

West Durrington, Worthing

Geophysical Survey and Ground Investigation Report

Project Ref: 5969/413

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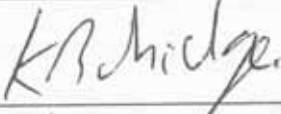
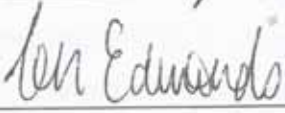
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EXECUTIVE SUMMARY

Peter Brett Associates have been retained to provide geotechnical advice for a proposed development at West Durrington, Worthing.

As part of a general ground investigation, anomalous ground conditions were encountered in two exploratory holes, possibly associated with the presence of solution features. Initial geophysical surveys on a 50m by 50m grid centred on these exploratory holes indicated that the anomalous ground extended over the areas surveyed. An electrical resistivity tomography survey was therefore carried out across the whole of the site to confirm the extent of the anomalous ground and any other features that may be present. A supplementary ground investigation was also carried out within the features revealed by the geophysical survey to confirm the interpolated ground conditions.

The following features have been identified by the surveys:

- Large scale solution feature in the south east margin
- The presence of a former cliff line across part of the site, infilled with Raised Beach Deposits and Brickearth
- A zone of discontinuity within the Lambeth Group and Chalk Formation
- Solution features along the sub crop interface between the Lambeth Group and Chalk

An assessment of the potential presence of solution features across the development has been carried out and a risk assessment has been undertaken to assess whether the features identified are likely to impact the proposed development or if the development may cause reactivation of features.

The results of the assessments indicate that for certain areas of the site there is a risk of solution features impacting the development and remedial measures are recommended.

The most significant feature encountered is the solution feature in the south east margin of the site associated with an existing surface depression, which is approximately 80m by 100m in plan, extending to a depth of around 24m and containing voided/micro voided areas. It is recommended that ground stabilisation measures are adopted within this feature and that additional foundation protection measures are adopted, together with the use of geogrids within pavement construction.

The other risk areas identified by the survey are the interface boundary between the Lambeth Group and the Chalk and within the zone of discordance. It is recommended that additional foundation protection measures are adopted in these areas, together with the provision of geogrids within pavements.

In addition to the above, surface water control measures in the form of impermeable liners are also recommended for the proposed drainage channels/swales and the proposed balancing pond to prevent the introduction of surface water into solution features. It is also recommended that all water pipes are of flexible construction to allow for the possibility of some differential movement.

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1 Introduction

Peter Brett Associates (PBA) were retained by a consortium comprising Heron Land Developments, Taylor Woodrow Developments and Persimmon Homes to provide geotechnical advice for a proposed development at West Durrington, Worthing.

PBA carried out a geotechnical investigation over the first phase of the development area in 2001 (PBA 2001). As part of the investigation, areas of anomalous ground and groundwater conditions were encountered, namely in the vicinity of BH 209 and TP 111. In both the above exploratory holes, bands of gravel were encountered at depths where Lambeth Group strata (clays) were expected based on the published geological information and the findings of adjacent boreholes. In addition, groundwater monitoring within BH 209 indicated the borehole to be dry, which again was anomalous compared to other boreholes.

Initial geophysical surveys were carried out in May 2004 over 50m by 50m areas centred on the above exploratory holes in an attempt to determine the cause and extent of the anomalous ground conditions. The geophysical surveys were carried out by Earth Solutions and comprised a resistivity survey and ground conductivity survey and confirmed the presence of anomalous features.

Following the findings of the initial surveys, it was recommended that a geophysical survey be carried out across the whole of the development area to confirm the extent of the anomalous ground identified and to locate any other anomalous areas that may be present.

Earth Solutions were appointed to carry out a geophysical survey using electrical resistivity tomography (ERT) techniques across the whole development area. The geophysical survey was carried out in two stages, namely in September/October 2004 and May/June 2005.

Based on the findings of the surveys, specific ground investigation programmes were implemented to confirm the ground conditions interpreted from the survey.

This report presents the findings of the geophysical surveys and the ground investigations, discusses the interpreted ground conditions revealed by the investigations and any potential impacts on the proposed development, presents a

risk assessment and makes recommendations for remedial measures and any additional fieldwork.

The comments made in this report and the opinions expressed are based on the sources quoted, the ground conditions encountered within the exploratory holes and the results of tests made in the field and laboratory. There may however be conditions pertaining at the site which have not been disclosed by the investigation and which therefore could not be taken into account.

The interpretation carried out in this report is based on a scientific and engineering appraisal. We have not taken into consideration the perceptions of, for example, banks, insurers, lay people etc.

2 Geology

2.1 General

Published information and the results of previous investigations indicate that the ground conditions across the site comprise the following sequence:

Recent Deposits	Head Brickearth
Solid Deposits	London Clay Formation Lambeth Group Upper Chalk Formation

An unconformity is present between the Lambeth Group and the Chalk which represents a break in the deposition sequence and a period of erosion before the Lambeth Group was deposited. A similar unconformity is present between the Lambeth Group and the overlying London Clay Formation.

The result of the geophysical survey generally confirms the published information and the findings of previous investigations. However, the survey has identified a number of potential dissolution features and other anomalies that may have an impact on the proposed development. The formation of and types of dissolution features that may be present are discussed in the following section.

2.2 Dissolution Features

These features are formed by the dissolution of the chalk under certain past geological conditions relating to the temperature, the presence of carbon dioxide and the hydrogeological regime. Several different types of dissolution features can occur and typical examples are indicated in Figure 1.

