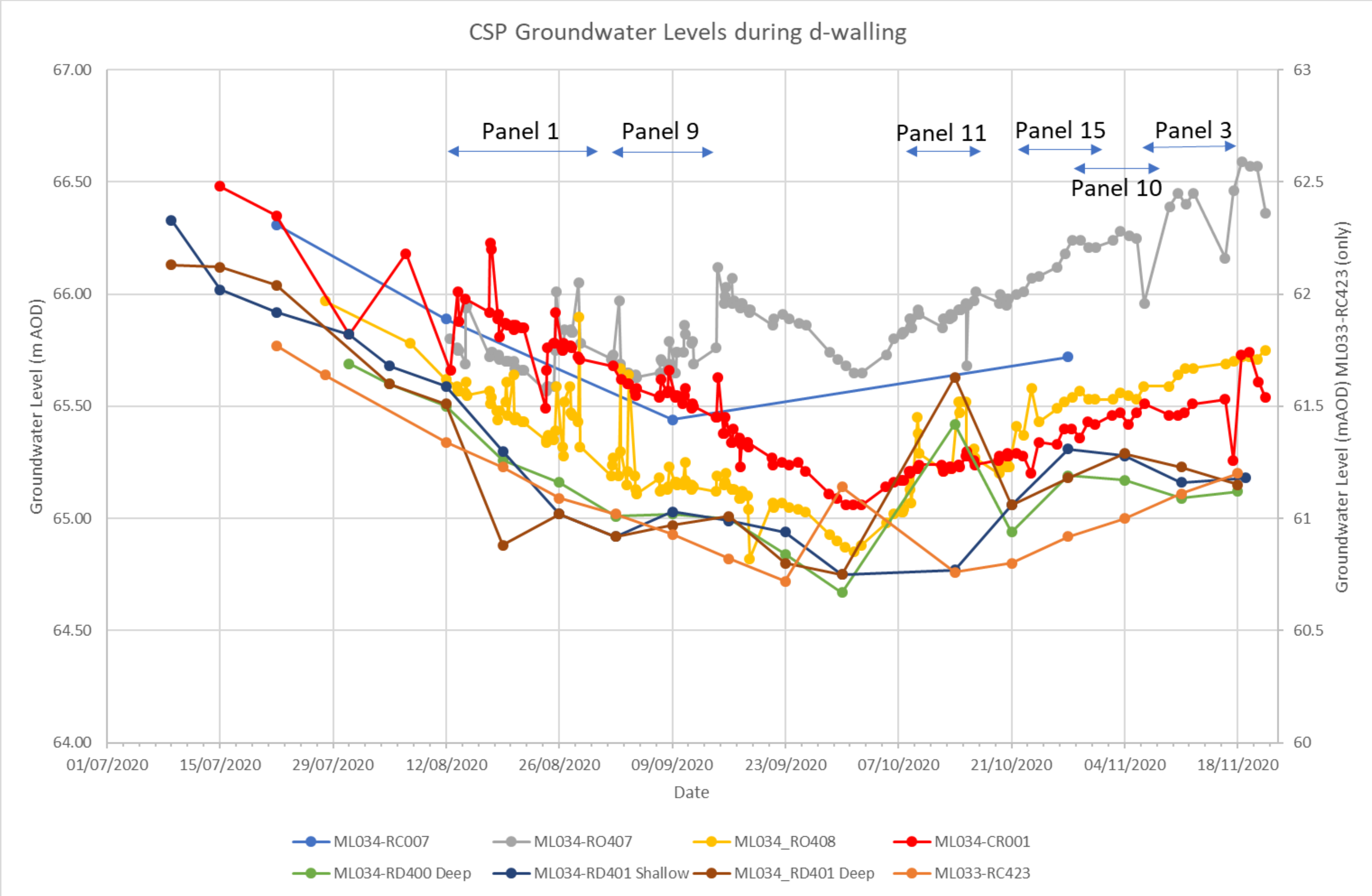

Figure 32 – Water level variations during d-walling

2.5.6 The water level data from the logger in RC423 s is presented in Figure33. This shows the seasonal water level recession into early October with no significant changes that could be associated with d-wall excavation. The scales for all logger outputs are set to the same time base and vertical range to allow direct comparison.

