Fontmell Close Sinkhole

St Albans

Transition Zone Investigation Report

For Hertfordshire County Council Highways

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Executive Summary

This executive summary presents the salient points of this specific report only.

This report presents the results of an assessment of the potential magnitude and effects of ground surface settlements in the Public Highway only in the close vicinity of the sinkhole area (termed the Transition Zone), due to the creation of a sinkhole on 1st October 2015 and the subsequent construction of a concrete "plug". It does not address the potential for additional subsidence or settlement of the concrete "plug", (as that is already covered by the PBA 'the Ground Subsidence Investigation report' and referenced 36121/3502 R001/Rev00, March 2016). This report does however offer proposals for highway repair works at Fontmell Close, St Albans, for the zone between the concrete "plug" and adjoining land.

The current assessment indicates mitigation is required in the area around the "plug" in the adjoining highway areas, which include excavation of the existing road and county maintained footway construction either side of the plug and reinstatement of a new road with the inclusion of a ground improvement system.

The conclusions of the report are as follows:

- The effects from the estimated ground settlements caused by the sinkhole and plug construction are considered to be significant, with existing settlements in the order of 35mm observed at the location of the plug, and approximately 20mm in the location of the adjoining Transition Zone.
- At the time of preparation of this report settlements were still occurring.
- Monitoring should be continued to confirm the above, and to allow for early warning of areas where the settlement effects may be greater than that predicted.
- Various options for reinstating the Public Highway are presented for consideration.

1 Introduction

1.1 Project Overview

In the early hours of the 1st October 2015, a large subsidence event resulted in a 12m diameter crown hole ("sinkhole") appearing at Fontmell Close in St Albans, Hertfordshire. The crown hole extended across the full width of the public carriageway including the footpath, and encroached into residential gardens on both sides of the road.

Following evacuation of homes in the immediate vicinity of the 'sinkhole', the emergency response involved backfilling of the resultant void with foamed concrete. It is understood that this has required around 500 cubic metres of concrete. The cul-de-sac estate road known as Fontmell Close has been closed to traffic since the incident of 1st October 2015 and as a result this has also prevented vehicle access onto Bridle Close along this route.

Following the subsidence event of 1st October 2016, Hertfordshire County Council Highways Department (HCC) (the Client) and Opus International Consultants (UK) Ltd (Opus) have undertaken a series of investigations relating to the issues arising from the public highway. In addition HCC and Opus have had sight of additional investigation works undertaken on behalf of HCC and adjacent property owners by Peter Brett Associates (PBA). Factual information relating to the broad issues at the site are included in the following reports:

- Opus prepared a Desk Study Report on behalf of HCC to collate general background information for a wider study area, which included Fontmell Close and Bridle Close (ref: Geo-Environmental Desk Study Report, Fontmell Close, Ariston Fields and Surrounding Area, for Hertfordshire County Council, Report No. G-AP004.Y3.109CO.R1.V1, dated January 2016).

- A geophysical survey was carried out by Geotechnology Ltd in November 2015 on behalf of HCC (ref: Ground Collapse at Fontmell Close, St Albans, Microgravity Report, Report Number 1531r1v1d1015, Geotechnology Limited). The fieldwork comprised microgravity across the full length of the public highway at Fontmell Close and Bridle Close.

- Peter Brett Associates LLP carried out an intrusive investigation at the location of the sinkhole to assess the cause of the sinkhole (ref: 'Ground Subsidence Investigation report' and referenced 36121/3502 R001/Rev00, March 2016). The scope of the works comprised rotary cored boreholes, cable percussion boreholes, dynamic probe holes and trial pits. These intrusive investigations were completed during December 2015 and January 2016.

- Environmental Scientifics Group Ltd (ESG) were commissioned by HCC to carry out an intrusive ground investigation in Fontmell Close (outside the sinkhole area) and Bridle Close with laboratory testing, and produce a Factual Ground Investigation Report (ref: Fontmell Close and Bridle Close, St. Albans, Factual Report on Ground Investigation, Report No. G5519-15, March 2016). The investigation was undertaken to assess the ground conditions across the local highway; the scope of the works comprised rotary cored boreholes, cable percussion boreholes and dynamic probe holes and was undertaken during December 2015 and January 2016

- Opus prepared a ground investigation report (GIR) using the factual information gathered by ESG and Geotechnology. The report was prepared on behalf of HCC to investigate the

potential ground instability beneath the public highway of Fontmell Close and Bridle Close (ref: Report No. G-AP011.Y3.101CO.R0, dated April 2016).

- Geotechnical Engineering Limited prepared a Factual Report (following additional investigation works in the so called 'Transition Zone'. The fieldwork comprised two boreholes, three window sample holes and six dynamic probes (ref: Factual Report on Ground Investigation, Prepared for HCC Report Ref: 31893, 2016).

The Geotechnical Engineering Limited report of 2016 was used primarily in the preparation of the current report where the scope and objectives are described in the following Section 1.2.

1.2 Scope and Objective of this Report

Opus was commissioned by Hertfordshire County Council Highways Department (HCC) to undertake the monitoring of settlement of the ground surface adjacent to the existing sinkhole, referred to as the Transition Zone, and to undertake additional site specific investigation works in this zone. The purpose of the site investigation works was to investigate if significant voids were present within a previously identified microgravity low anomaly to the south west of the concrete plug, and to obtain further parameters of the Made Ground (i.e. thickness and consistency) in the Transition Zone.

The aim of this report is to gain an understanding of the ground surface settlement of the public highway, in order to recommend design the remedial works for the reconstruction of the highway and to further delineate the potential extent of deep "workings" or other voids in chalk beneath the highway.

The proposed methodology was agreed with HCC, based on the technical proposal produced by Opus.

This report presents the results of an assessment of the potential magnitude and effects of ground surface settlements in the Public Highway, due to the creation of a sinkhole on 1st October 2015 and the subsequent construction of a concrete "plug". It does not address the potential for additional subsidence or settlement of the concrete "plug", (as that is already covered by the PBA 'the Ground Subsidence Investigation report' and referenced 36121/3502 R001/Rev00, March 2016). This report does however offer proposals for highway repair works at Fontmell Close, St Albans, for the Transition Zone between the concrete "plug" and adjoining land.

This report has been prepared by Opus International Consultants (UK) Ltd (Opus) with all reasonable skill, care and diligence within the terms of the Contract with The Client (HCC) and taking account of the information made available by The Client, as well as the manpower and resources devoted to it by agreement with The Client. Opus disclaims any responsibility to The Client and others in respect of any matters outside the scope of the above Contract.

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1.3 Report Overview

This report describes the results from the additional ground investigations in the Transition Zone and the settlement monitoring that has been undertaken at the location of the plug and adjoining highway. Specifically, the purpose of this report is to assess potential settlements associated with the ground movements and to propose a monitoring, mitigation and remedial works design for the highway for those effects, where required.

The assessment and reporting predominantly focus on the settlement and its effects of the Transition Zone adjacent to the plug. This report describes the existing environment in which the effects are assessed to take place. It has been based on the results of monitoring undertaken until the 11th May 2016. Monitoring should continue for as long as is reasonably practicable to confirm that the settlement remains within the expected range. Any significant acceleration of settlements should be viewed with concern, and the implications carefully considered in respect of the safety of the highway.

It should be noted that this report does not include any assessment of the stability of, or required remedial works associated with, areas under third party occupation (i.e. the "Transition Zone" as defined, only refers to the Public Highway).

In addition to the questions relating to the rate and quantum of ongoing settlement, the report also addresses the ongoing risk associated with the presence of mine workings beneath the Public Highway.

2 Existing Environment

2.1 Site Location

Fontmell Close is located in the Townsend area of St Albans, approximately 1.5km north-north-east of the centre of St Albans and immediately east of Bernard's Heath.

The site location is shown on the appended Drawing No. MK_G-AP011.Y4.100.

2.2 Site Description

A walkover survey was undertaken on the 28th April 2015. Selected photographs taken during this period are presented in Appendix 'A'. The aim of the walkover and site observations was to provide a description of the site and place the site "in context" within the surrounding area. The comments provided below give a general description of the site and features of relevance in terms of the requirements of this report, in particular potential for ground movement.

The site comprises a public road and footpath, which prior to the 'sinkhole' feature, was accessed off Seymour Road to the north east. Pedestrian access to this area of the site is via a temporary footpath constructed by St Albans Council, the footpath started at the end of Bridle Close and crosses an area of open access land joining an existing footpath off Sandridge Road to the south east of the site.

