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CONTENTS

1 Introduction 1

1.1 Summary 1

1.2 Case Studies 1

1.3 Target Audience and Competence 2

2 Current Issues and reasons for Guidance 3

2.1 Background 3

2.2 Typical difficulties with post earthworks gas monitoring in boreholes 3

2.3 Alternative assessment approach using lines of evidence 4

3 Gas Conceptual Site Model for Earthworks Sites 6

3.1 Background 6

3.2 Gas Sources 7

3.3 Pathways 8

3.4 Data Collection to Inform GCSM Prior to Earthworks 11

4 Routine Data Collection During Earthworks 13

4.1 General Earthworks Requirements 13

4.2 Soil Descriptions 14

4.3 Soil Re-Use / Import 14

4.4 Watching Brief 14

5 Additional Lines of Evidence to be collected During Earthworks 15

5.1 Background 15

5.2 Assessment and Control of Organic Content of Excavated Soils 15

5.3 Verification of Gas Emission Rate of Soils 16

5.4 Gas Emission Rate Measurement 16

1.1.1 Walkover Surface Emission Survey 17

1.1.2 Flux Chamber Tests 17

5.5 Drum Tests....17
5.6 Permeability Measurements....18
5.7 Trial Pits....20
6 Design of Earthworks Specification....21
6.1 Context....21
6.2 Lines of Evidence Summary....21
7 Verification Reporting....23
8 References....24

LIST OF TABLES

Table 1 – Typical ranges of permeability for fills (taken from BRE, 2015)

Table 2 – Potential lines of evidence depending on gas source

LIST OF FIGURES

Scenario 1: Removal of degradable materials, and void removal by compaction

Scenario 2: Removal of gas pathway due to land raise / increased elevation

Scenario 3: Removal of linkage to deeper ground gas sources through land raise

Scenario 4: Removal of ground gas source

Scenario 5: Venting to atmosphere following hardstanding removal

Scenario 6: Creation of gas linkage though excavation

Scenario 7: Creation of migration pathway through dewatering

Scenario 8: Initial gas generation following compaction, hardcover removal and water infiltration

LIST of APPENDICES

Appendix 1

Case study 1 – Project 2013 to 2017

Case study 2 – Project 2017 to 2020

Case study 3 – Project 2021 to 2024

Case study 4 – Project 2015 to 2025

Appendix 2

Total Organic Carbon Testing

1 INTRODUCTION

1.1 Summary

The principal aim of this guidance is to demonstrate that with a robust Gas Conceptual Site Model (GCSM) supported with appropriate lines of evidence there should not be a need to undertake post construction monitoring of ground gas in boreholes following completion of bulk earthworks. This is, of course, dependent on the GCSM and should therefore be determined on a site-specific basis. It should be recognised that installing and monitoring gas monitoring wells in recently placed fill is most likely to provide unrepresentative results, leading to delays in acceptance of works.

This guidance provides details on the collection and use of alternative data during earthworks to provide more robust lines of evidence than post fill gas monitoring in boreholes. It also provides alternative methods of assessing and validating ground gas risk, which should enable the GCSM to be updated/refined with confirmation of the gas risk on completion of the earthworks and prior to construction.

The guidance has been written with respect to bulk earthworks, including placement of engineered fill, it is not applicable to groundworks and/or stripping of shallow sub and topsoils.

This guidance has been sub-divided into the following sections:

1. Introduction
2. Current Issues and Reasons for Guidance
3. Gas Conceptual Site Model for Earthworks sites
4. Routine Data Collected During Earthworks
5. Additional Lines of Evidence to be Collected during Earthworks
6. Design of Earthworks Specifications (with respect to ground gas)
7. Verification Reporting

1.2 Case Studies

While some of the methods and techniques set out in this guidance are not currently common practice, they have been successfully used on several large sites to date with the findings accepted by regulators such that post earthworks gas monitoring was not required. Case studies for four such sites are included in **Appendix 1**.

Additional information on total organic carbon (TOC) analysis is presented in **Appendix 2**.

1.3 Target Audience and Competence

The target audience for this guidance is principally suitably competent ground gas risk assessors who have relevant knowledge, skills and experience of all aspects of ground gas risk assessment including gas generation potential, the influence of ground conditions and the earthworks process (e.g. SoBRA accredited risk assessor for permanent gas). Further examples of how competency may be demonstrated are available on the Environment Agency (EA) Land Contamination Risk Management (LCRM) pages [EA, 2025].

2 CURRENT ISSUES AND REASONS FOR GUIDANCE

2.1 Background

Development projects, particularly on brownfield sites, often involve the movement and/or placement of engineered fill during earthworks. Depending on the required final site levels this will often follow a cut and fill exercise and require the re-use of site won materials and/or the import of soils from an off-site source. Engineered fill must meet specific geotechnical and chemical acceptability criteria and be placed and compacted according to specific criteria to provide a geotechnically competent development platform for construction.

The necessity for ground gas assessment is determined by preliminary risk assessment and the development of the GCSM following site investigation(s). Site investigation and ground gas risk assessments are typically undertaken before any development works and enabling works such as remediation and/or earthworks can take place, prior to finalisation of development plans and/or final levels and/or earthworks requirements having been confirmed. This can lead to the following issues:

- The initial GCSM is not representative of site conditions post earthworks/development; and,
- Due to the uncertainty over the proposed development and the typically limited data on ground conditions, potential ground gas sources etc., a precautionary/conservative approach is often taken for initial gas risk assessments.

In the absence of continued assessment and development of the GCSM as the project progresses, there is often a requirement for post earthworks gas monitoring and risk assessment where potential ground gas risks have been identified in the initial assessments. However, gas monitoring data from boreholes installed in recently placed fill is typically unrepresentative of long-term ground gas conditions and considered in isolation frequently leads to misclassification and overly precautionary assessment of ground gas risks. On many sites, additional data routinely collected during the earthworks phase should be sufficient to allow assessment of ground gas risks without the need for post earthworks gas monitoring. This has the added advantage of removing the need for protracted gas monitoring after completion of earthworks.

2.2 Typical difficulties with post earthworks gas monitoring in boreholes

Post earthworks gas risk assessment is frequently focused solely on the collection of further gas monitoring data via the construction and monitoring of boreholes within engineered fill. As a result, valuable data/lines of evidence routinely collected during earthworks such as soil classifications, placement records, chemical analysis and in-situ testing is often under-utilised or not considered at all. In addition, the earthworks phase

also provides the opportunity to collect additional data/lines of evidence during the works to better inform the GCSM.