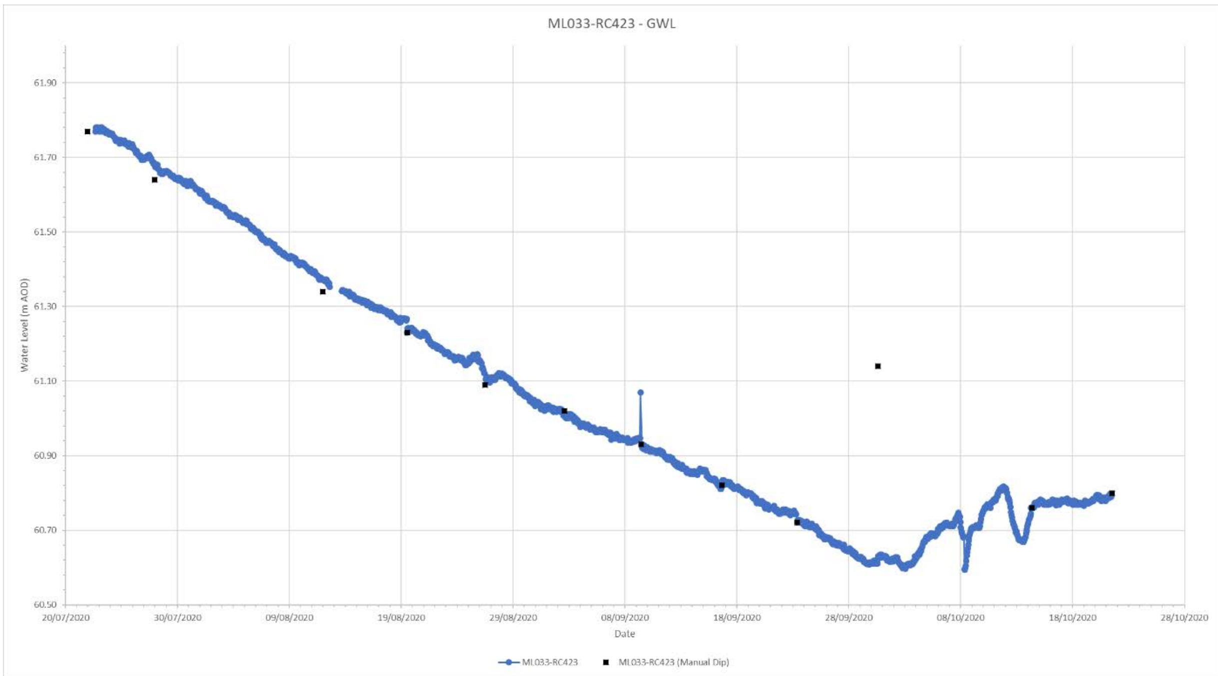

Figure 33 – Water level variations in RC423 during d-walling

2.5.7 The output from the data logger from RO407 is shown in Figure 34. As with the manual data shown in Figure 32 this shows significant variations during d-walling and an absence of the seasonal recession seen in RC423, although the water level rise following early autumn recharge is apparent.

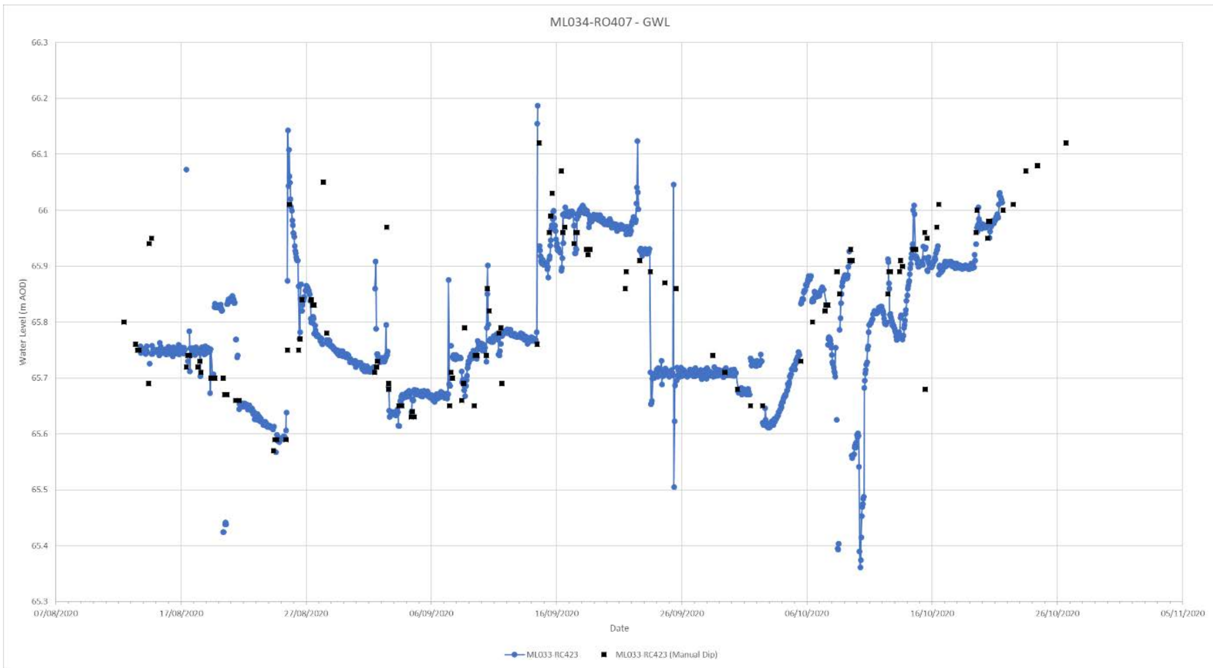

Figure 34 – Water level variations in RO407 during d-walling

2.5.8 The water level data from the data logger in RD400 deep is shown in Figure 35. The step change in water level on 16 September is currently being evaluated to determine the cause, but it is anticipated to be an anomaly rather than real data. Prior to this there is only one significant change in water level and that is on the 25 August at 13:00, exactly coincident with a change at RO407, even though RO407 is screened from 42 to 67mbgl and RD400 deep is from 76 to 86mbgl. However, the water level in RD400 is showing a seasonal recession, albeit with a slight rise at the beginning of September and the water level changes are not quite as "spikey" as at RO407. The change in water level in RD400 on 25 August is coincident with the first significant loss of bentonite from Panel 1, and as at RO407, there is a secondary peak on 27 August. This is unusual given that RD400 and RO407 are not close to one another nor are they screened to the same depth, with the top of the screen at RD400 being 10m deeper than the base of the screen at RO407. The water level readings generally show a c.0.3m difference between the two locations at the start of the period increasing to 1m at the end of September, with RD400 always being lower.