For the purpose of this report the site has been spilt into four areas and these are defined below:

1) The area comprising the infilled concrete collapse itself. This is defined by the presence of the concrete "plug" placed as an emergency response to the events of October 2015.

2) The "Transition Zone" of disturbed ground immediately around the "plug". This area has been described informally as comprising a "doughnut" around the "plug" and may be referred to as such in general discussion. Part of the scope of the additional investigation is to establish the spatial extent of the "Transition Zone", as it affects the Public Highway.

3) Fontmell East comprises the land to the east of the "plug" and "Transition Zone" that is unaffected by significant past or ongoing settlement arising from the impact of the events of October 2015.

4) Fontmell West comprises the land to the west of the "plug" and "Transition Zone" that is unaffected by significant past or ongoing settlement arising from the impact of the events of October 2015.

The Site Layout Plan (Drawing Ref: MK_G-AP011.Y4.101) shows the locations of these areas. A further drawing (MK_G-AP011.Y4.102) shows the positions of the all exploratory holes carried out during the current, as well as previous investigations in the immediate vicinity.

2.3 Ground Conditions

According to the inspected published geological information (British Geological Survey 1978) superficial Glacial Gravel occurs across the site. Beneath these the Reading Beds (mottled clay, sand and pebbles) are recorded to be unconformably lying on the Upper Chalk.

More recent publications (British Geological Survey 2015) employ updated nomenclature. The superficial Glacial Gravel deposits are now referred to as the Kesgrave Catchment Supergroup, the Reading Beds have been subsumed into the Lambeth Group and the Upper Chalk has been renamed as the White Chalk Supergroup. The White Chalk Supergroup has also been split into individual formations. The formations shown to be present beneath the site are the Seaford Chalk Formation and Lewes Nodular Chalk Formation (Hopson 2005).

The Kesgrave Catchment Supergroup, which lies unconformably on the Lambeth Group, commonly comprises yellow brown massively bedded silt to clay, fluvial gravel aggradations with sedimentary structures, lacustrine silts and clays with uncommon organics.

The Lambeth Group comprises vertically and laterally variable sequences mainly of clay, some silty or sandy with some sands and gravels, minor limestones and lignites with occasional sandstone and conglomerate (British Geological Survey 2016).

The Seaford Chalk Formation, which lies unconformably below the Lambeth Group, consists of firm white chalk with conspicuous semi-continuous nodular and tabular flint seams, some flint nodules are large to very large (CIRIA 2002). There are numerous beds within this formation.

The Lewes Nodular Chalk Formation, which lies conformably below the Seaford Chalk formation is composed of hard to very hard nodular chalks with interbedded soft to medium hard chalks (some grainy) and marls with regular seams of nodular chalks throughout. Nodular chalks are typically lumpy and iron stained (Hopson 2005). This formation also contain numerous identifiable beds.

Further detail of the above stratigraphy is presented in the Opus GIR (Report No. G-AP011.Y3.101CO.R0, dated May 2016).

Based on previous investigations, Made Ground is commonly found in the nearby area as a result of historic backfilling of clay pits. In some places the Lambeth Group was not present and the White Chalk was found to be closer to the surface. The depth to the top surface of the White Chalk was between 6m bgl and 38m bgl indicating that the top of the chalk varied significantly.

Made Ground comprised both cohesive and granular material. Cohesive material was found below Fontmell East and Fontmell West, and was present to depths of 6.0m bgl and 5.50m bgl respectively. The Cohesive Made Ground generally comprised soft to firm, brown or grey sandy gravelly clay with cobbles. The gravel consisted of fine to coarse, angular to rounded flint, brick, chalk, clinker, macadam and concrete. Cobbles are angular to sub angular brick. SPT 'N' values revealed corrected 'N' values in the range of 3 to 23 indicating a very soft to firm consistency cohesive strata. It was noted that the SPT results generally increase with depth.

Granular Made Ground was only found below Fontmell West and to a maximum depth of 1.90m bgl in BH102. The material generally comprised light greyish brown to black clayey silty sandy gravel with cobbles. Gravel is angular to rounded flint brick and concrete. Cobbles are angular brick. The SPT 'N' values revealed corrected 'N' value of 5 indicating a loose consistency granular strata.

All previous exploratory holes in Fontmell West and Fontmell East encountered a concrete layer of approximately 0.2m thick underlying a 0.1m thick asphalt surface layer.

2.4 Road Construction

The highway construction along Fontmell Close comprises a mixture of concrete and asphalt surface road pavement, with a typical thickness in the order of 200mm. The road pavement is underlain by a 400mm thick sub-base directly founded on the underlying natural superficial and made ground deposits (re-worked superficial materials).

2.5 Services

The highway alignment along Fontmell Close is understood to have the following services networks associated with it:

- Foul sewers– brick, concrete, vitrified clay;
- Storm water surface drainage (running directly beneath the highway)– Concrete;
- Water mains (running beneath the footpath) – Cement-lined steel, steel, polyethylene (PE);
- Gas (running beneath the footpath and crossing the highway at 9 Fontmell Close) – PE, steel;
- Cable Television (running beneath the footpath); - cable in PVC/PE duct
- BT Communications (running beneath the footpath and crossing the highway at 7 Fontmell Close) – cable in PVC/PE duct;
- Electricity (running directly beneath the footpath) – direct buried cable, cable in PVC/PE duct;
- HV Electricity (running directly beneath the footpath and crossing the highway at 11 Fontmell Close) –cable in PVC/PE duct.

Due to the sinkhole damage to the highway and footpath, a number of services including Electricity, BT, Gas and Water have been temporarily diverted above ground within the plug area to enable residents to be connected to the services.

These networks are primarily located within the footpath and highway of Fontmell Close. Some of these are anticipated to be over 40 years old and likely to be of varying condition.

An overall service plan has been prepared based on as-built information received and a topographical survey and is presented within the PBA report referenced 36121/3502 R001/Rev00, March 2016.

3 Additional Investigation Works

Additional ground investigation works have been carried out within the "Transition Zone" area. The investigation was undertaken for the purpose of assessing the shallow made ground and superficial deposits and the potential for voids within the Lewes Nodular Chalk at depth across the transition zone area. The investigation works comprised a combination of dynamic sampling, rotary open hole drilling, window sample holes and dynamic cone penetration tests. The investigation fieldwork was undertaken by Geotechnical Engineering Limited during April 2016 and is fully described in their report (Geotechnical Engineering Ltd 2016) enclosed as Appendix B.

This information has been used in conjunction with relevant geotechnical factual information obtained to date, in order to design the remedial works for the reinstatement of the highway at the location of the sinkhole concrete plug and adjoining areas.

3.1 Dynamic Probe Testing

Six Dynamic Probe Super Heavy (DPSH) tests were undertaken within the immediate area surrounding the sinkhole concrete plug (DP401 – DP406). The results of dynamic probe testing are shown as a composite plot of N_{100} versus Depth (see Figure C.1) in Appendix C.

From the results of the Dynamic Probing it is possible to extrapolate the general strength properties of the ground beneath the site. This classification requires the equivalent SPT 'N' blow counts to be derived from the dynamic probe tests, and this was completed by adding three consecutive results to give the blows per 300mm, to give an approximate equivalent N_{300} value deemed tentatively equivalent to the SPT 'N' value. These were in turn used to calculate the N_{60} value which is used to infer the strength of cohesive soils using the relationship suggested in Stroud (1974).

The plot shows N_{100} values in the range 0-1 to depths of between 4m and 7m below ground level. These values have been taken to be broadly equivalent to very loose relative density (granular materials) or very soft consistency (cohesive materials).

3.2 Dynamic Sampling and Rotary Open Hole Drilling

Two boreholes (CH401 and CH402) were drilled at the site to a depth of 45m below ground level to obtain further detailed information on the deeper ground conditions and to assess the potential for voids within the transition zone.

Borehole CH401 was advanced by rotary open-hole drilling techniques utilising an air-mist flushing medium. Borehole CH402 was advanced using heavy duty dynamic sampling techniques to produce a continuous disturbed sample as the borehole was advanced, and was continued by rotary open-hole drilling techniques utilising an air-mist flushing medium. The engineering logs and details of the exact locations are included in the drilling contractor's factual report (Geotechnical Engineering 2016) enclosed as Appendix B.