It is also important to note that there are significant drawbacks in monitoring boreholes within recently placed engineered fill or on sites undergoing earthworks, which include:

- **Short term elevated gas concentrations** – Elevated gas concentrations are often recorded in recently placed fill which are not representative of long-term gas regime. This is often due to a number of factors including:
    - Introduction of oxygen and moisture during earthworks / drilling of boreholes; and,
    - Compaction of soils and residual organic materials during earthworks activities can also increase the rate of methanogenesis in the short term (while pore pressures stabilise). As air voids reduce, air and water are forced out horizontally with conditions changing from aerobic to anaerobic with the increased water saturation and anaerobic conditions potentially resulting in methanogenesis to occur in organic materials, generating methane gas.
- **Short term elevated gas flow rates -** Excess pore water pressure generated in recently placed and compacted cohesive fills can result in artificially high gas flow rates within boreholes as the water displaces soil air;
- **Ongoing construction works** – Works such as piling, earthworks etc in areas adjacent to monitoring boreholes can result in temporarily elevated gas concentrations due to the mechanisms described above; and,
- **Monitoring timescales -** Given the issues listed above, a lengthy gas monitoring program may be required to obtain gas concentrations and flows representative of long-term conditions within engineered fill. If the monitoring period extends into the build phase, this introduces a risk to the developer since they cannot be sure that post construction remedial works will not be subsequently required to achieve acceptable conditions within the required timeframe.

2.3 Alternative assessment approach using lines of evidence

Given the potential issues listed above, this document aims to provide a clear, rational, and evidence-based framework for assessing ground gas risk during the earthworks, such that post earthwork gas monitoring in boreholes is not required. The document presents a guide to developing a post-earthworks GCSM in relation to ground gas risk and highlights the type of data that should be collected as part of site

investigations to inform the GCSM and which, in turn, also informs the data that should be collected during earthworks to confirm the GCSM at the end of the works.

As set out in LCRM (EA,2025) and BS10175:2011+A2:2017, risk assessment and the development of the GCSM is an iterative process and as further data is collected the GCSM can be further refined and updated. Where earthworks are undertaken, they typically represent the phase of the project where the greatest amount of information on post development ground conditions is obtained. Whereas a site investigation on an area of deep Made Ground may be limited to a few site investigation locations, earthworks may potentially require the excavation, classification, treatment and replacement of the entire body of Made Ground giving much greater confidence in the GCSM to determine if plausible ground gas sources and/or pathways are present. Much of this information (including details of material sources, descriptions, management of unsuitable soils) is collected routinely during earthworks and if supplemented (where appropriate) by additional data collection during earthworks the need for post earthworks gas monitoring can be removed entirely.

Even on sites with complex ground conditions and/or high gas risk, e.g. landfills, there is often sufficient data to classify the site whilst taking the development proposals into consideration. On sites such as these it should be possible to carry out validation of the earthworks whilst they are being undertaken such that there is no requirement for post construction monitoring. The same is the case for less complex and lower risk sites.

The methods and approaches described in this document have been successfully used on several sites to either:

- Remove the need for post construction gas monitoring in placed earthworks materials and to ensure that gas protection is not required in the buildings constructed over the fill (unless required for other gas sources); or,
- De-risking the placement of several thousand cubic materials of fill by adequately demonstrating that the fill materials would not generate significant quantities of gas. (Scott et al 2020).

Example sites for this are provided in **Appendix A1.**

3 GAS CONCEPTUAL SITE MODEL FOR EARTHWORKS SITES

3.1 Background

A risk assessment and GCSM for a given site should be prepared in advance of any earthworks in accordance with the following industry guidance and standards:

- BS 8576:2013 - Guidance on investigations for ground gas, permanent gases, and VOCs.
- EN ISO 21365:2020 Soil quality – Conceptual site models for potentially contaminated sites.
- BS 8485:2015+A1:2019 - Code of Practice for the Design of Protective Measures for Methane and Carbon Dioxide Ground Gases for New Buildings.
- CL:AIRE, 2021 - Good Practice for Risk Assessment for Coal Mine Gas Emissions.
- CL:AIRE, 2025 - Piling and Penetrative ground Improvement Methods on Land Affected by Contamination: Guidance on Pollution Prevention.
- EA, 2025 - Land Contamination Risk Management (LCRM).
- NHBC Foundation, 2023 NF94 Hazardous ground gas – an essential guide for housebuilders.
- SoBRA (2022) - Hazardous ground gas top tips.
- SoBRA (2025) - Ground Gas Flux

Assuming suitable desktop and site investigation information has been collected, this information plus the earthworks designs should be used to develop a post earthworks GCSM and identify credible contamination linkages. Examples of the data that should be collected to enable a robust GCSM to be produced are provided in **Section 3.4**.

Prior to earthworks, man-made gas sources (e.g., landfills, Made Ground, etc.) are typically poorly consolidated, may contain high organic matter, putrescible materials and/or organic contamination. Figure 6 in BS 8576:2013 can be used as a guide to inform a preliminary understanding of the gas generation potential of sources.

The likelihood, severity and risk of gas linkages should consider site topography, geology, nature of the source and receptor, the gas generation potential of the source, and the potential for preferential pathways to be present (NHBC Foundation, 2023, CL:AIRE, 2021, CL:AIRE 2025). Any identified data gaps or uncertainties should also be recorded during the development of the GCSM.

The credible linkages, data gaps and uncertainties identified as part of the GCSM should be used to inform the requirement for further assessments (e.g., targeted site investigations, detailed quantitative risk assessment) and data requirements for any earthworks phase.

The GCSM should be considered a working document, continuously being updated with new data collected throughout the lifecycle of the scheme in question. Importantly, any initial assessment of ground gas risk undertaken prior to the earthworks phase should make it clear that the gas risk assessment is an iterative process, identifying any data gaps and uncertainties plus requirements for data collection to enable the subsequent updating/re-appraisal of the gas regime during earthworks.

3.2 Gas Sources

If no credible ground gas source is identified, including the materials to be excavated and re-used in the pre-earthworks GCSM, further investigation or assessment should not be required but this must be appropriately assessed and documented.

Assuming the guidance listed in the documents at the beginning of this section is followed, the gas generation potential of typical Made Ground (non-landfill) is likely to be reduced. The mechanisms by which this occurs are summarised below:

- There will be an amount of trapped gas that is lost during excavation of soils, although, unless the soils are extremely granular this is unlikely to result in significant decrease in gas volume, due to the potential for gas being trapped in soil pore space. Increased emissions may result from removal of low permeability surfaces but, again, the significance of this is considered to be limited;
- Unsuitable materials (e.g., highly organic matter, degradable materials, contaminated soils, and other hazardous materials) are required to be removed (from the formation level) prior to earthworks filling activities as part of engineering good practice and industry guidance (NHBC Standards, 2025 – Chapter 4.6) materials are either treated to facilitate reuse or disposed offsite; and,
- The specification requirements for earthworks are stringent, with the fill layer thickness, compaction plant type, number of passes, and compaction requirement (e.g., >90% of the maximum dry density and <10% air voids) being specified (NHBC Standards, 2025 – Chapter 4.6). Therefore, gas is unlikely to build up in or migrate via voids within the engineered formation due to lower permeabilities.