Dissolution features can be infilled with water transported sediment or collapsed overlying sediments, which can comprise the Lambeth Group or Recent Deposits. It is therefore possible that these features can represent a zone of 'loose', unconsolidated or voided ground. In some circumstances, there may be a degree of self compaction as the infilled material subsides/settles into a feature, particularly if the infill material comprises older deposits that have been subsequently covered by younger deposits. However, whilst the actual material infilling the feature may have

been consolidated to a certain degree, there may be reduced strength or relaxed ground adjacent to the actual feature as a result of the collapse of the infill material.

In some situations where more competent ground is present, this may form a bridge to the upward migration of any dissolution features generated at depth. As such, and with the continued generation/erosion of the dissolution feature, infill material does not infill the feature and a void may be generated below the bridging depth. Over time, stresses/strains build up within the bridging layer which could lead to a potential sudden collapse and the rapid migration of a void to ground level.

Dissolution features can occur throughout the Upper Chalk sequence being related to geomorphological, geological, structural and hydrogeological controls. In Southern England solution features occur beneath the boundary/interface between Tertiary Deposits (such as the Lambeth Group) and the underlying Chalk. This may be intensified at the margins of Tertiary Deposits, where they are predominantly cohesive and surface water is directed to the outcrop margins where they form 'swallow holes'.

3 Ground Investigation

3.1 Resistivity Survey

An electrical resistivity tomography (ERT) survey was carried out across the whole of the site where access was available. The surveys were carried out during September/October 2004 and May/June 2005.

A total of 90 survey lines were carried out at approximately 10m centres. The lengths of the survey lines varied from around 280m to 560m to suit the site conditions and field/development area boundaries. Along each survey line, ERT data was acquired using a Wenner-Schlumberger array configuration. Penetration to depths of around 18m for the September/October 2004 survey and 30m for the May/June 2005 survey were achieved within the centre of the survey lines, reducing to shallower depths at the ends of each array.

The position of the survey lines was controlled by the use of a GPS system with a lateral accuracy likely to be better than 0.5m. Topographic corrections were applied to the data to incorporate level changes along the survey lines to enable the data to be presented relative to Ordnance Datum. The location of the survey lines is presented in Figure 2.

A single ERT measurement involves using 2 electrodes to transmit current (termed C1 and C2) and two electrodes across which the potential difference or voltage is measured (termed P1 and P2). The voltage divided by the current gives the measured resistance (R). As the positions of the current and voltage electrodes vary (controlled by the computer), each four electrode resistance measurement will investigate a different volume of the ground. The measured resistance values (in ohms) can be converted to apparent resistivity values using a geometric factor appropriate for the array used.

Sophisticated software packages were used to process the resistivity data for the final analysis to produce 2 dimensional sections of apparent resistivity against depth for each survey line. These are presented in Appendix 1.

It should be noted that the ERT surveys were carried out at different times of the year and there may therefore be a difference in the resistivity values recorded for the

strata present due to seasonal changes (i.e. changes in natural moisture contents, groundwater levels etc).

It should also be noted that, as discussed previously, the depth of penetration around the margins of the survey areas is reduced. In presenting some of the data, the findings of the surveys have been combined to aid interpretation. Care should therefore be taken in interpreting the combined survey plots around the survey boundaries for the above reason, together with the possible effects of seasonal changes described earlier.

3.2 Cable Percussion Boreholes

Fourteen boreholes (BH 301 to BH 314) were drilled using cable percussion drilling techniques to depths of between 14.3m and 26.0m. The boreholes were positioned within the features identified by the geophysical survey to confirm the ground conditions.

Representative disturbed and undisturbed samples were collected as drilling proceeded for further examination and laboratory testing. In addition, standard or cone penetration tests were also carried out at regular intervals. On completion of the drilling, the boreholes were backfilled with a bentonite/cement grout.

Details of the strata encountered, samples taken, in-situ test results and groundwater observations during drilling are given on the borehole records in Appendix 2.

The positions of the boreholes were determined relative to the National Grid and the elevations were determined relative to Ordnance Datum.

The locations of the boreholes are presented on Figure 3, which also indicates the position of historical exploratory holes carried out across the site.

3.3 Cone Penetration Testing (CPTs)

Twenty four CPTs (401 to 424) were undertaken using a piezo-cone rig within selected potential solution features to provide a continuous record of the ground conditions within the features and to attempt to identify any potential unstable/micro voided or disturbed zones. Four potential solution features along the northern boundary were investigated, with a north south orientated array of 4 CPTs at around

10m spacing carried out in each feature. Two north south orientated arrays of 4 CPTs were carried out in a suspected feature in the south eastern margin.

A 15cm² electric cone was used to measure end resistance (q_c) and local side friction (f_s). The cone resistance and local side friction are measured by strain gauges attached to the cone with the information being recorded on a data logger attached to a computer at 1cm intervals. The relationship between the measured side friction and cone resistance (friction ratio R_f) is calculated by the computer to assist in the interpretation of the ground conditions along with the cone resistance based on the recommendations given by Robertson et al (1997).

Measurements of pore water pressures during penetration were also recorded to provide additional information on the nature of the soils encountered. In addition, measurements of gamma concentrations were also recorded to aid in the identification of the soil types encountered.

The results of the CPTs are contained in Appendix 3 and the location of the CPT's is presented in Figure 3.

It should be noted however that the CPTs were spaced at around 10m centres to try to identify any zones of disturbance associated with a solution feature rather than to try to specifically encounter a feature, which may be relatively discrete and smaller in size than the CPT spacing.

3.4 Laboratory Testing

The following laboratory classification testing was carried out on samples recovered from the exploratory holes. The testing was carried out in accordance with the recommendations given in BS 1377 Method of Test for Soils for Civil Engineering Purposes as appropriate.

- Natural Moisture Content
- Plasticity Index

The results of the testing are contained in Appendix 4. A profile of natural moisture content versus depth is presented in Figure 4 and a plasticity chart is presented in Figure 5.