A graphical plot showing the variation of the SPT N value recorded in the made ground deposits with depth (in borehole CH402) is presented within Figure D1 in Appendix D. A full description of the SPT N values obtained in the made ground is detailed in Section 7.4.

3.3 Window Sample Holes

Four window sample holes were drilled at the site to obtain further information on shallow ground conditions (WS401, WS402, WS403, and WS403A). Dynamic sampling techniques were employed within the window sample holes to produce a continuous disturbed sample Further details are included in the contractor's factual report (Geotechnical Engineering 2016) enclosed as Appendix B.

SPT was also undertaken within the window sample holes, and the SPT N values obtained from these holes have been combined with the N values obtained from the dynamic sampling borehole (CH402) as presented in Figure D1 in Appendix D.

3.4 Contamination Testing

Eight selected soil samples were despatched to i2 Analytical Limited by Geotechnical Engineering, where chemical analyses were carried out to in-house methods for a suite of contaminants comprising asbestos, pH, sulphate, cyanide, sulphide, phenols, speciated PAHs and heavy metals. Waste Acceptance Criteria and Soil Organic Matter testing was also carried out. The results are presented in Appendix B of the Geotechnical Engineering factual report and discussed in Section 6.2.

3.5 Desk Study Detail

The site of the collapse, the surrounding Transition Zone and the undisturbed ground surrounding that, relate to the location of a specific recorded clay pit visible on historical mapping as shown in Figure 3.1. This is associated with both a *Limekiln* and a *Brickkiln*, apparently confirming that both clay and chalk were excavated from this pit.

The form of the excavated pit (at its maximum extent) will be reflected by the current thickness and disposition of Made Ground beneath the ground surface. This is also evident in the contoured plan showing the depth of overburden material from which an estimate of the location of the former quarry high wall can be made, as shown on drawing No. MK_G-AP011.Y4.103.

4 Description and Methodology of Settlement Monitoring

4.1 Methodology

Monitoring has been undertaken by three separate survey companies to date. Geotechnology commenced with the first survey from 10 October 2015 to 14 November 2015, Gryphon Surveys continued with monitoring from 3 December 2015 to 23 February 2016 and Tower Surveys has been monitoring from 5 April 2016 and are currently continuing with the monitoring.

All sets of data have generally been obtained using similar methods comprising the installation of Monitoring Points at surface level, taking an initial set of baseline readings relative to Ordnance Datum. Subsequent repeated monitoring visits then compare levels with the previously established monitoring data.

In total, forty one (41No.) monitoring points have been established in order to monitor and assess the potential on-going settlement of the concrete plug, Transition Zone and the adjoining Fontmell Close highway, footpath and residential gardens adjacent to the concrete plug. The locations of the monitoring points are presented on the site layout plan (drawing MK_G-AP011.Y4.101, Rev0). Some of the points were destroyed or lost and were re-established with the suffix "A" added to the point reference number. A few points were lost and never re-established, while some points were obstructed during one visit, and visible again the next visit. Table 4.1 presents the co-ordinates and initial levels, where these are available, of the monitoring points.

The initial monitoring, which was carried out by Geotechnology between 9th October and 14th November 2015, was commissioned by HCC. The primary objective of this exercise was to confirm the immediate stability of the ground to allow the geophysical survey contractor to undertake his work with a reasonable level of confidence that the ground would not collapse beneath the survey team. A TopCon QS Robotic total station was used in conjunction with a pole mounted reflector to measure points MP1 – MP17 over eight repeat visits. Digital level equipment was not available at the time. All measurements was taken relative to MP1, which was on the other side of the furthest observable crack in the road. The absolute level of MP1 was not precisely determined. It was related back to Geotechnology's gravity control stations using the QS Robotic total station. The gravity positions were related to a survey station put in with a network rover.

The subsequent monitoring phase during 3rd December 2015 to 23rd February 2016 was undertaken by Gryphon Surveys under instruction from Subsidence Management Services to undertake distortion surveys and level monitoring of 8, 9 & 11 Fontmell, as well as the level monitoring of the road/concrete plug on a weekly basis. Some of the Monitoring Points were destroyed or lost and re-established. A Leica Sprinter 250m Digital level was used to record level data. The quoted accuracy for this instrument from Leica per 1km double run is 0.7mm, and given other factors Gryphon quote their readings to +/-1.0mm. The initial value for MP1 of 122.1590 is believed to have been provided by PBA when Gryphon took over the monitoring on 3rd December 2015. MP1 was assumed the stable point throughout the monitoring, as defined by the previous readings and incorporated in the Gryphon data set.

Table 4.1 Monitoring Point Locations

Pin ID	Location	Easting	Northing	Original Elevation
MP1	Fontmell West	515436.118	208430.993	122.159
MP2	Fontmell West	515436.617	208430.364	122.138
MP3	Fontmell West	515440.207	208425.888	121.990
MP4	Fontmell West	515443.626	208425.224	122.090
MP5	Fontmell West	515444.245	208425.293	122.104
MP112	Fontmell West	515449.754	208431.094	122.140
MP113	Fontmell West	515447.367	208432.882	122.147
MP114	Fontmell West	515441.443	208429.485	122.067
MP115	Fontmell West	515445.909	208428.819	122.071
MP118	Fontmell West	515431.708	208433.484	122.110
MP6	Sink hole 'doughnut'	515450.083	208424.622	122.016
MP7	Sink hole 'doughnut'	515450.980	208428.573	122.100
MP8	Sink hole 'doughnut'	515464.919	208428.514	121.867
MP9	Sink hole 'doughnut'	515465.029	208419.719	122.085
MP10	Sink hole 'doughnut'	515447.685	208417.115	122.512
MP11	Sink hole 'doughnut'	515453.834	208413.280	122.713
MP116	Sink hole 'doughnut'	515447.277	208421.307	122.033
MP117	Sink hole 'doughnut'	515447.999	208421.273	121.988
MP14	Sink hole plug	515453.494	208421.919	121.141
MP14A	Sink hole plug			121.178
MP15	Sink hole plug	515458.190	208425.485	121.149
MP15A	Sink hole plug			121.107
MP16	Sink hole plug	515460.811	208422.758	121.237
MP17	Sink hole plug	515456.753	208419.138	121.223
MP100	Sink hole plug			121.108
MP101	Sink hole plug	515455.883	208427.528	121.090
MP102	Sink hole plug	515455.354	208424.673	121.085
MP103	Sink hole plug	515453.881	208421.508	121.075
MP104	Sink hole plug	515455.475	208418.627	121.120
MP105	Sink hole plug	515457.271	208422.014	121.168
MP106	Sink hole plug	515457.722	208424.677	121.154
MP107	Sink hole plug	515459.781	208425.955	121.240
MP108	Sink hole plug	515461.729	208420.762	121.206
MP109	Sink hole plug	515458.697	208420.417	121.178
MP12	Fontmell East	515463.687	208432.092	121.940
MP13	Fontmell East	515469.370	208426.995	121.893
MP13A	Fontmell East			121.897
MP110	Fontmell East	515465.541	208428.839	121.818
MP111	Fontmell East	515471.335	208432.515	121.760

The ongoing monitoring by Tower Surveys, which started on 5 April 2016 and is currently on-going, was commissioned by HCC. All available monitoring points from MP1 to MP17 were used where available, and additional 19 monitoring points MP100 – MP118 added. Monitoring points MP R1 to R5 were positioned around a drilling rig at borehole CH402 and was only monitored during drilling. Since a digital level was not available at the time a S8 Total Station was used for the first two readings, a S7 Total Station for the next one, and a digital level thereafter. Data obtained by Tower Surveys used a base point further to the west at STN/3.

A summary of the three survey phases is provided in Table 4.2. The data and graphs are presented in Appendix E.