Should the above industry good practices be implemented, it is considered that the gas generation potential of the resultant engineered formation of non-high-risk sites will be very low to low, equivalent of an inert landfill or Made Ground with low degradable organic content (BS8576:2013). However, the gas risk must be adequately assessed, and earthworks records/verification report are likely to form an important line of evidence.

The gas generation potential of higher risk sites, such as landfills, will also be reduced following earthworks but this will be dependent on the source material and the design of the earthworks. Detailed site assessment will therefore be required to predict, control and validate the gas generation potential of the earthworks.

As previously noted, degradable organic materials are not typically acceptable as part of an earthworks specification, but it both unnecessary and impractical to remove all organic material. For more sensitive sites such as historical landfill redevelopment (see Section 5), the amount of organic material that can remain is likely to be determined by gas risk assessment as well as geotechnical criteria.

3.3 Pathways

Earthwork activities typically change site levels, which can alter a site's GCSM. For example, a reduction in site levels, which results in a reduction in the mass of gas source material will likely reduce the risk from ground gas; however, if the overburden (the soils that require removal to achieve site levels) is not a source of ground gas but is overlying a source then a migration pathway may be introduced, or made more significant, thereby increasing the risk from ground gas. For developments where an off-site gas risk has been identified, consideration of changes to site levels will be required to assess the effect on migration pathways between the development and off-site source. The unsaturated zone thickness can also be increased following dewatering to facilitate earthworks excavations and the potential impact of this to increase gas migration should be noted.

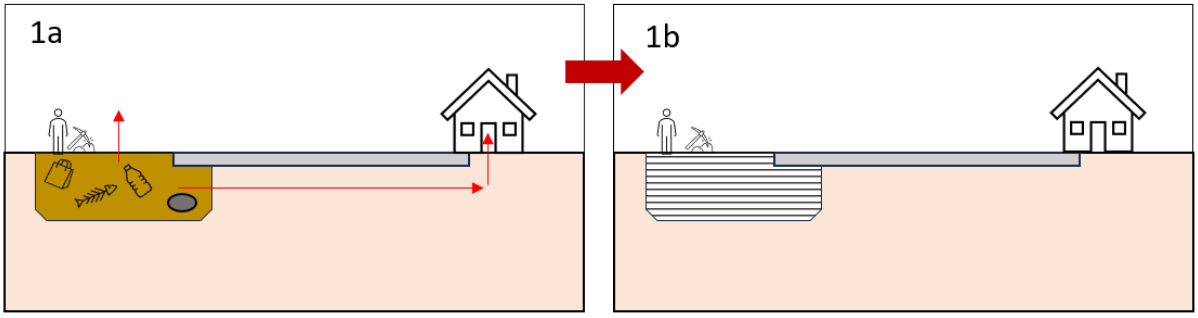
Deep excavations or land raises can lead to sensitive receptors being brought vertically closer to or moved vertically away from ground gas sources, which will affect the potential risk from preferential pathways. Furthermore, should the ground gas source be relocated further away from or placed at an elevation above sensitive receptors, then the risk will decrease or be removed since the migration pathway is no longer present.

Hardstanding surfaces are typically removed at the start of earthworks activities, limiting lateral migration and oxidizing organic materials in the ground. Likewise, the increase in hardstanding or low permeability layers at a new development may limit vertical migration and encourage lateral migration gases towards

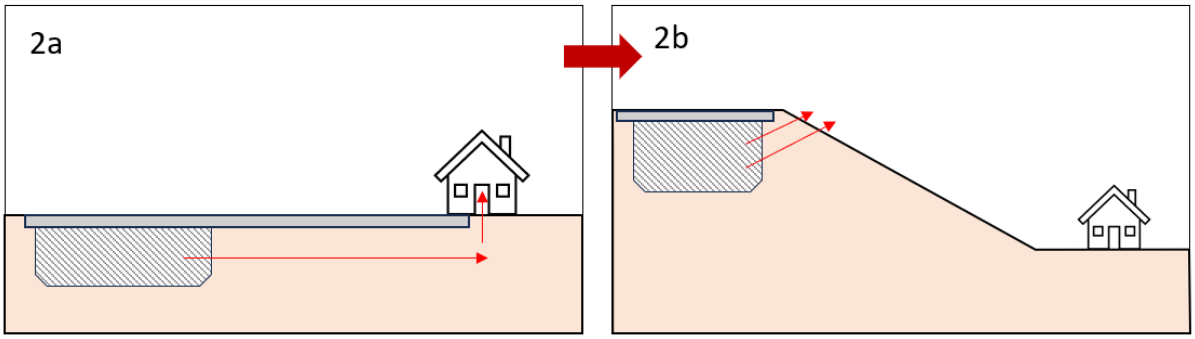
sensitive receptors, however this is not likely on the majority of sites and will only occur where there is high gas generation potential, e.g. sites classed as CS4 and above (NHBC Foundation, 2023). It is worth noting that the removal of hardstanding could also lead to moisture contents within organic materials increasing due to water infiltration, increasing degradation and gas generation rates temporarily until organic materials are fully saturated.

The above scenarios are presented visually in the images below.

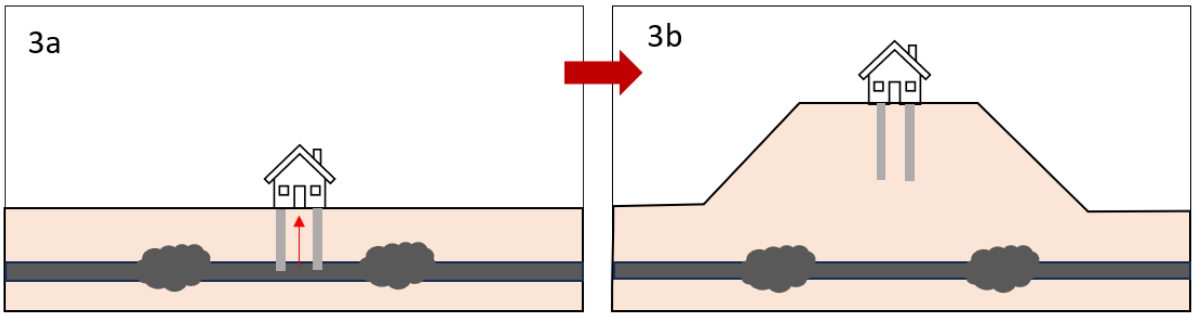
Scenario 1: Removal of degradable materials, and void removal by compaction