2.5.9 The meaning of these changes in water levels is not obvious but does suggest a hydraulic connection or the result of hydraulic loading from the bentonite being transmitted vertically downward through the aquifer.

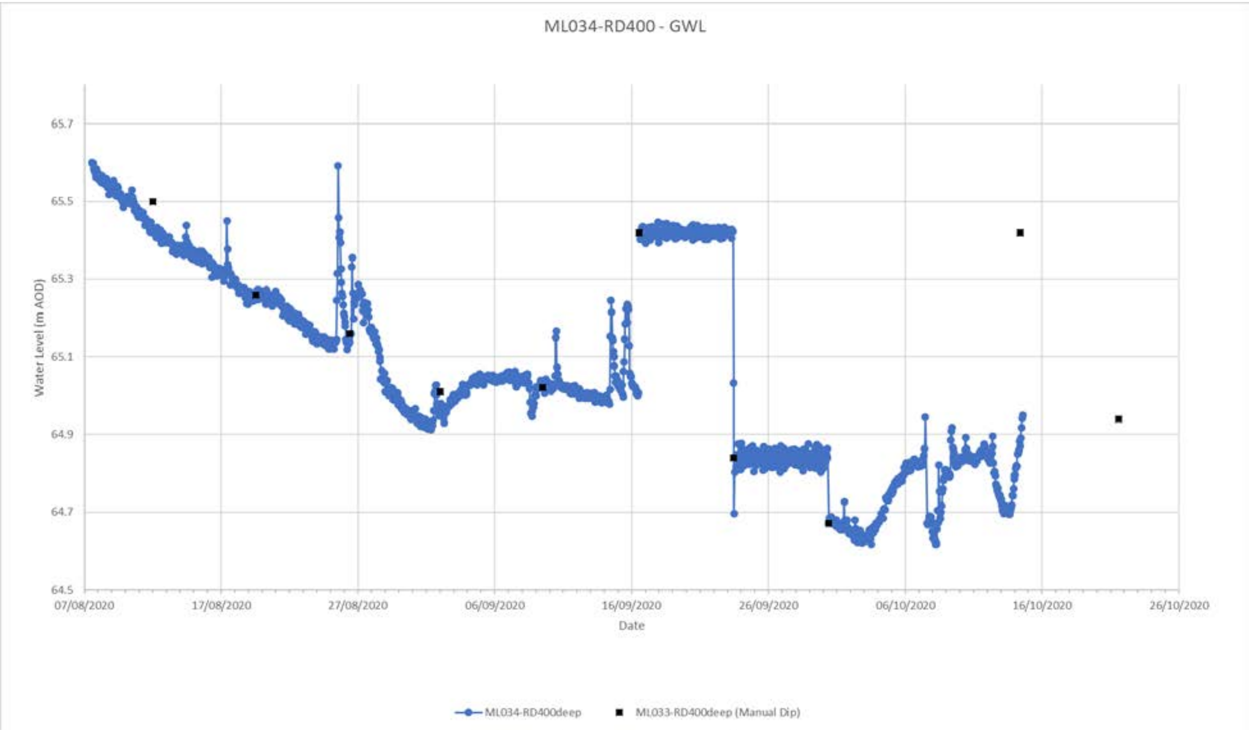

Figure 35 – Water level variations in RD400 during d-walling

3 Explanation of the bentonite losses

3.1 Geology overview

3.1.1 The D-walls are sunk into the chalk and go through different formations, from top to bottom:

- Superficials;
- Seaford Chalk Formation;
- Lewes Nodular Chalk Formation; and
- New Pit Chalk Formation.

3.2 Analysis of the GI data in the light of the bentonite losses

3.2.1 No voiding was encountered in any of the Geotechnical Investigation drill holes (section 1.3).

3.2.2 The interpreted ground model shows competent and good chalk from 35mbgl, hence no issues with regards to bentonite loss were identified prior to starting excavation.

3.2.3 Cross hole seismic data between ML034-RD427 and ML034-CR424 shows that the shear, bulk and young’s modulus all increase at 40mbgl (Figure 36). This indicates an increase in the ground stiffness and correlates well with the log and data from the surrounding boreholes.