Table 4.2 Summary of Monitoring Surveys

Survey period	10/10/'15 to 14/11/'15	3/12/'15 to 23/02/'16	05/04/2016 to 11/05/2016
Surveyor	Geotechnology	Gryphon Surveys	Tower Surveys
Client	HCC	Subsidence Management Services	HCC
Number of readings	8	12	6
Data points surveyed	MP1 – MP17	MP1 - MP12, MP14, MP13A, MP14A, MP15A, MP16 - MP17	MP1 - MP4, MP7 - MP12, MP16, MP101 - MP118
Survey equipment used	10/10/'15 to 14/11/'15: TopCon QS Robotic total station with pole mounted reflector	3/12/'15 - 23/02/2016: Leica Sprinter 250m Digital level	05/04/'16 to 12/04/'16: S8 Total Station 19/04/'16: S7 Total Station 26/04/'16 to 11/05/'16: Digital Level
Base point	MP1	MP1	STN/3

Unfortunately due to site access restrictions, loss during site works, and variations in approaches between the survey methodologies, the three sets of monitoring data are not directly comparable. Since the full data set from all three survey companies relates to two different datum points and Total Stations related to OS/ MAPOD with tolerances of such machines 30-40mm vertically, there is an apparent 40-45mm data gap between Gryphon Surveys and Tower Surveys data sets.

In order to use the monitoring data at all of the monitoring points, we have assumed the continuation of the data and hence corrected the 45mm difference across the monitoring data and adopted this "jump" at the locations where this is evident in order to gain a full assessment of the on-going settlement. The importance in the data is however not just the measured levels at a specific juncture (with an assigned value), but more importantly the rate of change.

With respect to the potential for given reasonably uninterrupted monitoring throughout the period, only the following data points have proven to be suitable for both:

Plug:	MP16
Transition Zone:	MP7, MP8, MP9, MP10, MP11
Fontmell East:	MP12
Fontmell West:	MP1, MP2, MP3, MP4

5 Findings from Settlement Monitoring

5.1 Monitoring Data – Summary of Results

The table below gives a basic summary of the monitoring results to date:

Table 5.1 Summary of Monitoring Results

Pin ID	Location	Total Settlement (mm)	Current rate of settlement (mm/ 2 weeks)	Comments
MP1	Fontmell West	3	0	Currently stable,
MP2	Fontmell West	2	0.6	Generally stable, small ongoing settlement
MP3	Fontmell West	6		Small ongoing settlement
MP4	Fontmell West	8		Ongoing settlement, accelerated during early April
MP5	Fontmell West			(1)
MP112	Fontmell West		-0.1	Data from April 2016. Small initial settlement, current slight heave
MP113	Fontmell West		0.4	Data from April 2016. Initial settlement, ongoing
MP114	Fontmell West		0.9	Data from April 2016. Slowing of rate of settlement apparent
MP115	Fontmell West		0.9	Data from April 2016. Slowing of rate of settlement apparent
MP118	Fontmell West		-1	Data from April 2016. Initial settlement, ongoing
MP6	Transition Zone			Only early data available, indicates low rate of settlement from Oct '15
MP7	Transition Zone	19	1.7	Full set of data, indicates steady and ongoing settlement
MP8	Transition Zone	6	-1.1	Relatively little overall movement, initial settlement, now slight heave
MP9	Transition Zone	5		After initial stable period during February began steady settlement
MP10	Transition Zone	17	2.8	Full set of data, indicates steady and ongoing settlement
MP11	Transition Zone	18	-2	Initial steady settlement but from April has been static / heaving
MP116	Transition Zone	-4	1.3	Data from April 2016. Slowing of rate of settlement apparent
MP117	Transition Zone		0.9	Data from April 2016. Slowing of rate of settlement apparent
MP14	Sink hole plug			Abandoned in December after initial significant settlement (2)
MP14A	Sink hole plug			Replaced MP14. Total settlement of 35mm, apparently now slowing (2)

Pin ID	Location	Total Settlement (mm)	Current rate of settlement (mm/ 2 weeks)	Comments
MP15	Sink hole plug			Abandoned in November after initial significant settlement (3)
MP15A	Sink hole plug			Replaced MP15. Total settlement of 21mm. No 2016 data (3)
MP16	Sink hole plug	30	-0.7	Significant settlement, but very recent survey suggests onset of heave
MP17	Sink hole plug			Significant early settlement, no data after January 2016 (4)
MP100	Sink hole plug			
MP101	Sink hole plug		0.6	Data from April 2016 only. Small ongoing settlement
MP102	Sink hole plug		1.4	Data from April 2016 only. Ongoing settlement
MP103	Sink hole plug			Data from April 2016 only. No very recent data
MP104	Sink hole plug		1.3	Data from April 2016 only. Ongoing settlement
MP105	Sink hole plug		0.3	Data from April 2016 only. Small ongoing settlement
MP106	Sink hole plug		-0.4	Data from April 2016 only. Showing evidence of recent heave
MP107	Sink hole plug		0	Data from April 2016 only. Currently static
MP108	Sink hole plug		-0.7	Data from April 2016 only. Ongoing settlement
MP109	Sink hole plug		-0.5	Data from April 2016 only. Ongoing settlement
MP12	Fontmell East	-4	1.3	Apparent initial heave replaced in April 2016 with ongoing settlement
MP13	Fontmell East			Apparent initial significant heave. Lost in November '15
MP13A	Fontmell East			
MP110	Fontmell East		0.6	Data from April 2016. Slowing of rate of settlement apparent
MP111	Fontmell East		0.3	Data from April 2016. Slowing of rate of settlement apparent

Notes to Table 5.1

(1) Only data available up until 11/12/15 showing 2mm heave
(2) MP14 and MP14A taken together indicate a total settlement of 13+22 = 35mm, with no data available after 23/02/16
(3) MP15 and MP15A taken together indicate a total settlement of 12+9 = 21mm, with no data available after 11/12/15
(4) Initial settlement of 30mm at 4th January 2016, however no subsequent readings available.

The monitoring data does yield some significant information with the key points being as follows:

- There has been significant settlement in the area of the concrete plug (in excess of 30mm to date), and the evidence suggests that over much of the area this movement is ongoing. A contoured plot of the total settlement (using only MPs with near complete records) is shown in Drawing MK_G-AP011.Y4.104.

- MP7, MP10 and MP11 show that there have been significant movements occurring in the Transition Zone, although these appear to be currently of the order of 50% of the total movements apparent in the concrete plug.
- The Transition Zone appears wider to the west of the plug than to the east.
- A plot showing the current rate of settlement over the last month (Drawing MK_G-AP011.Y4.105) shows an intriguing group of data to the south east of the plug and in the surrounding Transition Zone that are now apparently heaving. This is likely to be related to the "foundering" of part of the concrete plug, as illustrated in Figure 3.3, on a relatively firm element of the subgrade.
- Generally movements appear to be slowing, but uncertainties with respect to the compatibility of the data gathering methods suggest that it is unwise to draw a firm conclusion in this regard at this early stage of total settlements.
- Outside the area of the plug, (which it is anticipated should act as a monolith), the peak settlements within the Transition Zone to date, (as well as the current highest rate of ongoing settlement), are located near the south western corner of the plug centred in the vicinity of MP10.

6 Discussion of Results

6.1 Monitoring Data – Summary of Observed Results

In total, forty one (41No.) monitoring points have been established in order to monitor and assess the potential on-going settlement of the concrete plug, Transition Zone and the adjoining Fontmell Close highway, footpath and residential gardens adjacent to the concrete plug.

Based on the findings, differential settlement has occurred between the four identified zones, namely Fontmell West, the Transition Zone, the Concrete Plug, and Fontmell East. The total differential settlement over the full survey period (10 October to present) was greatest between the concrete plug and the Transition Zone to the east of the plug, with an apparent more gradual differential settlement profile between the concrete plug and the Transition Zone to the west, see Drawing MK_G-AP011.Y4.104.

There is a need to temper the desire to draw firm unequivocal conclusions from data sets that are monitoring the reaction of the ground to a complex range of variables that influence the particular value at a particular juncture. It is very common that monitoring systems set up in the immediate aftermath of a ground related movement record an early phase of relatively rapid movement, although with a significant amount of "noise" until the ground and the newly installed monitoring system settle down and offer a less "chaotic" response. The subsequent phase is often characterised by what statistician's term a "random" walk response, with data points scattered either side of a regression line. Eventually, with sufficient time, the response can settle down to a steady-state provided no external factor impacts on the system. Figure 3.4 illustrates this.

In this particular context, traditional soil mechanics theory would suggest that the soil should settle vertically in a manner characterised by three phases comprising "Primary Consolidation", "Secondary Consolidation" and long term "creep" settlement. Consolidation is a process that is associated with the performance of clayey soils. Where granular materials are present the mechanics are dominated by elastic compression, with less variability between the primary and secondary phases. However long term creep processes may still be present. Figure 3.5 illustrates how these principles represent a simplification of the actual conditions at the site.