4 Interpreted Ground Conditions

4.1 Geophysical Survey

4.1.1 5 to 100ohmm Plots

The results of the geophysical survey are presented as contoured section plots over the range of 5 to 100ohmm for each of the survey lines in Appendix 1. The results of the survey have also been prepared as series of plan plots for various depth slice intervals and these are presented in Appendix 5.

These plots confirm the presence of high resistivity granular Recent Head deposits from ground level over the eastern and northern areas of the site, typically to depths of between 2m to 4m. Over the western part of the site, cohesive Head deposits or the London Formation Clays/Basal Sands are indicated to be present from ground level.

With depth, the plots indicate the presence of the main lithological units over the eastern and northern parts of the site with the low resistivity Lambeth Group underlying the granular Recent Head deposits. The high resistivity Chalk Formation is present beneath the Lambeth Group/Recent Head, dipping at shallow angles to the south from around 14mAOD along the northern boundary to -10mAOD along the southern boundary. The plots indicate the unconformable boundary between the Lambeth Group and the Chalk Formation.

For the western part of the site, the plots indicate the presence of the low resistivity London Clay underlain by the higher resistivity Basal Sand member in the central north western margins. The Basal Sand appears to extend to depths of around 14m, which is consistent with the findings of the previous boreholes in this area of the site, with the sands underlain by the Lambeth Group. The Chalk Formation is indicated to be present at an elevation of around -20mAOD over the western half of the site based on the geophysical survey.

The depth slices indicate areas of higher resistivity within the Lambeth Group in the south eastern margin of the site, in an area coincident with a surface depression. The geophysical survey indicates isolated, high resistivity bands present at around 18 to

20m within the feature, with the feature tending to become smaller in plan size with depth.

The above is also indicated by the geophysical section profiles (see lines 42 to 45), which indicate that the material infilling the feature varies over short lateral distances and appears to narrow with depth. It should also be noted that the boundary between the high resistivity granular Recent Head deposits and the low resistivity clays on the above profiles is erratic compared with other areas of the site, possibly indicating movement within the more recent deposits in this part of the site.

The 5-100ohmm depth slices and profiles indicate the possible presence of smaller scale dissolution features in the northern area of the site, approximately along the sub crop boundary between the Lambeth Group and the Chalk Formation.

The 5-100ohmm depth slices and profiles also indicate an area of higher resistivity within the Lambeth Group within the central southern area of the site, extending to a depth of around 12m.

4.1.2 0- 40 ohmm Plots

By constraining the survey results to within the 0-40 ohmm range, it is evident that the geophysical depth slices indicate additional features to those described that have not been revealed by the wider ranging 5-100ohmm depth slices. The depth slices covering the range 0-40ohmm are reproduced in Appendix 6.

It should be noted that care is required when interpreting the 0-40ohmm depth slices as the more brightly coloured areas may be interpreted as representing higher resistivity material (such as gravel or chalk) which may not be the case because of the resistivity range constraint that's being artificially applied by the software for interpretative purposes (i.e. cohesive strata may have a resistivity of around 40 ohmm or greater). The 0-40 ohmm plots should therefore be considered as reflecting subtle changes within material of similar lithology (i.e. the 0-40 ohmm range plots pick out subtle variations within materials having a cohesive lithology).

The main feature indicated by the 0-40 ohmm depth slices is a roughly linear band of 'higher' resistivity material within the Lambeth Group over the southern section of the site. This feature has been termed the 'zone of discordance'. This zone, which is around 100m wide, extends to the eastern site boundary but appears to terminate at the eastern margins of the feature in the central southern area indicated by the 5-100

ohmm depth slices, although it may not be as well defined further to the west and may extend to the area of the site where the London Clay Formation is present. The zone of discordance therefore does not appear to extend laterally along the same trend into the area of the site underlain by the London Clays/Basal Sands, although it is possible that the zone may extend to the south around the margins of the Basal Sands. The zone of discordance is present from around 4m depth to 12m depth although it may be being masked beneath 12m depth by the presence of material with a similar resistivity value present over parts of the site.

Based on the 0-40 ohmm depth slices, the western margins of the zone of discordance appears to be marked by a circular, higher resistivity feature, approximately in the same position as the possible dissolution feature in the southern central area identified in the 5-100 ohmm depth slices.

The zone of discordance is also reflected in the geophysical survey profiles (see Appendix 1), with the northern boundary of the zone marked by an apparently near vertical, trough like feature in places extending through the Lambeth Group into the underlying Chalk. Between survey lines 29 and 37, a band of higher resistivity material is indicated within the zone of discordance from around 8m to the depth reached by the survey. Between survey lines 1 and 6, a band of higher resistivity material appears to be present overlying and extending to the north of the zone at depths of around 2m to 8m approximately, dipping gently to the south.

The zone of discordance also appears to run through a fault in the Lambeth Group/Chalk at around Easting 510750E (see section D-D, Figure 7), implying that the zone is younger than the fault, although the position of the fault is approximately commensurate with the area where the zone of discordance is less well defined.

4.2 Exploratory Holes

4.2.1 General

A series of exploratory holes were carried out within the features identified by the geophysical survey to confirm the ground conditions. The findings of these exploratory holes in each of the features are discussed in the following sections. Geological sections across the site based on the findings of current and historical exploratory holes are presented in Figures 6 and 7. The exploratory holes have been superimposed on to the 12 to 14m 0-40ohmm depth slice in Figure 8, which also indicates the features identified by the geophysical survey.

4.2.2 Potential Solution Feature South East Margin

The boreholes carried out in this feature indicates that the depth to the top of the chalk varies over a relatively short lateral distance, with the chalk encountered at 14.5m depth (1.45mAOD) in borehole 309 located around the margins of the feature and 21.5m depth (-6.2mAOD) in borehole 310 located in the centre of the feature. The results of standard penetration tests in these boreholes also indicate a scattered in the N values recorded indicating 'disturbed' ground compared to the boreholes outside of the feature.