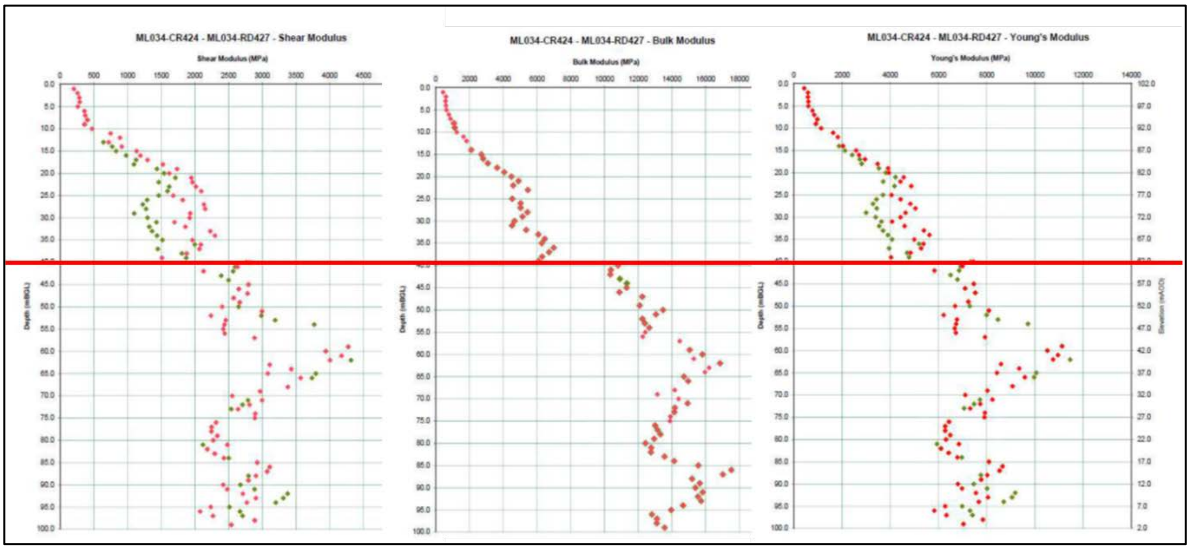

Figure 36 - Cross hole seismic between ML034-RD417 and ML034-CR424

3.2.4 From 30 to 40mbgl the logs as well as the geophysics undertaken in the boreholes indicates fractured ground with opened fractures as shown in Figure 37. The maximum aperture of the fractures estimated from the televiewer is around 50mm. The caliper performed in the abstraction well (ML034-RO404) used to perform the pumping test also shows fracturing around 40mbgl as shown in Figure 38. These fractures were not considered to be a major issue for diaphragm wall excavation and are consistent with the baseline statement within the GBR.