In order for a soil response to perform in close correlation with these theoretical principles it would need to comply with a number of simplifying assumptions which are not valid in this case. These include:

- The soil profile would need to be reasonably uniform, in this case the presence of the former clay pit high wall, and the potential for a collapsed shaft to be present imply that the ground profile is locally highly variable
- There should be no potential for lateral movement, and all loadings should be vertical
- The applied load should be on a uniform rigid footing (which the plug clearly is not) and should not be free to pitch / yaw or roll in response to obstructions / firm spots in the underlying subgrade
- There should be no through flow of water with associated piping / erosion of fine silty materials

- There should be no significant open voids in the soil profile (the presence of such "Swiss Cheese" type materials can lead to significant "collapse settlement".

In the case of Fontmell Close it is reasonable to assume that all of the contributory factors listed above may be present, to a greater of lesser extent, and consequently any explanations of past performance and particularly predictions of future performance should be considered tentative. Further monitoring into "steady state" performance would increase the confidence we have in long term predictions.

Based on the evidence available to date it would appear that the current rate of settlement may be, in general slowing, in part as a consequence of the plug's south eastern edge bearing on to firmer ground in the sub-grade. Reference to Figure 3.1 shows how this location corresponds to the recorded position of the former clay pit "highwall". The observed relative heave of the south eastern corner is therefore consistent with the anticipated ground conditions.

6.2 Contamination Test Results

Loose chrysotile asbestos fibres were identified in the sample WS403A (0.2m – 0.4m). Asbestos fibres were not identified within any other tested samples. Since no asbestos quantification data is available for this sample to date, it is conservatively assumed that this could potentially exceed the Hazardous Waste threshold of 0.1% volume. Consequently, all the asbestos impacted waste soil in the vicinity of WS403A would need to be disposed of as Hazardous Waste until proven otherwise.

Given that the disposal of all waste soil material as Hazardous Waste would incur significant costs, it is recommended that asbestos quantification testing is undertaken on this sample to determine whether the 0.1% threshold is potentially exceeded.

In addition to the quantification testing, delineation sampling of the same soil strata should be undertaken around the positive sample location prior to excavation to determine the lateral extent of the asbestos impacted soils. It should also be noted that the presence of any pieces of visible asbestos would also result in a Hazardous Waste classification. Based upon this delineation asbestos identification and quantification testing, any asbestos impacted material should be segregated and disposed of in accordance with the relevant waste legislation. The remaining made ground material test results should be subjected to waste classification assessment in accordance with Environment Agency Technical Document WM3. This assessment and the waste acceptance criteria (WAC) testing results from WS401 between 0.5m – 0.6m should be provided to the waste disposal contractor prior to disposal.

Any excavation works involving asbestos impacted soils should be carried out in accordance with the Control of Asbestos Regulations 2012. Under these regulations an asbestos risk assessment must be undertaken. The risk assessment must make a prediction of the expected exposure to asbestos caused by the working method and compare this with the Control Limit in the regulations. Based on the predicted exposure, the risk assessment should detail the requirement for personal protective equipment (PPE), respiratory protective equipment (RPE), decontamination procedures and on-site facilities and air monitoring.

6.3 Potential Mine Workings

The two boreholes CH401 and CH402 were drilled in, and just outside, the Transition Zone to the west of the "plug" and were intended to provide further information with respect to the risks associated with potential chalk mine voids beneath this part of the highway. Neither borehole indicated significant voiding or broken ground and as such suggest that risk associated with the potential presence of deep chalk mine voids beneath the western Transition Zone is low.

As with any borehole investigation we cannot offer any direct information relating to ground between, or away from the actual borehole positions. However, when considered in combination with the PBA boreholes in this area their original conclusion "*No evidence was found by the investigations that indicated further significant mined voids or laterally extensive mined ground present that impacted… the ground beyond the margins of the collapse*" stands, with respect to the area immediately west of the plug.

The ongoing (minimal) risk associated with potential catastrophic collapse is dealt with in the proposed remedial highway design option appraisal from a H&S/ public liability perspective by the recommendation of a geotextile basal reinforcement that is sufficiently robust to span voids (up to 3m diameter) in the short term allowing vehicles to move off the immediate location should a further significant collapse occur.

7 Engineering Discussions

7.1 Differential Settlement

The key concern for any highway undergoing settlement is not just the total settlement at a particular time, but the extent of any differential settlement that occurs during the course of that settlement. In the event that total settlement was even and continuous, the requirements for repair and maintenance would be relatively low. On the other hand, even relatively small total movements can lead to a significant repair and maintenance requirement, if the settlement is unevenly distributed, or indeed if it is temporally progressive (i.e. occurs in different locations at different times).

Within the context of Fontmell Close, Opus have identified four site areas that have differing settlement characteristics:

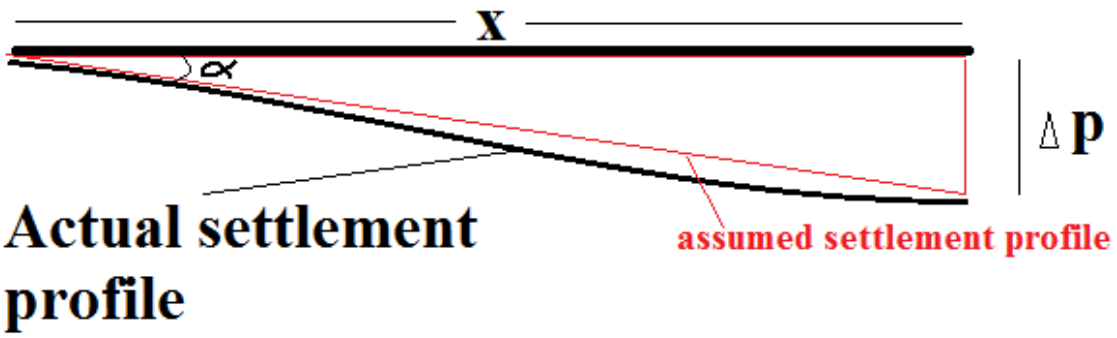
- the stable external areas of Fontmell East
- the stable external areas of Fontmell West
- the Transition Zone (or "doughnut")
- the concrete "Plug" itself

It should be noted that the key elements of differential settlement will probably occur at the boundaries between these areas rather than within them (although see the subsequent discussion relating to potential "rocking" of the concrete slab itself). The location of the boundary between the stable external areas and the Transition Zone relates to the original position of the former clay pit high wall, and is defined by a relatively rapid change in fill thickness, from the general 3m-5m of Made Ground to the excavated and backfilled 7m-9m + that is typical of the former clay pit areas.

Tolerable differential settlements are normally expressed as the angle of the settlement profile, measured in radians where differential settlement (Δp) is:

$\Delta p = X \tan\alpha$ which for large X relative to Δp approximates to:

$\Delta p = X\alpha$ (expressed in radians)



The anticipated maximum settlement of the concrete plug has been calculated by others to be 50mm although qualified with a "or more" addendum (Peter Brett Associates LLP 2016). This is considered to be a reasonable lowest order estimate by Opus. The differential settlement (Δp) from the point of maximum settlement at the plug perimeter (assuming no rocking of the plug) to the shortest distance to the nearest quarry highwall (dimension X) equates to a linear differential settlement of 0.05m over a distance of 35m, or expressed as defined above is equivalent to a differential settlement of

(0.05/35) X (3.142/180) radians, which is 0.000025 radians. This is less than usually deemed critical tolerable differential settlements associated with, for example wall finishes, brick built load bearing walls, or well-built utility structures. However, it is anticipated that the majority of the differential settlement will not be spread out over the full width of the Transition Zone, but would be concentrated in the area immediately surrounding the plug.

The concrete "Plug" is anticipated to settle as a monolithic structure without any significant structural bending. The interface between the plug and the immediately adjacent Transition Zone is anticipated to be the point most likely to suffer differential stress and by implication would be expected to suffer the maximum differential settlement. It will be necessary to stiffen the response of the Made Ground immediately surrounding the plug, and to use mechanically stabilised fill to aid stress redistribution into the wider Transition Zone.

Figure 3.2 shows the conceptual settlement characteristics associated with the key areas identified above together with the anticipated remedial treatment required to minimise ongoing maintenance and anticipated repeated resurfacing works. All sizings shown on the sketch are nominal and will require confirmation by the specialist designer / installer).