Two rows of CPT's were carried out within the feature (417 to 420 and 421 to 424) and the results are presented in Figures 9 and 10. The CPT's confirm the variable nature of the material within the feature. Chalk was encountered at depths of between 14m and 24m based on the gamma logs, being deepest in the centre of the feature.

It is therefore considered that this feature represents a dissolution feature within the chalk that is around 100m by 80m in plan and extends to a depth of around 24m in the centre of the feature (see Section DD, Figure 7).

The areas of high resistivity recorded in this feature may also represent the presence of open, unsaturated micro-voided or voided material, particularly at depth. The SPT at 22.5m in borehole 310 dropped to around 24m depth under the weight of the rods confirming the presence of voided/micro voided material.

4.2.3 Potential Solution Feature Southern Central Area

The results of the boreholes carried out in this area indicate that the top of the chalk is present at a relatively consistent depth of around 22m (see Section E-E Figure 7) and standard penetration tests carried out in these holes has not revealed the presence of any 'disturbed' material in either the Lambeth Group or the Chalk. The geophysical survey did not reveal the presence of high resistivity material at depth as for the feature in the south eastern margin.

It is therefore considered that the area of higher resistivity recorded in the south central area of the site does not represent a dissolution feature. The reason for this apparent area of higher resistivity is discussed further in the following section.

4.2.4 Zone of Discordance

A number of cable percussion boreholes were drilled within the western and eastern margins of the zone of discordance, where high resistivity material is indicated to be present at depth. The results of the boreholes however did not reveal a significant variation in the nature of the materials below around 8m depth, with cohesive materials (low resistivity) being encountered above the chalk as would be expected from the known geology. The elevation to the top of the Chalk was approximately similar in the boreholes at either end of the feature (save the variations that would be expected due to the unconformity between the Lambeth Group and the Chalk) and hence did not reveal a steep side chalk interface as suggested by the geophysical survey.

The results of the boreholes did however reveal the presence of gravels at depths of between 6m to 8m which would not be expected based on the geology as they would be present in the Lambeth Group. These gravels are the same as those recorded in the original ground investigation exploratory holes BH 209 and TP 111 which were considered to be anomalous and initiated the original geophysical survey. The gravel bands appear to be continuous in an east west direction within the zone of discordance, although it should be noted that the boreholes carried out concentrated on the western and eastern margins of the zone of discordance and hence only limited information is available for the central area.

The boreholes carried out just to the north of the zone of discordance (boreholes 307, 311 and 314) did not reveal the presence of the gravel layer indicating that the northern boundary of the extent of the gravels is steep sided.

The gravels, where present, vary in thickness from between 0.35m and 3.3m, with the thickest layers present adjacent to the northern boundary of the zone of discordance.

It is considered that the northern end of the zone of discordance denotes a former cliff line, with the granular material representing former beach deposits (termed Raised Beach deposits as they were deposited when sea levels were much higher than present day). The thickness of the gravels is greater along the northern boundary of the zone of discordance and these represent the former shore line/high water mark, with the deposits fining to the south representing the low water mark.

The elevation to the base of the Raised Beach indicated by the boreholes was relatively consistent at around 7mAOD, although there are local variations to this.

The results of the laboratory and in-situ testing indicate that the clays that overlie the gravels have different properties to the Lambeth Group and it is considered that they probably reflect recent Brickearth strata. This is demonstrated by the plasticity test results (see Figure 5), where three distinct groups of test results can be seen, although there is some overlap. Material thought to represent the Brickearth strata is typically of intermediate to high plasticity range whereas material thought to represent the Lambeth Group forms either low to intermediate plasticity or high to very high plasticity materials. The low to intermediate plasticity Lambeth Group tends to be present in the upper sections of the sequence with the high to very high plasticity material present in the basal sections of the Lambeth Group.

The former beach deposits and Brickearth strata were subsequently covered by the deposition of the Recent Head deposits.

As discussed previously, the zone of discordance does not appear to extend laterally along the same trend into the area of the site where the London Clay/Basal Sand is present and the reason for this is not apparent. It is possible that, because the Basal Sand is more resistant to weathering due to cementing, this area was more resistant to erosion and hence formed a headland along the former cliff line. The zone of discordance/former cliff line may therefore extend in a southerly direction in parallel with the headland formed of the Basal Sands.

The approximate extent of the Raised Beach deposits inferred from the survey is indicated in Figure 11.

The results of the geophysical survey line sections has indicated the presence of high resistivity material commensurate with the Raised Beach deposits encountered in the boreholes, with the depth to the top of the Raised Beach indicated in the survey profiles being similar to that recorded in the boreholes. The survey profiles however indicate that the high resistivity band extends to depths greater than that recorded by the boreholes, particularly between survey lines 29 and 37.

The Raised Beach deposits appear to form a discrete localised band and it is possible that these are influencing the results of the geophysical survey, giving rise to the presence of 'higher' resistivity material present at depths greater than that revealed by the boreholes. This may be more pronounced at either end of the zone, where more extensive gravel deposits appear to be present. The exploratory holes indicate that the northern extent of the feature is steep sided (the inferred former cliff

line) and this could be influencing profiles, reflecting in the trough like/steeply dipping chalk boundary indicated in the survey profiles along the northern boundary of the feature.

As discussed, the survey indicates that the gravels are only present against the northern boundary of the zone, with a fining sequence apparently present to the south. The gravels are replaced by sands and then Brickearth deposits, with the Raised Beach deposits eventually being replaced by the Brickearth deposits resting directly on the Lambeth Group. The Brickearth and the Lambeth Group are likely to have similar geophysical properties (particularly if both are saturated) and hence the geological boundary between the Brickearth and Lambeth Group may not be discernable from the geophysical survey outside of areas where the Raised Beach deposits are present.