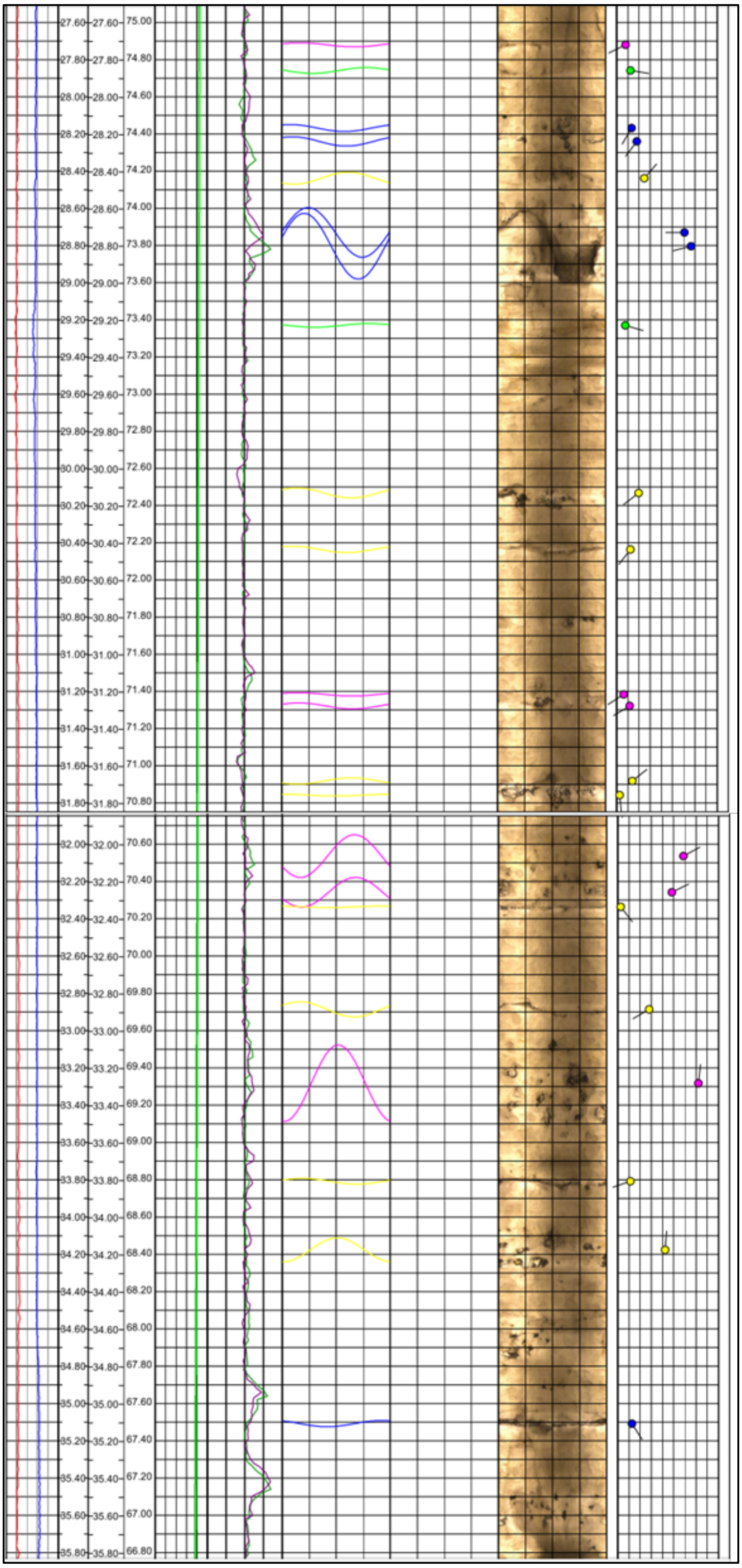

Figure 37 - ML034-RD427 Optical televiewer and caliper extract

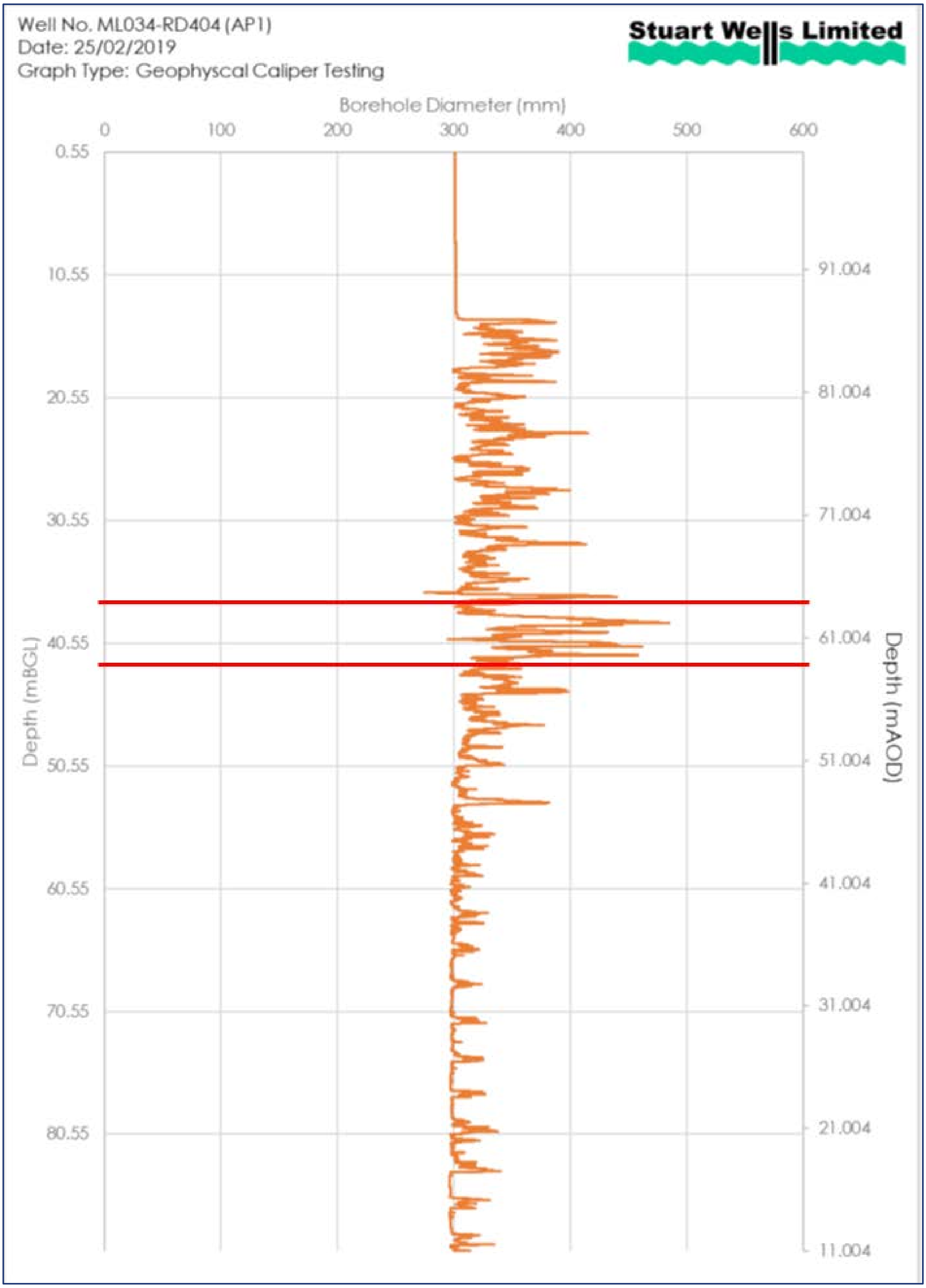

Figure 38 - Caliper result in abstraction well ML034-RO404

3.2.5 From 47m to 64mbgl, it has been noted that hardgrounds are present in the Lewes Nodular Chalk formation (Chalk Rock Member). These are identified in the cores, where the Total Core Recovery (TCR) is decreasing due to the contrast in strength between the hardgrounds and the interwoven marls. These marls can potentially be washed out, leaving open fractures with a good hydraulic connectivity. This was not a consideration prior to commencement of the works, based upon the available information.