The assumption of a relatively consistent settlement across the plug itself will need to be confirmed by monitoring. In the event that the plug "founders" on an area of more solid ground within the Made Ground it is conceivable that the plug may show a further rotation due to rocking causing a heave on one side coupled with settlement on the other (See Figure 3.3 as an illustration of this effect). Recent monitoring results do indicate some potential for this performance being observed.

Alternative methods of providing the same local ground improvement are available including dynamic and vibro-compaction, and shallow sub-soil grouting. However, given the close proximity of residential housing, and the associated disturbance, as well as the presence of existing utility services, these alternative, much more disruptive techniques, have not been recommended.

7.2 Predicted and Observed Settlements to Date

Initial predictions of settlements by PBA indicated anticipated settlements "*anticipated to be at least 50mm or more*" and suggesting (as at March 2016) that "*about half of the predicted settlement has already been achieved during the monitoring period*". Opus consider the estimate of 50mm to be a reasonable lower bound estimate of total settlement given the status quo, but note that as at May 2016 peak movements of 35mm have been recorded, and movements are continuing. In addition, associated with any remedial works to reinstate the road to a serviceable condition the existing road will need to be backfilled with approximately 1m of imported material, implying the need to surcharge the plug by a further 20 kPa or thereabouts (depending on the material imported and the ground treatment proposed. This will inevitably lead to additional settlements above and beyond those anticipated to date.

The majority of the monitoring points currently being used to observe ongoing settlement will be lost during the proposed remedial treatment. Careful consideration should be given to establishing a suitable array of monitoring stations/ instruments that will allow any ongoing settlements during the construction works to be recorded and assessed.

7.3 Impact of Potential Flooding/ Leaking Infrastructure

The predictions made by PBA and the design recommendations made by Opus with respect to the remedial treatment of the highway are predicated on the assumption that the fill materials are not impacted by flood or major drainage issues associated with leaking sewers, drains, or water supply. It would be prudent to agree with the loss adjusters prior to agreeing any remedial options what their intentions are in the case of the existing soakaways either being still active or being reinstated in close proximity to the sinkhole. It would seem prudent not to have ANY leaking pipes or soakaways in the close proximity of the concrete plug or Transition Zone, and indeed remove and prevent any soakaways at this location for the foreseeable future.

Opus strongly recommend therefore that prior to finalising the remedial design solution HCC engage with neighbouring properties and utility providers to establish:

- Will Fontmell Close 8, 9 and 10 and 1 Bridle continue to have soakaways?
- How will the junction between private drives and the Highway be created and how will the inevitable future differential settlement be accommodated?
- What restrictions will there be on current or future utilities, (both construction and location) to prevent leakages?

7.4 Assessment of Near Surface Ground Conditions in Transition Zone

The ground conditions encountered within the additional investigation undertaken within the transition zone comprised made ground underlain by Kesgrave deposits, which in turn is underlain by Lewes Nodular Chalk.

The made ground was encountered to a depth of between 4.2m (WS03A) and 8.45m bgl (WS401). The made ground deposits encountered within the holes undertaken across the transition zone are inherently variable, comprising a mixture of interlayered very soft to firm gravelly sandy Clay, very loose slightly sandy gravelly Silt, or very loose sandy Gravel.

Twenty five SPT tests were carried out within the boreholes in the made ground deposits. The tests recorded blow counts of between 0 and 27, which indicate a very loose to dense consistency or a very soft to stiff strength. The high SPT N value of 27 can be ignored, as it is likely to be associated with the presence of obstructions encountered within the made ground.

The range indicated an average N value of 3. These N values for this material, giving an average of very loose or very soft. The results generally follow a trend of increasing N value with depth, with an inferred increase of N value of 1 per metre depth below ground level, as shown on the design line (Figure D1).

The DHSP results also show a trend of increase with depth with the made ground deposits, with a typical equivalent N_{300} of 2, which is reasonably consistent with an average SPT N value of 3 recorded within the boreholes.

The recommended geotechnical soil parameters presented in Table 7.1 have been assessed using the in-situ test results and engineering descriptions contained on borehole logs.

Table 7.1 Recommended Geotechnical Soil Properties for the Made Ground

Geotechnical unit	Consistency or density	Unit weight γ (kN/m3)	Undrained shear strength (4) c_u (kPa)	Peak effective shear strength parameters		Elastic Modulus (5) E' (MPa)	SPT 'N' Value (Typical)
				Cohesion c_p'(kPa)	Friction angle ϕ_p' (deg)		
Made Ground Cohesive	Very Soft	16	10	0	20	2	2
	Soft	16	20	0	22	4	4
	Firm	17	35	0	24	7	7
Made Ground Granular	Very Loose	16	-	0	28(3)	3	3

Notes:

1. Table 7.1 provides a selection of recommended geotechnical parameters for the made ground material that were encountered underlying the Transition Zone.
2. Geotechnical laboratory testing was not undertaken, subsequently the recommended geotechnical parameters presented within Table 7.1 have been produced using a combination of in-situ test data, correlation with published data (BS8002, CIRIA 143) and experience of similar soils.
3. Based on Peck, Hanson and Thornburn 1967.
4. Based on Stroud, 1975.
5. Based on CIRIA 143.

8 Design of Remedial Works

8.1 Design Proposals

Opus have previously discussed (Opus, 2016) five potential ways of dealing with the issues at Fontmell Close these were:

Option A – Do nothing.

Option B – Do minimum – Carry out routine monitoring/ site walkover to assess the ongoing geotechnical and site conditions across Fontmell Close. Install survey points in order to monitor any potential ground surface movement of the road and footway areas.

Option C – Preventative maintenance (Basic) – Ground improvement. Excavate existing road construction and install geogrid and reinstate road surface.

Option D – Preventative maintenance (Intermediate) – Partial Ground Treatment. As Option C, but locally grout up near surface voids and areas of settlement.

Option E – Preventative maintenance (Full) – Full Ground Treatment. Full grouting of the underlying ground across Fontmell Close and construct new road surface.

In the context of the area around the sinkhole collapse, and Transition Zone, these are considered more accurately described as:

Option A – Do nothing.

Option B – Measure and Monitor – Regularly observe survey points in order to monitor ground surface movement of the road and footway areas.

Option C – Preventative maintenance (Basic) – this has been divided into three separate aspects

Option C1 Reconstruction of standard Highway, and instigate regular assessment and maintenance.

Option C2 Ground improvement. Reconstruction of the Highway with geotechnical reinforcement to Control of Differential Settlement and reinstate existing road.

Option C3 Ground improvement. Reconstruction of the Highway with geotechnical reinforcement to provide Void Spanning and reinstate existing road.

Option D – Preventative maintenance (Intermediate) – Partial Ground Treatment. As Option C, but locally grout up near surface voids and areas of settlement.

Option E – Preventative maintenance (Full) – Full Ground Treatment. Full grouting of the underlying ground across Fontmell Close and construct new road surface.

Based on the findings of the investigation to date it is considered that the "Do nothing" option should be discounted. Option B has been ongoing for the last few months, and it is apparent that movement is continuing, and whilst there are perhaps some initial signs of slowing, the settlement is by no means completed, and is likely to continue for some time to come.

Each of the remaining options (C,D & E) have various merits as a way forward, but given the ongoing ground movements and the uncertainty in the rate and total ground movements likely to be

experienced, plus the preference to minimise short term capital expenditure, Opus considers that HCC should consider carefully the various merits of Option C, as discussed below.

The monitoring data suggests that the maximum linear length of highway and footpath that will require remedial works to address any further differential settlement and potential catastrophic failure of the near ground surface from associated sinkhole features is in the order of 60m. The 60m length of affected highway includes the concrete plug, transition zone and eastern and western adjoining areas of Fontmell Close.

This area is defined by where current monitoring indicates that it can be reliably assumed that there has been no significant settlement (i.e. <5mm) to date. The approximate contour establishing where 5mm settlement is apparent (measured along the centre line of the road) is approximately 39m on Fontmell West from the centre of the plug, and 13m on Fontmell East, giving a length of road of some 52m already affected by significant settlement. An additional 4m length of road has been allowed for to tie in the impacted length of road (at each end) to the more stable ground beyond.