It is possible that the presence of the Raised Beach deposits are also influencing the local hydrogeological regime. For example, the standpipe in BH 209 was installed within the Raised Beach deposits and the monitoring of the standpipe did not record the presence of groundwater in this borehole, which is anomalous compared to adjacent standpipes installed in the Lambeth Group. The presence of the Raised Beach may therefore be leading to under draining of the overlying strata which could be influencing the depth slice plots at shallow depths, leading to apparent areas of higher resistivity above the Raised Beach deposits.

The above appears to be being reflected in the moisture content testing (see Figure 4). The results of the testing of samples from boreholes 301 and 302 located in the western part of the zone indicate a roughly linear reduction in moisture content with depth until around 9m to 11m (below the Raised Beach deposits). Below this depth, moisture contents increase until stabilising at around 12m to 14m depth. Boreholes 301 and 302 are located within the southern central feature and seem to be confirming the findings of the 5 – 100 ohm plots which indicated bands of higher resistivity to depths of around 12m to 14m.

Moisture content analyses were also carried out for boreholes 307 (to the north of the zone), borehole 305 (within the zone) and borehole 304 (to the south of the zone). The analyses indicate that the moisture content profile to the south of the zone is relatively consistent to a depth of around 10m before reducing with depth. The moisture content within the zone indicates that moisture content reduces approximately linearly with depth to around 12m before increasing. The moisture

content profile to the north of the zone is however not clear, with no discernable pattern evident.

The presence of the Raised Beach deposits may therefore be causing local variations to the drainage patterns within this part of the site and are of higher permeability than the cohesive Lambeth Group, both of which could affect the geophysical survey results.

It is also possible that the apparent zone of higher resistivity beneath the Raised Beach deposits within the zone of discordance and the apparent trough like feature in the chalk indicated in the geophysical sections may be reflecting karstic features within the Chalk. At the time the cliff line was formed, the fresh/salt water interface would have been present approximately along the line of the former cliffs. The geophysical survey and boreholes indicates that a number of north south trending faults are present within the Lambeth Group and Chalk. Groundwater flow within the Chalk will be controlled by its secondary permeability, with water being stored in and flowing through fractures in the Chalk, such as a fault line. Fresh water from the higher ground to the north of the former cliff line is therefore likely to have preferentially flowed along the fault lines.

As fresh water is less dense than salt water, fresh water flow from faults will be inclined to flow laterally or even flow upwards to create a spring line at the surface due to the density difference between salt and fresh water. This concentration of groundwater at the margins of fault lines could therefore lead to local dissolution of the Chalk or the increased generation of solution widened discontinuities.

The above could account for the circular patterns at either end of the zone of discordance, which are consistent to where faults are thought to be present. The dissolution may have locally increased the discontinuity aperture/opening in the south eastern margins of the zone of discordance leading to the generation of the solution feature identified in this part of the site, which appears to have been generated by a different mechanism than other possible solution features identified across the site.

A sketch section through the zone of discordance indicating the various processes described above is given in Figure 12.

4.2.5 Potential Solution Features at the Lambeth Group/Chalk Subcrop Interface

The results of the geophysical survey indicate the possible presence of solution features within the northern sector of the site, coincident with the sub crop boundary between the Lambeth Group and the Chalk Formation. The positions of these features are indicated on Figure 8. Cone penetration tests were carried out within 4 of these features (labelled feature 1 to 4) and these results of these tests are discussed below.

Feature 1

CPTs 401 to 404 were carried out within feature 1 and the results are presented in Figure 13. The results indicate the presence of the granular Recent Head deposits to around 3m depth, underlain by cohesive material thought to represent the Lambeth Group. All the CPTs terminated at depths of around 8.5m to 10.0m on a 'very dense' layer that could not be penetrated by the CPT rig. It is thought that this 'dense' layer may represent a cemented layer towards the top of the chalk sequence based on some of the historical exploratory holes, although the geophysical survey suggests that the chalk is present at greater depths in this part of the site.

The results of the CPTs within feature 1 indicate fairly uniform ground conditions to depths of around 10m. Whilst it is possible that a feature may be present below this depth, any such feature does not appear to have impacted on the overlying ground with no evidence of disturbed or voided ground recorded in the CPTs.

Feature 2

CPTs 405 to 408 were carried out within feature 2 and the results are presented in Figure 14. CPT's 405 and 408 carried out on the margins of the feature indicate similar ground conditions, with around 3m of granular Recent Head deposits overlying the Lambeth Group. Both these CPT's terminated on a 'very dense' layer at depths of between 7m and 9m. The 'dense' layer could be the cemented layer at the top of the chalk, with the chalk apparently dipping to the south which would be expected.

CPTs 406 and 405 carried out in the centre of the feature also indicate the presence of the Recent Head deposits to a depth of around 3m. With depth however, 406 and 407 indicate variable ground conditions with interbedded granular and cohesive layers recorded beneath the Head deposits in 406 and mainly cohesive materials beneath the Head deposits in 407. The Chalk Formation appears to have been

encountered at depths of 14m in 406 and 16m in 407 based on the gamma logs. Both CPT 406 and 407 terminated at shallow depths into the chalk on 'very dense' layers.

It is therefore considered that these CPTs have revealed the presence of a solution feature within the Chalk to a depth of at least 16m. The CPTs however have not revealed any disturbed or voided areas within the solution feature, although a zone of reduced end resistance around 0.1m thick was recorded towards the base of the feature in 407 at 15m depth.