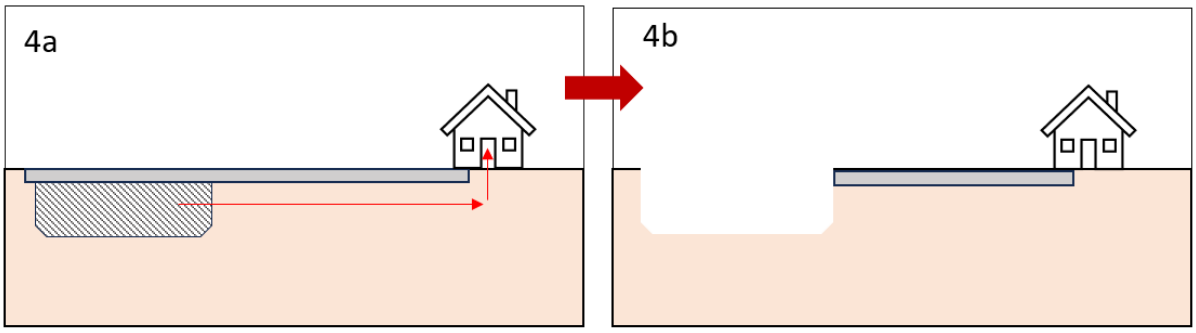
Scenario 2: Removal of gas pathway due to land raise/ increased elevation



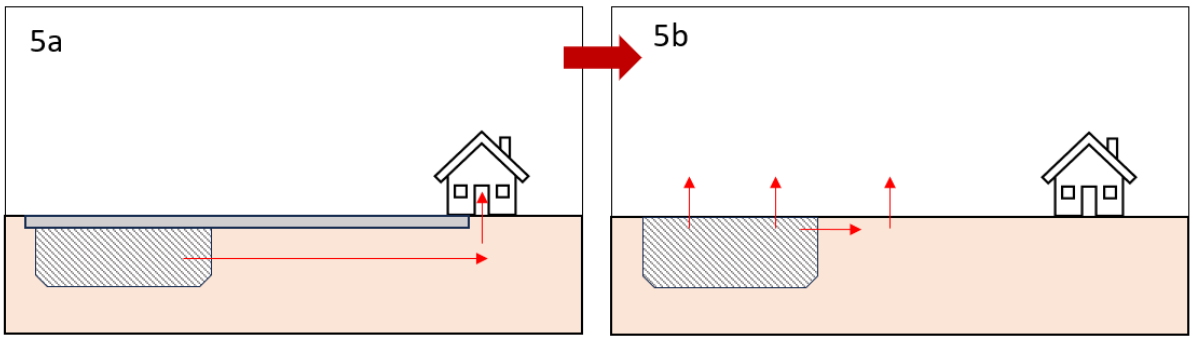
Scenario 3: Removal of linkage to deeper ground gas sources through land raise



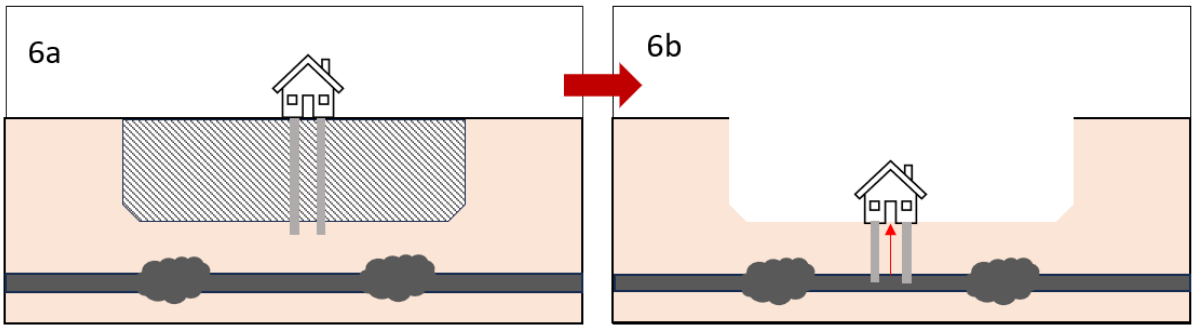
Scenario 4: Removal of ground gas source



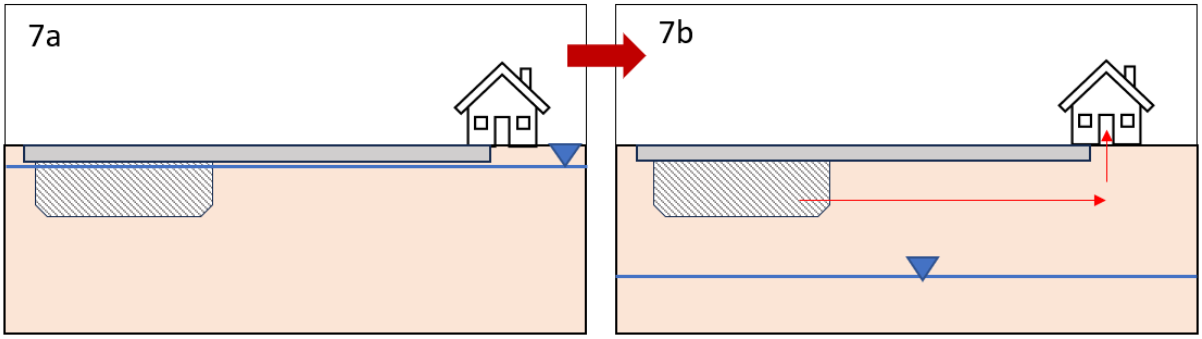
Scenario 5: Venting to atmosphere following hardstanding removal



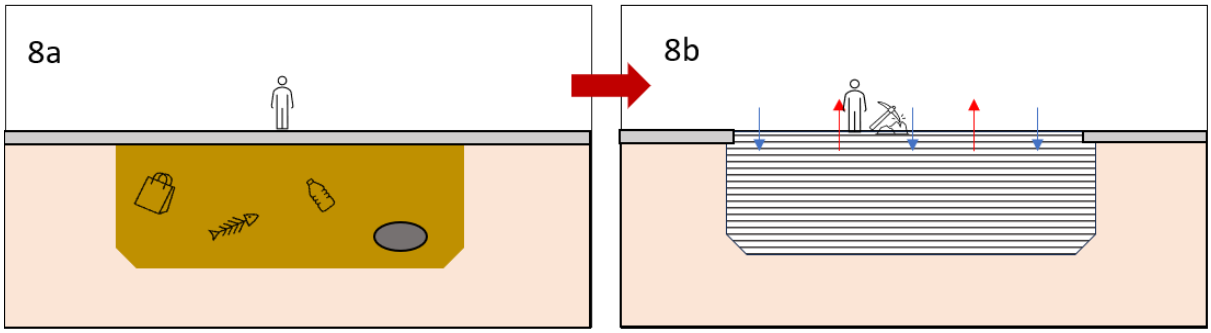
Scenario 6: Creation of gas linkage through excavation



Scenario 7: Creation of migration pathway through dewatering



Scenario 8: Initial gas generation following compaction, hardcover removal and water infiltration



The changes to the GCSM due to earthworks must be considered as part of a consultant's risk assessment prior to earthworks commencing. The potential implications identified will then inform the amount of additional data that will be required during the earthworks. If additional pathways are introduced, such as scenarios 6 and 7 above, then it is more unlikely that the gas risk can be confidently stated until the earthworks are complete, which may be undesirable from the developer's perspective. However, a conservative assessment can be used to inform budget considerations, and these are then investigated during the earthworks using the methodologies detailed in **Section 5**.