3.2.6 The hardgrounds were also identified in the geophysics as shown in Figure 39.

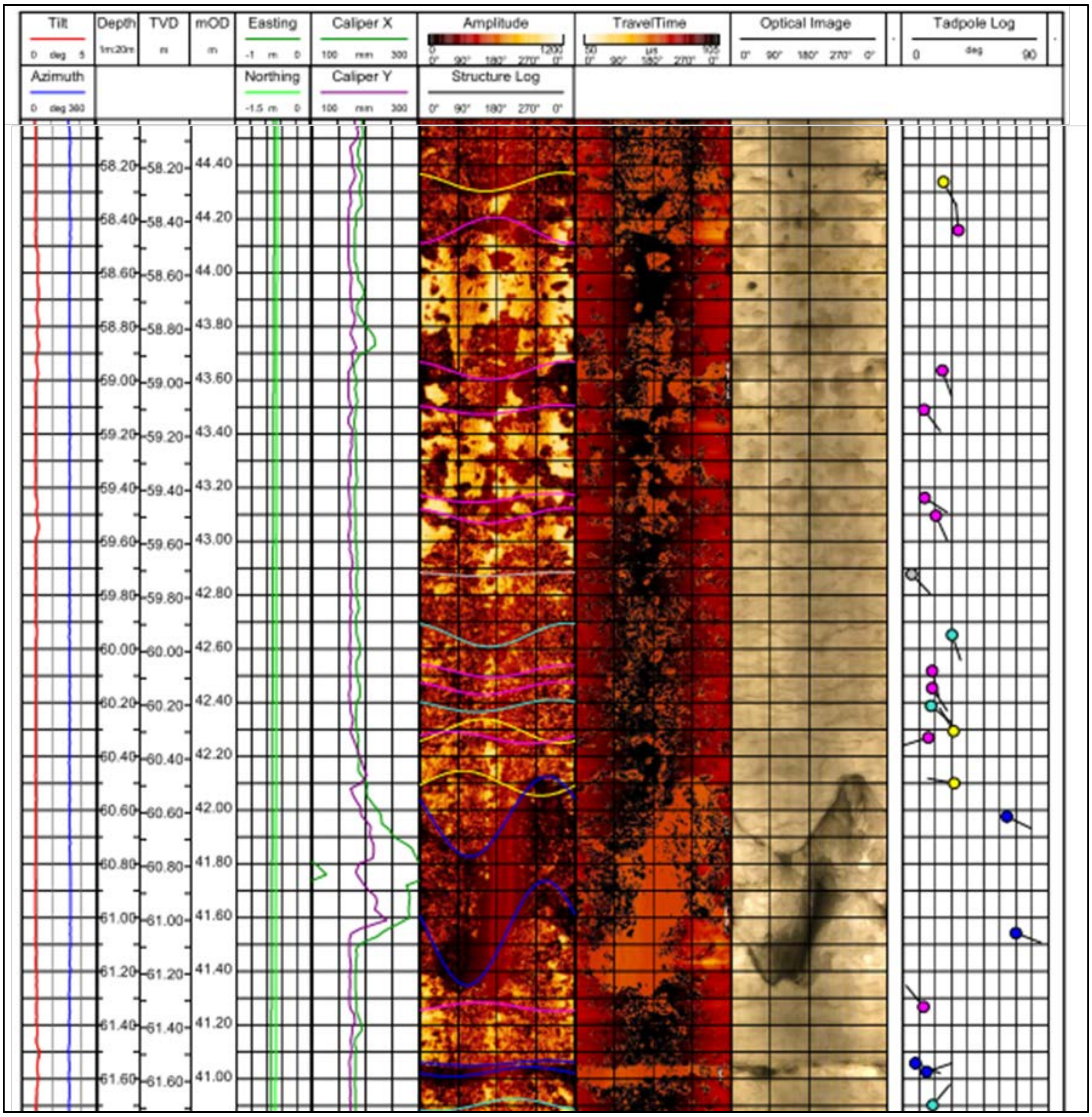

Figure 39 - Extract of the Acoustic televiewer for ML034-RD427

3.2.7 These hardgrounds can contain animal burrows dug as the chalk was depositing. These networks of burrows are preferentially dissolved, leaving an extensive and well connected infilled network as shown in Figure 40. It is likely that the burrow network infilling has been washed out through the action of the hydrofraise, due not only to the mechanical action of the cutter but also the suction pump operating at 400m^3/hr at the bottom of the trench. This can flush out the fines in the hard grounds, opening new apertures.

Figure 40 - Extract from *Logging The Chalk* from R. Mortimore showing dissolved burrows in chalk hardground

3.2.8 This network of burrows was not indicated in any of the drill holes, and their presence has been inferred as a result of the slurry loss. Therefore, this was not given any consideration prior to commencement of the works.

3.3 Hydrogeological interpretation

3.3.1 Rising and falling permeability tests have been undertaken in the area and all of them yielded results between 0.07 and 0.3 m/d associated with response zones ranging from 45 to 88mbgl. A pumping test was completed with well screen at 76 to 88mbgl and the interpreted permeability was the same ranging from 0.07 to 0.3m/d (albeit from a range of analyses in one borehole). No significant voids were encountered during drilling of the pumping test borehole but a well fractured zone was identified between 35 and 45mbgl (Figure 38).

3.3.2 At the start of diaphragm wall excavation, the water table was at a depth of about 35mbgl which meant that there was 35m head of bentonite at the water table. The bentonite slurry has a density of around 1.02 when fresh increasing to 1.1 when used. In all likelihood the gelling properties of the bentonite, which are due to electromagnetic charges between the clay particles, were sufficient to prevent substantial bentonite losses at shallow depths and across very fine fractures and fissures. However, when a critical situation was reached associated with a combination of hydraulic head and fracture / fissure width the gelling properties of the bentonite were overcome resulting in a loss of bentonite mud from the d-wall trench. In the case of Panel 1 this happened at just over 40m depth, whilst in Panel 9 it occurred at 30m depth. Post ground treatment it tended to happen a little deeper at 49m in Panel 11 and 50m in Panel 3 and the amount of bentonite lost was significantly reduced.