Feature 3

CPT's 409 to 412 were carried out in feature 3 and the results are presented in Figure 15. CPT's 409 and 412 carried out on the margins of the feature indicate the presence of the granular Recent Head Deposits to depths of around 3.5m, underlain by cohesive material (probably the Lambeth Group). At depths of around 5.0m to 5.5m, these CPT's terminated on a 'very dense' layer, thought to be the cemented layer at the top of the Chalk sequence based on the findings of Borehole 208.

CPT's 410 and 411 were carried out within the feature and indicate similar ground conditions, with the chalk indicated to be present at depths of around 6m based on the gamma logs. However, both CPT's 410 and 411 were able to penetrate into the chalk to depths of 12m and 10m respectively, where they terminated on very dense layers. It is therefore possible that the cemented band at the top of the chalk may have been disturbed by the presence of localised softening of the Chalk (which may be karstic in origin) in CPT's 410 and 411 allowing these CPT's to penetrate the cemented layer. The CPTs however do not indicate any disturbed or voided zones.

Feature 4

CPT's 413 to 416 were carried out in feature 4 and the results are presented in Figure 16. The results of the CPT's indicate granular Recent Head deposits to be present to depths of around 4m, underlain by cohesive deposits, which probably represent the Lambeth Group. At depths of around 5m to 6m, the top of the Chalk was encountered based on the results of the gamma logs. The cemented band towards the top of the chalk encountered in the other CPT's does not appear to be present in this area of the site, although 413 terminated at shallow depth, which again may be indicating local 'softening' of the chalk due to the presence of karstic features.

The results of the CPT's that penetrated the Chalk did not reveal the presence of any disturbed or voided ground. It is therefore possible that the geophysical anomaly may be indicating a change in the degree of cementing or a localised variation in the lithology of the chalk in this part of the site due to karstic action

5 Potential Engineering Implications

5.1 Potential For Solution Features

The result of the geophysical survey and exploratory holes indicates the presence of a number of features across the site which may have a potential impact on the proposed development. The master plan has been superimposed on the 12 to 14m geophysical depth slice in Figure 17 to correlate the proposed end uses with the features identified.

The solution features identified may be meta stable and hence have the potential to result in gradual subsidence or sudden ground loss. As a result of human activities, the rate of subsidence can be influenced or apparently stable features can be reactivated. The most common human activities that can affect the propagation of solution features are listed below:

- Dynamic loading
- Static loading
- Adoption of soakaways
- Leaking drains or water pipes
- Changes to the existing hydrogeological regime

5.2 Remedial Options

Several remedial options could be considered in areas where solution features have the potential to be present to minimise the impacts of ongoing subsidence or the reactivation of solution features on future developments. It is impossible however to predict the exact nature of any future subsidence in terms of the surface expression of continued subsidence/sudden ground loss or the time scales for any future subsidence to impact the development following construction.

The remedial options that could be considered are summarised below.

Do Nothing

For the do nothing option, no remedial measures are implemented and the impacts from any subsidence that occurs will be treated on an ad-hoc basis, whether this be damage to individual structures or areas of pavements for example. The advantage of this option is that only the impacted areas, should they occur, will require remedial measures rather than a blanket treatment strategy. The disadvantage of this option is that it is impossible to predict when any impacts will occur and hence a long term commitment will be required from developers to treat any impacted areas. A long term maintenance programme may also be required as any continued subsidence may occur at a slow rate rather than as a sudden failure.

The Health and Safety implications also need to be assessed for this option. It is possible that continued subsidence could result in sudden ground losses of around 1m to 3m size say beneath structures, pavements, services or public open spaces. There will therefore be a potential for serious injury to future residents.

Excavation and Replacement

One potential option is to remove the material within the solution feature and replace with suitably compacted engineered fill. However, due to the presence of a significant thickness of Recent Deposits across the site, this option will not be practical.

Foundation Design

For this option, the foundations in all areas where solution features are present are designed to accommodate any future subsidence or sudden ground loss.

This can be accomplished by the adoption of raft foundations or the adoption of additional reinforcement within traditional foundations. It is common practice where solution features have been identified to design the foundations to be able to bridge over a distance of 3m should continued subsidence occur or to be able to accommodate 1m of ground loss should sudden collapse occur.

For this site however, a significant thickness of superficial deposits are present and hence it will not be possible to specifically identify features prior to or during construction unless very extensive ground investigations are carried out for each structure and, even then, some uncertainty may exist. Additional foundation precautions will therefore be required in all areas of the site where there is the potential for solution features to be present.

The main advantage of this option is that the developer should not incur any long term commitments with regard to future failures or maintenance issues. The main disadvantage of this option is that all the structures within an area potentially susceptible to solution features will need the additional foundation precautions.

It should be noted that local Building Control Officers usually require the provision of additional foundation precautions in areas where solution features may be present.

Pavements/Public Open Areas

For pavements or open areas within solution features, consideration could be given to the adoption of geogrids to minimise the potential impact that continued subsidence or sudden ground loss may have. As for the foundations however, the geogrids will be required in all areas where there is a potential for solution features to be present.

Ground Stabilisation

This option involves the stabilisation of disturbed/meta stable areas of ground by the injection of grout. The grouting will be required across the whole of the plan area and depth of a feature to ensure that all potentially disturbed ground is treated. The grouting should initially be carried out on a regularly spaced primary grid of injection holes, with a secondary grid on a closer spacing carried out in areas where significant grout takes have been recorded. Validation testing will be required to confirm the effectiveness of the grouting.

Several different types of grouting schemes could be considered such as compaction grouting or permeation grouting. The grouting scheme can be designed to either treat a feature to its full depth or to provide a bridging layer at an intermediate depth to prevent any deeper seated features from migrating to the surface.

The main advantage of this option is that specific information on the proposed layout of future structures need not be known as an area will be treated and hence there will be long term flexibility for the end use of the site. This option will also allow the adoption of traditional foundations where deep features are present and will remove the need for any long term maintenance.