3.4 Data Collection to Inform GCSM Prior to Earthworks

As a minimum it is assumed that phase 1 (desk study) and, usually, appropriate phase 2 (intrusive investigation) information is available prior to development of the earthworks strategy. This guidance is not intended to repeat requirements for a suitable gas risk assessment and so it is assumed that the reader is familiar with the requirements. The records listed below are therefore intended to be additional to those more traditionally associated with phase 1 and 2 works, although it is intended that these should become part of a standard checklist when designing earthworks that require consideration of ground gas risk.

Phase 2 intrusive investigations should be designed to assess any ground gas risk identified as potentially present by the phase 1 desk study. The required works are well documented, as referenced earlier in this section (BS8576:2013, etc.)

Gas monitoring via borehole installations is a tried and tested methodology but other lines of evidence are available and often ignored. A key consideration for any GCSM, which can be assessed as part of the site investigation, is the organic content of the soils, since this dictates the potential for ground gas emissions. Analysis may be via standard total organic carbon (TOC) analysis or fTOC (forensic TOC, in accordance with Annex E of BS8485:2015), with the decision determined by the site and the amount of organic material expected – further details are provided in **Section 3**. There are acknowledged limitations to TOC testing,

which must be understood but it remains the most readily available and simple method for assessing organic load - a summary of the limitations to be considered is provided in **Appendix 2**.

The permeability of soil material is also a very important variable in understanding gas risk (Ground Engineering, 2018), which directly informs gas risk, but which is often not assessed to inform the GCSM. This is detailed further in **Section 5**.

Based on the above, production of a good GCSM should be possible. And this can then be refined as further details are obtained regarding the site development, prior to the earthworks. Further details include (but are not limited to) the following, which inform the development scenarios (1 – 8) previously discussed:

- Cut and fill plans – allow a better understanding of material excavation and movement, which is important where areas of organic rich soils have been identified, for example;
- Confirmation of proposed site levels;
- Confirmation of site finishes – areas of hard and soft landscape, etc.;
- Confirmation of foundation design (slab design, requirement for piled foundations, ground improvement, etc.);
- Confirmation of services and their potential to act as migration pathways; and,
- Confirmation of potential changes to water table - either short or long term.

4 ROUTINE DATA COLLECTION DURING EARTHWORKS

4.1 General Earthworks Requirements

All significant earthworks should be undertaken in accordance with the following industry guidance and standards:

- BS 6031:2009 - Code of Practice for Earthworks.
- BS EN 16907 – Earthworks, all parts.
- Building Research Establishment (BRE), 2015 FB 75 Building on fill: geotechnical aspects, 3rd Edition.
- National Highways, 2025 - The Manual of Contract Documents for Highways Works, Volume 1 and Specification for Highways Woks, Series 600 – Earthworks.
- NHBC Standards – Chapter 4.6.

In managing the ground gas risk, it is critical to understand the earthworks design and any other remediation requirements. The cut and fill plans required as part of an Earthwork Specification should be used to help inform the GCSM to better understand the ground gas risk. As noted previously, areas of cut may be removing a ground gas source, and therefore confirmatory validation works either during, or post earthworks would not be required. Conversely, movement of organic soils may result in introducing a new risk to receptors for which there was previously no pathway.

General earthworks details that should be included in an Earthworks Specification to enable ground gas to be assessed and validated are detailed below. These do not include specific geotechnical requirements that would be needed for ground stability and foundation purposes:

- Pre-earthworks and final site levels;
- Cut and fill proposals (e.g. isopach drawings);
- Sources of earthworks materials – site won or imported and soil descriptions/classifications;
- Site preparation works required prior to placement of engineered fill;
- De-watering details, if proposed;
- Testing requirements and threshold criteria (the frequencies stated in the specification should be sufficient to characterise the volume of material being placed, taking into consideration the homogeneous or heterogeneous nature the material);
- Management, treatment and segregation proposals for site won materials; and,
- Removal and/or re-use of unsuitable materials (e.g. topsoil, highly organic matter, contaminated soils etc.).

Re-use of soils must be undertaken in accordance with current waste legislation requirements (e.g. Materials Management Plan, environmental permit, exemption, etc.).

4.2 Soil Descriptions

Soil descriptions of materials should be completed and reported by qualified professionals with descriptions of the soil encountered in accordance with BS5930:2015+A1:2020. Made Ground and natural soils should be clearly described including if the material is cohesive or granular in nature. Made Ground, including landfill material, should have good, detailed descriptions of putrescible organic material to better understand if such material can be reused during earthworks, or if segregation can be completed to allow a fraction of the material to be reused as part of the earthwork activities.

4.3 Soil Re-Use / Import

To ensure maintenance of the GSCM it is vital that soil properties – both that of the existing in-situ material and that placed (site won and imported) are understood. The requirements for soil material should be set out in the Earthworks Specification. The source(s) of the material to be used should be known - site won or imported material should be subject to suitable analysis prior to re-use or import. The testing requirements and threshold values should be incorporated in the Earthworks Specification together with the on-site management and treatment (if required) of soil material plus the management/removal of unsuitable materials.

4.4 Watching Brief

A watching brief should be carried out as part of any earthworks operation. The purpose of this is to provide visual confirmation that placed fill material is consistent with the classifications and to ensure any unsuitable materials are removed prior to placement. From a ground gas perspective, the watching brief would concentrate on readily degradable organic material such as fresh vegetation, food waste, sawdust etc and other potentially degradable materials (see NHBC Foundation, 2023 for discussion), although it is noted that these materials will also be geotechnically unsuitable.

5 ADDITIONAL LINES OF EVIDENCE TO BE COLLECTED DURING EARTHWORKS

5.1 Background

Data requirements for the gas risk assessment will be specific to the site and based on the GCSM. Many low-risk sites may not require any additional information above and beyond the routine earthworks data set out in **Section 4** whereas high risk sites will likely require most, or all the additional lines of evidence summarised below. In summary, additional lines of evidence that can be collected during earthworks may comprise:

1. Assessment and control of organic content of the soils;
2. Verification of gas emission rate of soils for more high risk sites; and
3. Assessment of permeability/migration pathways.