3.3.3 As the loss of bentonite was driven by 35m of head in the unsaturated zone its direction of movement was not controlled by the groundwater hydraulic gradient but by the orientation of fractures and fissures. With the exception of closing panels which are constrained on either side, bentonite movement could readily occur in 360° around the d-wall trench if the fractures were orientated such. Insofar as the location of the monitoring boreholes allows assessment, the bentonite moved more across the hydraulic gradient than down it. It is recognised that the location of a monitoring borehole and the depth of the well screen can significantly constrain interpretation of groundwater (and in this case bentonite slurry) movement.

3.3.4 The initial loss of bentonite could have been turbulent, driven by the high hydraulic head and continual excavation of bentonite topping up in the trench. However, once this had ceased the low hydraulic gradient in the area and relatively small size of the factures and fissures would mean a return to laminar flow. The combination of the loss of the bentonite driving head, low hydraulic gradient, laminar flow, small fractures and fissures and gelling properties of undisturbed bentonite would likely result in it remaining *in situ* in fractures and fissures in the area around the shaft. Subsequent movement could occur as further panels are excavated and the bentonite head is in place once more, but only if the new panels penetrate the same fracture or fissure system as previous panels. This is likely at Chalfont St Peter shaft at about 30 to 40mbgl, although some bentonite would have been forced into blind / unconnected fractures and fissures and it will remain in these.

3.3.5 Some 1600m^3 of bentonite has been lost to ground from Panels 1 and 9. With regard to the potential distance that the lost bentonite has moved an order of magnitude assessment has been carried out to give a possible indication of the distance the bentonite has travelled. It is recognised that there are short comings in this assessment but it at least provides a guide to the possible distance travelled. It is based on the following:

- Thickness of the zone where bentonite has been lost into fractures and fissures of 5m.
- Chalk porosity of 0.05%, 1% or 3%.
- Bentonite migration through 180° or 360° around the d-wall panel.

3.3.6 With a porosity of 3% and losses in 360° the bentonite could all be contained within a distance of just under 60m from the shaft, increasing to around 100m with 1% porosity. If the losses are confined to fractures or fissures along dominant directions then assuming 180° migration and 1% porosity the bentonite could all be contained within about 140m of the shaft, increasing to some 640m with 0.05% porosity.

3.3.7 This does of course assume that all fractures and fissures within a 5m aquifer thickness are bentonite filled. The monitoring at RO407 and RO408 does not show ongoing effects on turbidity or pH, although these boreholes are screened through 25m of saturated zone (from 42 to 67mbgl) so there remains 20m of aquifer available for water movement if 5m is blocked by bentonite. No ongoing effect on water quality has been detected in boreholes RO407 and RO408, although this may be due to the low groundwater velocity achieved during purging and sampling being insufficient to mobilise gelled bentonite in fractures and fissures, particularly when there are open fractures and fissures to allow water movement into the borehole around any blocked fractures and fissures. This notwithstanding, water level data from RO407 does indicate a change in local groundwater levels.

3.3.8 These order of magnitude estimates suggest that the bentonite slurry could be easily contained within an area of 500m around the shaft in a 5m thick zone of rock and likely much less as 0.05% effective porosity is extremely low even in interfluve areas. The full active thickness of the saturated zone could be around 35m at this location assuming that the pumping test data from the shaft location is representative as this indicated a very low permeability at 76 to 88mbgl (i.e. over 35m below water table). This means that there remains a reasonable thickness of unaffected aquifer for water to be re-routed around any blocked fractures.

3.3.9 In all cases when the concrete was poured after construction of each d-wall panel the concrete take was very close to the theoretical volume of the excavation. This indicates little if any penetration of concrete into the aquifer which supports the assertion that there is no significant voiding in the aquifer at the shaft location. Unlike the bentonite slurry the concrete is too viscous and the particle size too large to penetrate the fine fractures and fissures that the bentonite has entered.

3.3.10 Once d-walling progresses beyond a certain point the bentonite losses are likely to reduce irrespective of ground treatment. This is due to a combination of factors, including the fact that closing panels will be constrained on either side by completed panels and as the d-wall nears completion any bentonite loss into the shaft area will be constrained by panels on the opposite side of the shaft.

3.4 Potential for remobilisation of lost bentonite slurry

3.4.1 The assessment above suggests that the bentonite slurry moves out of the d-wall panel being excavated and into fractures and fissures due to the very high hydraulic head resulting from the thick unsaturated zone. Once the head is removed due to concrete pouring the bentonite does not move significantly as evidenced by the water quality data. The bentonite remains in fine fractures and fissures in the Chalk.

3.4.2 The hydrogeology of the Chalk is characterised by diffuse recharge, fracture flow and high storage. The overall effect of this is a hydrogeological system with a relatively slow response to rainfall in comparison to many truly karstified aquifers. This is not to say that in some areas of the Chalk there is not concentrated recharge through stream sinks and that the water then flows rapidly through solutionally developed conduits, but this is not the norm in the area around Chalfont St Peter shaft.

3.4.3 Although voids can be present beneath interfluve areas such as at the shaft location they tend not to be as well connected as they are beneath valleys and rapid groundwater movement is the exception rather than the norm. This is reflected in groundwater fluctuations which tend to show gradual long term rises and falls rather than large sudden large increases in level. Although spikes can occur they tend to be fairly small (<0.5m) and steep hydraulic gradients generally tend not to develop although it is recognised that there are local variations. The effect of this is that once bentonite slurry enters fine fractures and fissures it will tend to gel and not migrate.