The three options for the remedial works of the highway comprise:

- (C1) Reinstatement of standard road, and instigate regular assessment and maintenance;
- (C2) to minimise long term differential settlement; and
- (C3) to prevent a potential catastrophic failure from near surface voids up to 3m diameter underneath the road formation.

Alternatively, solutions C2 and C3 could be combined in order for a design solution to encompass both differential settlement and catastrophic failure from voids. Other alternative solutions associated with various forms of what are loosely termed "ground improvement" have been considered. Whilst techniques such as "vibro" ground treatment or lime stabilisation can increase bearing capacity significantly, they do not improve the tensile strength of the ground, and therefore are unable to minimise the differential settlement between the concrete plug and the transition zone. They are also extremely disruptive with respect to local residents, and may also be associated with damaging ground movements, vibration etc.

The near surface ground conditions along the highway area typically comprise soft to firm cohesive infill deposits underlain by firm to stiff glacial deposits, which are in-turn underlain by Lewes Nodular Chalk deposits. For preliminary design purposes, the CBR value for the near surface infill deposits is considered to be in the order of 2%.

The anticipated traffic loading will be typically limited to light vehicles, cars and vans, with the exception of occasional service trucks and emergency services.

8.2 Option C1 – Reconstruction of the Highway

A standard thickness of pavement (sub-base and capping) of around 1000mm, which will allow for future standard maintenance of utilities, and deform and crack as a result of ongoing ground movements, and would require regular monitoring and maintenance, as a result of settlement, differential settlement and potential further void creation.

8.3 Option C2 - Reconstruction of the Highway with Geotechnical Reinforcement to Control of Differential Settlement

Adopting the preliminary design CBR value of 2%, a minimum thickness of unbound pavement layer (sub-base or sub-base and Capping) of around 450mm is required with two layers of Tensar biaxial (minimum SS40) reinforcement geogrids. The geogrids should be laid orthogonally on the ground at formation level at the underside of the sub-base layer. Additionally, a layer of Tensar TriAx geogrid could also incorporated within the sub-base layer, with a minimum of 150mm of granular fill cover over each geogrid layer. The TriAx generally offers better performance in respect of differential settlement control (but is not currently tested in void spanning applications).

The imported granular fill material for the unbound pavement layer (sub-base) should be a well graded angular stone, for e.g. MOT Type 1/ 6F1 fill material, with a maximum particle size of 75mm. The imported fill material will be suitably compacted in accordance the appropriate specification as deemed necessary.

The installation of 2 layers of Tensar (or similar) SS geogrids in the unbound pavement layers will help mitigate differential settlement. The geogrids effectively interlock and stiffen the pavement foundation but they cannot of course prevent settlement of the subgrade taking place below. If such settlement does occur then the stiffened pavement foundation will partially bridge localised depressions and reduce peak settlement locally.

It is considered that with 450mm thickness of well compacted Type 1 sub-base over the geogrid, as long as the real subgrade CBR was not less than 1% then the road surface should not deform beyond normal serviceability conditions, if subject to normal in-service vehicle movements.

With regard to void spanning then Tensar SS geogrids are not appropriate in these situations, and using the SS40 geogrids is not a permanent solution. However, it can be used in the absence of full protection measures, to provide ~~a~~ partial temporary catastrophic collapse control where the void's potential diameter is no greater than 2m. Should a void open up in the area, the SS40 geogrids will strain and deformation will be observed at the surface and the affected area will be protected for up to an estimated 72 hours, to enable a permanent solution to be employed over the affected area. This catastrophic collapse control method is used commonly under roads.

It is possible that the thickness and reinforcement detail of the proposed new pavement could differ following detailed assessment by a specialist contractor.

8.4 Option C3 – Reconstruction of the Highway with Geotechnical Reinforcement to Provide Void Spanning

To provide a long term permanent design solution to guard against catastrophic failure of potential large voids (in the range of 2m - 3m in diameter), it is recommended that a high strength geotextile such as Tensar BaseTex is adopted within the design. Two layers of Tensar BaseTex (anticipated typical 800/50) high strength reinforcement geotextile will offer sufficient tensile strength to act as a support in the short term to a nominal 3m diameter void. The BaseTex geotextile should be laid orthogonally on the ground at formation level at the underside of the sub-base layer.

Adopting the preliminary design CBR value of 2%, a minimum thickness of unbound pavement layer (sub-base or sub-base and Capping) of around 450mm is required with a single layer of Tensar TriAx geogrid ideally at 225mm above the base, up to a maximum of 300mm. A minimum of 150mm of granular fill cover over the geogrid layer is required.

In order to achieve the required resistance against "pull-out" failure in the event of a collapse, the basal reinforcement layer will need to be appropriately anchored into the surrounding ground and given the close proximity to the residential properties immediately adjacent to the highway, it is anticipated that this will require either:

- anchoring using an appropriate wrap around technique, possibly coupled with drilled in soil anchors, or
- laying the geotextile material beneath 3rd party owned land with appropriate mitigation and reinstatement requirements.

The lateral extent of any such anchoring will be determined during detailed design.

The imported granular fill material for the unbound pavement layer (sub-base) should be a well graded angular stone, for example MOT type 1/ 6F1 fill material, with a maximum particle size of 75mm. The imported fill material will be suitably compacted in accordance the appropriate specification.

It is possible that the thickness and reinforcement detail of the proposed new pavement could differ following detailed assessment by the specialist contractor.

Further protection against surface damage associated with ongoing settlement can be provided by the use of asphalt pavement reinforcement which acts to reduce reflective and fatigue cracking, and therefore offset future operational expenditure (OPEX) against current planned capital expenditure (CAPEX).

8.5 Services

8.5.1 New Build Services

Where any deep services are required within the area of the highway, then it possible to use a geogrid to reinforce the base of the service trench in order to assist with the stability and mitigate potential pipe movement and differential settlement.

Traditional pipe support, in the form of a high quality graded granular aggregate, is considerably improved by the use of Tensar geogrids to form a stabilised granular mattress. The stabilised granular mattress is employed in weak ground initially to provide a working platform on the trench invert and in-service, to provide pipe support to help preserve levels and falls.

The interlock mechanism between grid and aggregate creates a flexurally stiff supporting mattress which provides an efficient load spread into the underlying weak ground, and also helps to mitigate and control longitudinal differential settlement across the service pipes and joints.

It is recommended that an over deep reinforced "bolster" be provided around the perimeter of the "plug". It is anticipated that this should be up to 1m deep, and will act as a stiffening element in the sub-grade at the point of maximum differential settlement. This bolster could be utilised as a

convenient base for provision of new build service ducts between, say 0.75m and 0.45m depth below finished road level.

8.5.2 Future Service Installation

The use of the geotextiles recommended in the remedial road construction requires recognition of the need to repair any future damage to maintain the integrity and function of the geotextiles. The Tensar TriAx and SS40 type mechanical stabilization geotextiles can be repaired with appropriate stitching/ overlapping techniques in accordance with the manufacturer's detailed method statements.

However, it is not possible to repair the Tensar BaseTex basal reinforcement layer, and in the event that the material is damaged, it will need to be replaced in its entirety.

It is recommended that consideration be given to laying ducting in the bolster supported zone to allow installation of future electrical / telecoms services without disruptive excavation works.

8.6 Estimated Volume of Road Material to be Removed

The length of highway that requires remedial works to be carried out is approximately 60m, and is approximately 9m wide (including the footpath).

The recent ground investigation indicate that the existing road surface comprises a concrete slab with a typical thickness of around 200mm, which is underlain with a sub-base in the order of 400mm, giving a total thickness of around 600mm. Therefore we would anticipate that a total thickness of around 650mm (allowing for a 50mm over-dig) will need to be excavated in order to accommodate the new road construction. The total volume would be in the order of 110m^3 of existing concrete road and approximately 250m^3 of existing sub-base material. These materials are unlikely to be suitable for re-use and will need to be removed off-site and disposed of appropriately.

8.7 Approximate Costs of Ground Improvement Products

The approximate costs of the ground improvement/ reinforcement Tensar products are provided below:

- Option C2 - £2.00 per m^2 of supplied SS40 Geogrid per layer (2 layers required) and if required, 1 layer of TriAx TX170 geogrid at £1.70 per m^2 supplied. Total supplied cost of ground improvement Tensar products is approximately £5.70 per m^2.