These are detailed separately, below.

5.2 Assessment and Control of Organic Content of Excavated Soils

This is undertaken by the following methods:

- Watching brief during the excavations as described in **Section 4.4**.
- Analysis of soils to confirm acceptable organic content. This is likely to be specified prior to the earthworks as part of the ground gas assessment if maximum gas emission rates have been calculated. As noted previously, this is undertaken via standard TOC or fTOC analysis (see **Section 3.4** and **Appendix A2**).

The testing required during earthworks should be detailed in the Earthworks Specification and the frequencies stated in the specification should be sufficient to characterise the volume of material being placed, taking into consideration the homogeneous or heterogeneous nature the material. Sufficient TOC data should be obtained prior to final placement of fill to determine if the material is suitable for re-use (e.g. 1 test per 100 – 500 m3 with actual rates determined by the heterogeneity of the soils). The organic load of the soils to be used in the fill should be controlled so that the gas generation potential of the soils is known.

For sites where the gas risk has been identified to be low, such as inert or clean and natural soils with low organic content, then validation methods may not be required, although it is recommended that good industry practice is always maintained and a watching brief is carried out through the works to confirm the

absence of significant organic material. Confirmatory TOC analysis could be undertaken if further evidence is required. Where the GCSM has identified a higher risk then fTOC analysis may be required and if a significant risk is likely to be present, where there is uncertainty over the gas emission potential of the soils, then drum tests may also be appropriate (SoBRA, 2023).

5.3 Verification of Gas Emission Rate of Soils

This is undertaken by a number of methodologies, which are listed below and detailed separately:

- Gas emission rate measurement (including surface emission monitoring, flux box tests).
- Drum tests.
- Permeability measurements.
- Trial pits.

The actual works required will be dependent on the gas risk for the site.

5.4 Gas Emission Rate Measurement

This can take two forms, depending on the gas risk identified at the site, but it is unlikely to be required for low-risk sites. The works can be undertaken at excavation formation level, during and/or following placement of the soils to form the engineering platform. The timing of the works will be dictated by the site and the identified gas risk.

If the residual site soils, i.e., those at excavation formation level, are known to be a potential gas risk, then the monitoring would be carried out once these are exposed. An example of a site where this would be relevant would be landfill where organic rich soils are left in-situ beneath an engineered cap. In some instances, it may be preferable to repeat the monitoring, either during buildup of the engineered cap or at the surface.

If the residual site soils are not identified as a risk, e.g., the soils at excavated formation level are natural, but the engineered fill has been identified as a gas risk then the monitoring would be carried out following placement of the soils to form the engineering platform. Acceptable emission rates would be defined as part of the gas-risk assessment for the site.

The works are carried out by in-situ monitoring using one or both of the following methods:

1. Walkover Surface Emission Survey; or,
2. Flux chamber tests.

The works should be carried out by a suitably qualified specialist with appropriate experience of the works and when meteorological and surface saturation conditions are acceptable (i.e. not on waterlogged ground and not when it is too windy).

1.1.1 Walkover Surface Emission Survey

The specifics of the monitoring will be site specific and dependent on the gas risk potential and the GCSM but the basic methodology comprises a surface emission mapping survey carried out over a pre-determined grid (e.g. a series of traverse lines spaced at 5m centres). Monitoring over a small grid spacing would be more suitable for a site with an identified gas risk (e.g. a landfill) where there is some uncertainty over the emission rate potential. Whereas the grid spacing could be relaxed for a site with a lower risk and/or more certainty over the gas emission rate.

Typically, the measurements for methane are taken at 10 mm above ground level with a tuneable laser diode methane detector calibrated to detect methane and with a limit of detection of 1 ppm (an instrument with a similar level of detection should be used for carbon dioxide if that is of concern). The instrument should have a response time less than 5 seconds and readings taken every 3 seconds. The results should preferably be time stamped with the time and GPS location.

The results should ideally be reported as a table of results alongside a contour plot of the emissions recorded. The wind speed/direction, temperature, atmospheric pressure, and rainfall on the site at the time of the survey should be recorded. Further guidance is provided in the Environment Agency LFGTN (EA, 2010).

1.1.2 Flux Chamber Tests

The number of flux chamber tests will be site specific and dependent on the gas risk potential and the GCSM. The tests provide an indication of the gas flux at specific locations and should be undertaken in accordance with the guidance in the EA. As well as being carried out as another line of evidence flux chamber tests are normally used to further investigate any potential ‘hot spots’ identified in the surface emission monitoring.

The reporting should include an Excel spreadsheet, including the flux calculations (SoBRA, 2025), which can then be converted into a volume flow rate (l/hr).

5.5 Drum Tests

An additional method for assessing the potential gas risk of the soils can be provided by gas generational field tests, otherwise known as ‘Drum Tests’. These should not be required for all sites but are useful for

sites where organic content is known to be high, such as landfills. The tests mimic actual ground gas generation from the site soils and so the results can be used in a 'lines of evidence' approach with the fTOC results to more accurately predict gas emission potential from the residual soils. The method is in general accordance with industry guidance such as the Ground Gas Handbook (CIEH, 2009). Laboratory gas generation tests can also be undertaken to provide an estimate of the total theoretical methane generation from fill.

5.6 Permeability Measurements

The use of permeability testing can be used to inform if a migration pathway for ground gas within the placed material would be feasible (i.e. soils with a high permeability may allow the migration of ground gas, if a source is present).

Ground permeability is a key factor in the level of risk posed by ground gas (Ground Engineering, 2019). Lower permeability soils/fill (i.e. permeability less than 1 x 10^{-4} m/s) are likely to limit gas flow/emissions where a plausible gas source is present.

Table 1 gives the following typical ranges of permeability for fill materials (based on values from BRE, 2015):

Fill Type	**Permeability k (m/s)**
Clay Fill (compacted)	10^{-8} to 10^{-10}
Sand fill	10^{-2} to 10^{-4}
Rockfill (well-graded)	10^{-2} to 10^{-5}
Colliery spoil (coarse)	10^{-3} to 10^{-8}
PFA	10^{-5} to 10^{-8}
Refuse landfill	10^{-3} to 10^{-6}

Table 1 – Typical ranges of permeability for fills (taken from BRE, 2015)

Therefore, where the post earthworks GCSM indicates a potential gas source remains, provided no preferential pathways are present and the gas source is at a depth greater than 1 m below building floor slab, assessment and measurement of permeability of the fill material is potentially an important line of evidence in the ground gas risk assessment. Based upon the typical permeabilities of engineered fill material, permeability measurement may not be required for the following fill materials:

- **Compacted clay fill**: Given typical permeabilities 10^{-8} - 10^{-10} m/s, and assuming a consistent source, information provided in the earthworks verification report (including material sources/classification, as built survey records, test results and certificates etc.) may be sufficient to demonstrate a plausible gas migration pathway is not present without any additional assessment; and,
- **Sand fill or other coarse granular fills**: with minimal clay content (where permeabilities are likely to be > 10^{-4} m/s) are unlikely to provide a barrier/limit to gas flow.