3.4.4 There is a risk that as the effects of climate change become larger these have a greater effect on water level changes in the Chalk such that dormant bentonite could be sufficiently agitated to be remobilised and migrate. It is not possible to accurately forecast how much water levels will change but in general it is likely that winters in South East England will become wetter and summers will become drier such that the rate of water level change from one period to the next will increase thereby steepening hydraulic gradients. An assessment of the effects of climate change has been made by Align (Methodology for estimating the 120yr + climate change groundwater levels along the Chiltern Tunnel (doc ref 1MC05-ALJ-EN-NOT-CS02_CL04-410020). This report assessed various models of climate change predictions and suggested a long term increase in winter rainfall of some 22%.

3.4.5 In addition to an increase in winter rainfall volume it is more likely that the rainstorms will become more intense such that a larger volume of rain falls in a shorter period of time. However, it is often the case that more intense rainstorms result in greater proportion of surface runoff so that although recharge to groundwater will increase, it will not increase in the same proportion as the total rainfall.

3.4.6 At Chalfont St Peter shaft there is a thick unsaturated zone that includes relatively low permeability superficial deposits and clay like weathered chalk and rapid recharge routes have not been identified. The combination of these is such that recharge to groundwater will remain relatively slow even if there is an overall increase in rainfall and an increase in rainfall intensity. Under this conceptual model the potential for climate change to cause sufficiently rapid groundwater level fluctuations to induce turbulent flow and remobilise bentonite slurry in fine fractures and fissures is very low. It is therefore highly likely that bentonite that is present in fractures and fissures around the shaft will remain and not be transmitted through the aquifer.

4 Conclusions and recommendations

4.1 Conclusions

4.1.1 The very high head of bentonite slurry through the unsaturated zone is a key reason for the bentonite losses during d-wall excavation. The losses do not occur until at least 30m depth at which point it is likely that the head overcomes the gelling properties of the bentonite across the openings of the fractures and fissures and results in a release of slurry into the aquifer.

4.1.2 The spacing and aperture of the fractures previously identified in the geotechnical investigation may not be sufficient to account for all of the slurry loss that occurred during excavation of the diaphragm wall panels P1 and P9. The fractures are relatively small (<50mm max, <3mm in average) and well-spaced (spacing > 600mm below 35mbgl). These have been described as filled with clayey materials, which therefore reduces permeability. The gradual manner of the bentonite loss indicates that this is likely due to the presence of open fractures and potentially burrow networks across the extensive hardground. This new information is inconsistent with the previous GI undertaken prior to commencement of the works.

4.1.3 The action of the hydrofraise may have contributed to the washing out of fines and infilling material within the fractures and burrow networks, causing a localised increase of permeability that can account for some of the loss of slurry. This was not a consideration prior to commencement of the works based upon the available information.

4.1.4 The bentonite lost during excavation of Panels 1 and 9 was detected in two monitoring boreholes within 35m of the shaft with significant effects on pH, turbidity and other water quality parameters. Water level changes due to d-walling were identified in two or possibly three monitoring boreholes. No significant effect was detected on dissolved aluminium concentrations due to leaching from bentonite slurry, although minor changes were identified. Significant concentrations of total aluminium were detected associated with bentonite in suspension and away from the d-wall there is a correlation between the total aluminium concentration and turbidity.

4.1.5 Given the amount of the bentonite lost, the local hydrogeology and the behaviour of bentonite it is likely that the bentonite remains within an area around the shaft with a maximum of some 500m radius. This bentonite is unlikely to move further unless it is caused by disturbance associated with further d-wall excavation or head changes induced by high hydraulic heads from bentonite slurry at panels yet to be constructed.

4.1.6 Ground treatment has resulted in a significant reduction of bentonite slurry loss during d-wall panel excavation. However, large losses of bentonite still occur including during weekends when planning permission restricts working. Excavated panels that remain open at depths greater than 30m over a weekend can result in bentonite losses of up to $100m^3$. However, this volume of loss is markedly reduced where the panel that is left open over a weekend is a closing panel as the potential area for loss is more constrained (e.g. Panel 16 which was completed at the time of writing only suffered losses of $18m^3$ over the weekend). It is possible, though not proven, that ground treatment has limited effect on bentonite losses at closing panels.

4.1.7 As bentonite losses occur over weekends when d-wall panels are open to depths greater than 30m wherever practicable working patterns are timed to avoid large open trenches at these times. However, Align is constrained from stopping such losses completely as:

- weekend working is prevented by planning permission;
- stopping excavation early on a Friday when a d-wall panel would progress to below 30m is not practicable due to the very high standing costs of plant and equipment and the impacts on programme; and
- pumping a lean concrete mix into the base of the excavation on a Friday would impact on programme (time taken to install and then remove concrete), cost (concrete supply and cost of delays) and sustainability (carbon impact and generation of additional waste).

4.1.8 Losses of concrete are minimal during d-wall construction as the concrete is too coarse and viscous to penetrate significantly into fractures and fissures.

4.2 Recommendations

4.2.1 To limit further losses of bentonite into the ground for environmental reasons as well as operational reasons pre-treatment is being carried out and it is recommended that this is also considered at Amersham and Little Missenden shafts. At Chalfont St Giles ground treatment is already underway to manage the effects of voids identified at that location. However, it is recognised that the Chalfont St Peter shaft location is where the highest bentonite slurry head is present due to a thick unsaturated zone.

4.2.2 Future drilling for ground treatment should be outside of the d-wall alignment to prevent the risk of delays caused by lost tools.