Piling

The adoption of piled foundations will require detailed ground investigation works to confirm the depth to the base of a feature beneath a proposed structure to ensure the

piles are taken down into undisturbed/stable ground. The investigation indicates that some of the features present across the site are present to depths of around 25m which are in excess of the depths that can be achieved with some conventional piling techniques such as continuous flight or displacement augered piles.

It is therefore considered that the adoption of piles alone for the site is unlikely to be economic compared to the other options available. It is possible that the option of piles could be feasible if carried out in conjunction with a ground stabilisation scheme.

Control of Surface Water

As discussed previously, one of the most common causes of the acceleration of subsidence or the reactivation of features is the introduction of water within features. Concentrated flows of water can cause washing out of material within the meta stable infill to solution features, resulting in breakdown and collapse.

As part of the development, remedial measures will also be required to control the management of surface water across the site following development and these are discussed in detail in Section 5.7.

5.3 Risk Assessment

An assessment of the potential for solution features to be present across the whole of the site has been carried out and is summarised in Figure 18.

A risk assessment has been carried out on the impacts that the proposed development may have across the site based on the potential for solution features to be present. The results of the risk assessment are summarised over, together with the remedial options that could be considered.

Risk Assessment

Potential for solution features to be present	Area of site	Comments	Risk of development activating features	Remedial Options that could be considered
Negligible	Western 1/3 where London Clay/Basal Sands present	Ground conditions not conducive to the formation of solution features	Not anticipated	Not considered to be necessary
Low	Northern sector where chalk sub crops beneath Recent Deposits	Ground conditions not particularly favourable to the formation of solution features	Low	Not considered to be necessary
Moderately high	Southern sector excluding zone of discordance and where London Clay/Basal Sands present	Ground conditions potentially favourable to the formation of solution features (although no specific features identified)	Low/moderate Development will change pattern of surface water drainage and infiltration into the ground.	Control of surface water Adoption of additional reinforcement in traditional foundations to be able to span 1m ground loss.
High	Lambeth Group/Chalk boundary	Ground conditions conducive to formation of solution features. The investigation indicates a number of these features to be present in this area of the site although some of these features appear to contain stable infill	Low/moderate Development will change pattern of surface water drainage and infiltration into the ground.	Adoption of raft foundations or additional reinforcement in traditional foundations to span 3m ground loss. Use of geogrids in pavement/public open areas
High	Zone of discordance (excluding south east corner)	Ground conditions conducive to the formation of solution features. The investigation suggests that karstic features may be present in the chalk, together with small scale solution features.	Moderate Development will change pattern of surface water drainage and infiltration into the ground.	Adoption of raft foundations or additional reinforcement in traditional foundations Use of geogrids in pavement/open areas.
Very High	South east corner	The investigation indicates disturbed and voided ground associated with a surface depression and probable underlying large scale solution feature.	High Proposal to infill existing depression will load the feature and affect local surface water regime	Ground stabilisation. Adoption of additional reinforcement in traditional foundations to be able to span 1m ground loss.

Based on the results of the risk assessment, it is considered that remedial measures will be required across certain areas of the site together with the provision of surface water control measures and these are discussed in the following sections.

5.4 Solution Feature South East Margin

The results of the geophysical survey and the exploratory holes indicate that a large solution feature is present in the south eastern margins of the site, delineated by a surface depression. The feature is around 100m by 80m in plan at ground level, reducing with depth and extends to a depth of at least 24m in the centre. The result of the investigation confirms the presence of voids or micro-voided areas within the feature.

As part of the development, it is proposed to infill the existing surface depression to provide a level site to enable the infrastructure works to be constructed. As such, ground levels will need to be raised by around 2m to 2.5m over the whole of the solution feature. The effects of this ground raising will be to superimpose loads onto the feature and this may cause reactivation of the solution feature or the collapse of voided/micro-voided zones that may migrate to the surface and impact foundations or infrastructure works. The reactivation of the feature or the collapse of voids may not occur immediately after the loads from the ground raising exercise have been applied as they may be time related, dependent on changes to the existing stress-strain regime.

The infilling of the existing depression will also affect the existing surface drainage system in this area of the site which, as discussed previously, may also trigger subsidence.

It is therefore recommended that remedial measures are carried out before the ground raising exercise is carried out and any infrastructure works are implemented. Whilst details on the position of the proposed infrastructure works are currently known, specific details on the layout of the proposed structures in this area of the site are not known. The remedial works should therefore be designed to take into consideration the future use of this part of the site to ensure the site can be safely and cost effectively developed.

It is considered that the most appropriate remedial treatment will be to carry out a grouting scheme within the solution feature to produce a 'bridging' layer say from 2m

to 3m depth (the shallowest depth at which compaction grouting will be effective) down to 15m depth (approximate depth to the top of the chalk at the margins of the feature) by stabilising any disturbed or meta stable areas within these depths. The formation of the bridging layer will prevent the migration of any deeper seated features from migrating to the surface.

Detailed discussions will be required with the Environment Agency as the grouting will be required within the Chalk which is a major Class 1 aquifer.

Compaction grouting is only likely to be effective beneath depths of around 2m to 3m depth due to the lack of adequate confining overburden pressures at shallower depths. It is therefore possible that some residual disturbed areas may be present at shallow depths following the treatment. Consideration could be given to adopting a different grouting technique (permeation grouting say) over the shallow depths, although this may influence the excavations for services/foundation trenches.

As discussed previously, it is proposed to infill the existing surface depression, which will require the placement of fill to various depths over the feature. Provided that the fill is placed as engineered fill with an appropriate allowable bearing capacity, traditional footings could be adopted within this feature following infilling. However, the thickness of the engineered fill beneath the structures will vary and some structures may be founded on both the engineered fill and the natural ground which may lead to potential differential settlement problems.