For other soil types (with sufficient clay content for the engineered fill to behave as a cohesive soil), or where there is more uncertainty/variation in fill materials, options for collecting soil permeability measurements in the unsaturated zone include:

- Laboratory testing of undisturbed soil cores (including triaxial test, or constant head);
- Soak away tests (BRE 365);
- Borehole tests (constant head, not rising/falling head tests); and,
- In-situ permeameter/infiltrometer testing.

While laboratory testing and trial pit soak away testing are well understood and commonly used in the UK, the use of borehole tests, constant head permeameters or infiltrometers to undertake in-situ measurements of permeability is preferred and is more robust. There are also significant health and safety and practical issues in undertaking trial pit soakaway tests as per the guidance in BRE, 2016.

Constant head permeameter tests typically comprise coring a small hole into the fill material, maintaining a constant depth (head) of water and measuring the water recharge required until steady state conditions are achieved, and the field saturated soil/fill permeability can be calculated. Key advantages over other testing approaches are:

- No significant health and safety issues;
- Testing apparatus is relatively lightweight/easy to set up;
- Only relatively small volumes of water are required for each test, therefore more sustainable than delivery of water to site in a tanker;
- There is minimal disturbance of the earthworks with no large plant required to either drill boreholes or test pits;
- Tests can also be undertaken relatively quicky; and,

- With appropriate management/phasing with the earthworks program, tests can be undertaken during earthworks, enabling lateral and vertical variations to be assessed and a representative range of permeability values obtained.

Further discussion of the different methods of measuring the coefficient of permeability is given in ASTM D5126-16E1 – 'Standard Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone' (2016).

Where measurement of permeability is required, the selection of test method(s) and frequency and locations of testing should be designed to provide the required confidence/line of evidence for the gas risk assessment and ideally included in the specifications for the earthworks. Once the data is collected it can be used together with other lines of evidence to support/develop the CSM for the earthworks or potentially be used to support gas risk assessment in line with (Ground Engineering, 2019).

5.7 Trial Pits

On some sites, notably landfills, there may be a requirement to confirm the gas emission potential of residual soils, i.e., those not excavated as part of the earthworks. Soils exposed at depth will only have been previously assessed via boreholes, which is not ideal when attempting to predict the amount of organic material in a soil mass, since it is likely to be reliant on borehole logs as only limited soil material is exposed. As such, it may be prudent to undertake confirmatory trial pits at excavated formation level.

The purpose of these trial pits is therefore to inspect for organic material that has the potential to be ground gas generating. It has the added use of also being able to identify soft/organic material that could present a ground settlement issue.

The soils should be photographed, logged and bulk samples taken, where appropriate, for fTOC analysis. It is noted that groundwater levels may prevent excavation to full depth, in which case further excavations can cease and observations and samples taken of the available material.

It is possible that the pitting may identify soils that present a risk to the development, from a contamination, ground gas and/or geotechnical perspective. In which case an assessment will be required and, if necessary, remediation completed (e.g., removal or treatment of the affected soils).

6 DESIGN OF EARTHWORKS SPECIFICATION

6.1 Context

As discussed previously, earthworks have the potential to significantly alter both the ground gas source (if present) and/or the migration pathways on a site. However, earthworks also provide an opportunity to obtain additional data to further characterise gas risks on the site through both the collection of routine information required for earthworks records/verification (see **Section 4**) but also through additional testing (see **Section 5**).

The ultimate aim of the verification procedure during the earthworks is to confirm that the soils excavated and placed as part of the works conform to those identified in the GCSM. As such, the earthworks specification should be designed to ensure that sufficient and appropriate lines of evidence are collected so that on completion of the works the gas risk / classification stated in the GCSM can be confirmed. As previously noted, unless the works introduce uncertainties that cannot be resolved without further assessments, then there should be no requirement for post earthworks monitoring of ground gas.

The scope of validation works included in the earthworks specification should be based on the assumption that the GCSM has confirmed the gas risk for the site, whether this be that no gas protection measures are required or that specific measures are needed, e.g., in accordance with a classification such as CS2. There are limitations to the use of this guidance in that it does not comprehensively cover ground gas issues associated with coal mining areas. Although this guidance may still be used to inform the works, a more bespoke assessment may be required for these sites.

6.2 Lines of Evidence Summary

As previously noted, the required lines of evidence will be site, and GCSM, specific. Different approaches will be required depending on the nature of the gas source and pathways present and identified data gaps/uncertainties but following completion of the earthworks any uncertainty should be greatly reduced and the gas risk assessment/GCSM should be revised accordingly. Table 2 below provides a summary of likely lines of evidence required depending on gas risk that should be incorporated into the earthworks specification.

Potential Gas Source	Potential lines of evidence
Low risk sources (as per NHBC, 2023) e.g. shallow Made Ground (with no significant degradable content), alluvium etc.	GCSM on its own may be sufficient or include one or more of the following depending on risk / uncertainty: ● Soil classifications/description. ● Watching brief. ● Evidence for removal of unsuitable materials. ● Compaction/air void/dry density testing. ● TOC analysis.
Higher risk sites e.g. former landfills, deep Made Ground with high percentage of biodegradable materials	As above but depending on nature of gas source and type of engineered fill, lines of evidence could also include: ● Emissions testing. ● Drum or laboratory gas generation tests. ● Trial pits within placed fill. ● In-situ permeability tests in unsaturated cohesive soils.
Potential gas source off-site or underlying placed earthworks material (could include land raise)	Review of earthworks design and cut & fill drawings (note: gas risks could increase in areas of cut): ● Soil classifications/description ● Watching brief ● In-situ permeability testing (assuming cohesive soils have been placed)

Table 2– Potential lines of evidence depending on gas source

7 VERIFICATION REPORTING

Following the placement of the engineered fill, a verification report should be provided confirming the works undertaken. As per traditional verification reports produced for validation of remedial works, it should include reference to the GCSM and detail any variations to the works detailed in the earthworks specification works.

It should confirm whether the works and verification results support the GCSM, whether additional works were needed to do so, or whether the GCSM has been updated and any implications regarding the development. Importantly it must confirm that the ground gas generation potential and the migration potential of ground gases through the engineered fill is sufficiently understood to confirm that the proposed gas exclusion measures, if any, remain appropriate.