- Option C3 - £6.50 per m^2 of supplied BaseTex 800/50 (2 layers required) and 1 layer of TriAx TX170 geogrid at £1.70 per m^2 supplied. Total supplied cost of ground improvement Tensar products is approximately £14.70 per m^2.

- Additional costs to be considered include off-site disposal of unsuitable excavated material, cost of importation of suitable granular fill, road pavement/ running course, costs associated with service installations, fill placement and earthworks, detailed design and supervision.

- It should be stressed that the efficacy of the stress distribution mechanism of the reinforced geotextile material will be compromised if the geotextile is damaged. It is understood that the BaseTex material cannot be stitched together in the event it is damaged by a utility provider when retrospectively installing services.

- Option C solutions will minimise immediate Capital Expenditure, but there will be an ongoing Operational Expenditure associated with settlement monitoring, maintenance and end of life renewal. Establishing an appropriate design life and renewal cycle for the road will be based on the monitoring of the settlement, and the estimated elongation of the geotextile fabric.

8.8 Need for Partial/ Total Grouting

It should be noted that infilling of the voids present is the only way of removing the prospect of ongoing long term settlement entirely. However, both partial (Option D) and total grouting (Option E) will be disruptive for local residents in the short term, and given the continued uncertainty with respect to the nature of the ground the potential grout takes, could be prohibitive in terms of cost. Partial grouting (Option D) is not considered a feasible realistic option as there is insufficient knowledge of the condition of the collapsed shaft to ensure that remnant voids behind any potential shaft lining are not missed.

9 Summary and Conclusions

9.1 Summary

Significant settlements of the plug and Transition Zone have occurred in the months since the initial collapse. These have already reached a peak measured displacement of 35mm on the plug (combined total of MP14 and MP14A) and 18mm in the Transition Zone. Movements are still ongoing and in the Transition Zone movements over the last two weeks have been of the order of 2-3mm locally.

There is some evidence that the rate of movement in general is decreasing, and that along the south eastern corner of the plug there appears to be some heave. This may be attributable to the "foundering" of the plug on a firm horizon within the subgrade.

Two boreholes drilled to the west of the plug did not reveal the presence of further mined out voids associated with chalk working.

With respect to the road reinstatement works, we have identified the following options:

- Option C1 - Standard road reconstruction;
- Option C2 - Install geogrids and sub-base to mitigate differential settlement, then standard road construction to surface;
- Option C3 - Install BaseTex to provide a degree of protection from void collapse of up to 3m in diameter.
- Combination of Option C2 and Option C3 - Incorporate both Geogrids and BaseTex with thickened road construction and utilities re-connected using flexible couplings, within buffer zones.

A summary of risks and benefits of the four main design options is provided in Table 9.1.

Opus advise that only provision of both Options C2 and C3 together, provide an appropriate level of protection against both differential settlement and risks associated with potential catastrophic collapse. It is however acknowledged that there may be various operational reasons why HCC may conclude that other options may be more suitable. Option C1 has the highest onus on active regular monitoring and maintenance, but is the simplest in terms of the interaction with utility suppliers in the future, and is a simple non-technical option. Options C2 and C3 are more passive with reliance on the geogrids and geotextiles. Option C3, albeit providing a robust solution, has a significant constraint in terms of maintenance of any sewer located beneath the geotextile.

We advise caution in the process that HCC adopt to choose their preferred option and consideration of the various relative merits of each aspect. This report has been prepared without knowledge of HCC operational reasons which may make certain options more attractive to them than others.

Table 9.1 Summary of Risks and Benefits of the Four Main Design Options

Remedial Option	Construction detail summary	Long Term Integrity	Implications to Public Highways	Implications to utilities	Residual risk	Advantages	Disadvantages
Option C1	Standard road construction with normal thickness compacted granular backfill above concrete plug and Transition Zone, and utilities re-connected using flexible couplings.	Potential for settlement (both total and differential) to cause damage to Highway requiring regular maintenance. Not able to withstand sudden induced settlement.	Highly likely that regular and frequent monitoring and maintenance required. Risk that any further subsidence could have catastrophic consequences at surface. Reliant on high confidence that there are no residual voids and that fines will not migrate. Lowest initial cost, but potentially high monitoring and maintenance costs.	Need to accommodate significant settlements, in design of replacement utilities. Possible restriction of route of sewer, such that Highways may not permit tunnelling or excavation into existing concrete plug. Utilities will need maintenance, but no restrictions to future excavations through geogrids or geotextiles.	Does not address issues of any ongoing settlement or subsidence. Reasonably expect ongoing surface expression of ground movements and regular monitoring & maintenance. Does not address potential of further collapse in the event that further void space opens up. Due to scale of movements reinstalled pipes may well leak in future and require maintenance. Standard measures required during maintenance.	Simple construction, reliant on regular and frequent monitoring and maintenance. Settlement and subsidence visible at surface. Normal maintenance for Utilities.	No measures adopted to address issues of future differential settlement and subsidence.
Option C2	Incorporate series of Geogrids within thickened road construction and utilities re-connected using flexible couplings, within buffer zones.	Reduced potential for settlement (total and differential) to cause damage to surfaces , hence requiring less long term maintenance. Provides a 72 hour holding period before ultimate collapse in the event of a catastrophic failure due to a void opening up below the geogrids.	Future settlement expected but smoothed such that may be accommodated through monitoring and normal frequency maintenance.	Need to accommodate settlements, in design of replacement utilities. Possible restriction of route of sewer, such that Highways may not permit tunnelling or excavation into existing concrete plug. Subsequent utility excavations would need to be controlled, with geogrids cut and replaced in accordance with manufactures' recommendations.	Reasonably expect reduced surface expression of ground movements. Does not address potential of further collapse in the event that further void space opens up.	Future settlement smoothed such that may be accommodated through monitoring and normal frequency maintenance.	No measures adopted to address issues of future subsidence. Geogrids cause a constraint to standard utility excavations. Continued and on-going subsidence does limit the design life of the geogrids which may need to be replaced if excessive strain occurs
Option C3	Install BaseTex to provide degree of protection from collapse of up to 3m diameter void.	Reduced potential for subsidence to cause catastrophic collapse at surface. Differential settlement still likely to occur.	Future settlement expected requiring regular monitoring and maintenance.	Need to accommodate differential settlements, in design of replacement utilities. Utility services above geotextile available to normal maintenance, but those below (sewer) severely restricted.	Significantly reduced potential for any further catastrophic collapse impacting operation of highway. Surface expression of ground movements still expected.	Reduced potential for subsidence to cause catastrophic collapse at surface.	Differential settlement still likely to occur. Geotextiles cause a constraint to future deep service excavations.
Combination of Option C2 and Option C3	Incorporate both Geogrids and BaseTex with thickened road construction and utilities re-connected using flexible couplings, within buffer zones.	Reduced potential for settlement or subsidence to cause significant damage to surfaces. Would be able to withstand sudden induced settlement in the short to medium term but would require remedial maintenance occasionally.	Lowest risk option with highest initial cost, and should be a robust long term treatment, without the need to grout.	Robust solution to reduce both differential settlement and subsidence in the scale of a 3m wide void. Subsequent utility excavations would need to be controlled, with geogrids cut and replaced in accordance with manufactures' recommendations, but those below (sewer) severely restricted. Lowest expected onus on ongoing maintenance.	Robust and long term solution.	Robust and long term solution requiring little on going monitoring and maintenance.	Geotextiles cause a constraint to future sewer excavations. Continued and on-going subsidence does limit the design life of the geogrids which may need to be replaced if excessive strain occurs

9.2 Conclusions

In Opus' opinion Options C2 and C3 together, are considered the best solution as the combination will provide an appropriate level of protection against both differential settlement and risks associated with potential catastrophic collapse. This does however bring with it a need for ongoing OPEX involving long term monitoring, and a limited life span requiring eventual replacement.

To mitigate the low risks associated with potential catastrophic collapse of further unrecorded chalk mine workings, or mobilisation of loose fill by flood/ inundation, it is recommended that the proposed mechanical stabilisation should include basal reinforcement capable of spanning a nominal 3m diameter collapse zone.

In the event that a fully stabilised (i.e. grouting) solution is required, then Opus would not support "partial grouting" techniques as a consequence of the remaining uncertainties associated with the condition of the collapsed shaft.

The remaining Option E (full depth grouting) will be extremely disruptive for residents, and costs cannot be accurately estimated due to uncertainties with respect to grout take.

10 References

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