It is therefore recommended that, due to the potential for differential settlement and the fact some residual disturbed areas may be present following the grouting, raft foundations or reinforced traditional foundations are adopted within this area of the site following grouting and infilling.

It is also considered prudent to allow for the provision of a geogrid (Tensar SS30 or similar) within the pavement construction in this area of the site to accommodate any potential long term or differential movement beneath pavements.

5.5 Lambeth Group/Chalk Interface

Of the four potential solution features investigated along the Lambeth Group/Chalk sub crop boundary, only potential disturbance due to the presence of a solution feature has been positively identified in one of the CPT arrays, namely in the area of CPT's 405 to 408. The result of all the CPT's carried out has not revealed the

presence of disturbed or meta stable materials in any of the potential features investigated.

It should be noted however that the CPTs were spaced at around 10m centres to try to identify any zones of disturbance associated with a solution feature rather than to try to specifically encounter a feature, which may be relatively discrete and smaller in size than the CPT spacing.

The geophysical survey indicates that the boundary between the Recent Deposits and underlying Lambeth Group or Chalk Formation is relatively planar in this part of the site, as opposed to the solution feature in the south east margins of the site, where the boundary is irregular, probably as a result of movement within the feature.

It is likely that traditional footings founded at a minimum depth of 0.7m in the granular Recent Head Deposits will be the preferred foundation option for this part of the site. Foundation widths are likely to be the order of 0.45m to 0.6m. As such, the stresses imposed by the foundations will all be within the Head Deposits, which are present to depths of around 3 to 4m.

It is considered that there is a low to moderate risk that the future development will be affected by the presence of solution features or will cause the reactivation of solution features. As a risk is present however, it is considered prudent to either adopt raft foundations or allow for additional reinforcement in traditional foundations in this part of the site.

Consideration should also be given to the adoption of geogrids within the pavement construction to minimise the potential impact of movement within any solution features present.

Surface water control measures will also be required and these are discussed in section 5.7.

5.6 Zone of Discordance

The results of the investigation indicate that karstic features within the Chalk may be present within the zone of discordance. Whilst no specific information from the investigation has confirmed that solution features are present within the zone, there is a risk that these features are present that may impact the future development.

As for the Lambeth Group/Chalk boundary area, the likely preferred foundation option within the zone will be the adoption of traditional foundations at shallow depths within the granular Recent Head Deposits. It is therefore considered prudent to allow for the use of raft type foundations or reinforced traditional foundations in this part of the site.

Consideration could also be given to the adoption of geogrids within the pavement construction to minimise the potential impact of movement within solution features.

5.7 Surface Water Control Measures

As discussed previously, a potential cause of the reactivation of solution features is the introduction of water within the feature, washing out fines material or causing the breakdown of voids.

One of the common causes is the introduction of water into a feature by the adoption of soakaways, although the Environment Agency has not permitted the use of soakaways at this site. However, it is proposed to adopt a system of linear drainage channels/swales across the site to control surface water run off.

A number of these proposed channels/swales are in open cut in areas of the site, where potential solution features are present. It is therefore recommended that these features are lined to prevent the local hydrogeological regime from being influenced and the possible introduction of water into solution features, which may cause reactivation of these features.

5.8 Balancing Pond

The results of the investigation indicate the presence of a former cliff line and the presence of Raised Beach deposits over part of the site including within part of the proposed balancing pond. The exploratory holes indicate that the elevation to the top of the Raised Beach deposits typically varies from around 9mAOD to 10mAOD, with the base of the deposits typically around 7mAOD.

It is understood that it is proposed to construct the balancing pond to an elevation of 9mAOD and hence the Raised Beach deposits are likely to be present in the base and sidewalls over parts of the pond.

A borehole was installed in the vicinity of the proposed balancing pond as part of the 2001 investigation (BH 205) and the log indicates that this borehole was installed in

the margins of the Raised Beach deposits. Groundwater monitoring carried out in this borehole indicated standing water levels of around 1.7m depth (around 11.4mAOD). Recent boreholes carried out within the central area of the Raised Beach deposits encountered groundwater during drilling towards the top of the Raised Beach Deposits at depths of between 4.25m to 5.1m (around 9.35mAOD to 7.8mAOD). After 20 minutes, standing water levels of 0.7m and 0.3m (around 12.6 to 12.9mAOD) were recorded, indicating sub artesian water pressures within the Raised Beach Deposits.

It will therefore be necessary to line the balancing pond where the Raised Beach deposits are present in order to prevent the natural groundwater table from infilling the pond. Lining of the pond will also prevent changes to the existing hydrogeological regime (i.e. the balancing pond may introduce preferential flow paths for storm water) which may reactivate solution features).

The excavation for the balancing pond is likely to encounter cohesive Brickearth strata over the Raised Beach Deposits. The results of the plasticity testing on samples of the Brickearth strata indicate that it is of intermediate plasticity and hence is likely to be suitable as an engineered liner for the balancing pond. Specific testing will be required on the Brickearth to confirm its compaction and permeability properties. The Brickearth may contain a significant amount of silt or fine sand in places and hence some screening of the material may be required.

It is also likely that dewatering will be required during construction of the balancing pond as significant inflows could be expected where the granular Raised Beach deposits are encountered. As discussed previously, the groundwater within the Raised Beach deposits appears to be sub artesian and hence there is a possibility of basal heave occurring due to uplift pressures in areas where the Raised Beach deposits are not exposed during construction of the pond. Groundwater control measures are therefore likely to be required during the construction of the pond/placement of the lining in areas where the Raised Beach deposits are not encountered.

An assessment will also be required on the possible effects of basal heave following construction as this may occur at times when the pond is dry.