The report should include:

- Reference to the ground investigation, earthworks specification and the updated detailed GCSM and ground gas risk assessment;
- 'As built' drawings of the filled and cut areas;
- All laboratory verification results;
- All results of any works required by the earthworks specification, such as logged descriptions of fill materials, surface emission testing, fill permeability testing, etc.;
- Summary of waste soil disposal (it is assumed that waste / soil duty of care requirements will be covered in the wider site verification report);
- Summary of all imported soils (as above, it is assumed that waste / soil duty of care requirements will be covered in the wider site verification report);
- Details of any variations to the design specification or contingency actions that have been taken during placement of the fill material; and,
- Appropriate assessment of results if needed to confirm the gas classification.

The verification report should be made available to the regulators and future site developers to provide clear justification for any recommended gas exclusion measures or for the absence of a requirement for them.

8 REFERENCES

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APPENDIX 1

The following case studies show how the approaches described in this paper have been refined over time as experience has been gained.

Case study 1 – Project 2013 to 2017

The remediation of Sandford Farm in Reading is an example of how good earthworks practices can reduce the gas generation potential of man-made sources (Scott et al 2020). Sandford Farm previously comprised former quarries, which became licensed industrial landfills between 1981 and 1991. The historical landfills were to be redeveloped for residential use. However, the contamination within the landfill complex posed a significant risk to future residents, with ground gas being the principal concern.

As part of the remediation works, waste materials were excavated and processed into stockpiles of varying particle sizes and materials, to remove the degradable fraction. Once processed, acceptable materials were placed to provide suitable development platforms for the proposed residential development.

It was a requirement that the houses to be built over the fill would have a ventilated sub floor void and gas membranes.

From the outset it was recognised by the remediation contractor's specialist ground gas consultant that gas monitoring in the recently placed fill materials was likely to provide unrepresentative results and was fraught with programme and financial risks. However, at that time regulators, warranty providers and the client's consultants insisted that gas monitoring was necessary. It was however made clear to them that it would not be the primary line of evidence and that the other data would take precedence over gas monitoring results.

To verify the removal of the degradable fraction from the waste materials, and an acceptable ground gas risk the remediation contractor and its consultant completed the following:

- Drum tests measuring ground gas from processed waste;
- Forensic assessment of TOC content;
- Walkover surface emission survey with flame ionisation detector;
- Flux box tests; and,
- Sub floor monitoring under some unoccupied units to show that gas emissions would not overwhelm the sub floor void ventilation and that the gas protection measures were adequate (sub floor void and gas membrane).

The contractor was able to reuse 95% of the landfill materials as part of the earthworks, downgrading the gas generation potential of the source and subsequent ground gas risk to future residents and adjacent properties.

The reduction in ground gas risk was confirmed by TOC testing and drum tests along with permeability tests.

The gas monitoring that was completed did record high flow rates and gas concentrations in some parts of the site that were not representative of the long-term risks to the development. These gradually reduced over time but did result in monitoring of ground gas following the completion of the works continuing for a minimum of 6 months but extending to 18 months in some areas. (Scott et al, 2020). Additional surface emission and flux chamber monitoring was required, as well as continuous monitoring in underfloor voids, to show that the gas risk was acceptable.

This work was completed under a mobile plant environmental permit so there was no requirement for surrender.

Case study 2 – Project 2017 to 2020

The remediation of Emerson's Green near Bristol is the second example of remediation of a former landfill for residential use. This project developed on the experience gained at Sandford Farm in Case Study 1.

The landfill contained approximately 60,000m^3 of commercial/industrial waste buried within a former valley during the 1980's and 90's on a dilute and disperse basis.

A similar approach was taken to Sandford Farm with the primary lines of evidence for verification being:

- Drum tests measuring ground gas from processed waste;
- Forensic assessment of TOC content;
- Walkover surface emission survey with flame ionisation detector;
- Flux box tests; and,
- Sub floor monitoring under some unoccupied units to show that gas emissions would not overwhelm the sub floor void ventilation and that the gas protection measures were adequate (sub floor void and gas membrane).

The warranty provider still required gas monitoring to be undertaken but it was made clear by the remediation team that the above data would take precedence over gas monitoring results (because the team now understood that the monitoring wells placed into recent fill become flooded and cause unrepresentative flow rates and gas concentrations). A key difference for this project was that the Environment Agency insisted it was undertaken under a Recovery of Waste Environmental Permit. This applies to the site and requires surrendering which was a significant contractual risk for the remediation contractor.

During the application for the permit the verification for surrender was agreed. This relied only on drum tests measuring ground gas from processed waste and forensic assessment of TOC content (for ground gas – there were other requirements with respect to chemical contamination and groundwater risks). Thus, the contractual risk of relying on gas monitoring in the fill and the likelihood of unrepresentative results and protracted timescales for surrender was removed.

Case study 3 – Project 2021 to 2024

The remediation of Liverpool Festival Gardens is the third example of remediation of a former landfill for residential use. This is the most complicated of the three case studies and the regulators and warranty provider were comfortable with not using gas monitoring in wells as part of the verification process.

The site is a former landfill site that spans approximately 40ha and is divided into three sections: the Development Zone in the north, the Gardens in the middle, and the Southern Grasslands in the south.

The remediation strategy aimed to prepare the 10ha Development Zone for residential use while addressing environmental concerns. These included the decommissioning of an existing landfill gas extraction system that had been installed to manage the risk from methane, carbon dioxide and that was still operational under contract with the city council.

The project involved the excavation of more than 450,000m^3 of contaminated soil and waste, with more than 95% of this material being reused or recycled.

The primary line of evidence was the TOC content of the materials as they were placed. There was no requirement for gas monitoring wells in the fill. A series of three surface emissions surveys were completed on completion of the filling to confirm that gas emissions were below acceptable limits.

Case study 4 – Project 2015 to 2025

The development of the 132ha site at Kilnwood Vale, Crawley, West Sussex included the remediation of a former 50ha landfill to deliver over 2500 homes, new school, commercial space, social facilities, roads, river re-alignment, and infrastructure. The historical landfill license conditions indicated that fill comprised inert materials, but the subsequent investigations proved the presence of biodegradable materials such as timber, organic alluvium, and isolated incidents of hydrocarbons. The landfilling occurred between 1977 and 2006 and the depth of fill was proved to circa 16m. Methane was detected above 20% v/v at over 90% of the historical exploratory hole locations, with several locations recording concentrations in excess of 90% v/v. Over a third of all historical locations recorded flow rates above 3.5 l/hour.

Additional investigations were carried out to collect data, predominantly to include an assessment of organic content and emission potential, in order to enable suitable remediation. The remedial works were designed to accommodate both geotechnical and geo-environmental considerations, and to mitigate risks associated with long term consolidation, creep and collapse settlements, and ground gas. The assessments concluded that gas protection could be restricted to traditional measures in accordance with CS2 – CS3 (gas membrane installed with suitable verification, and ventilated void), provided the earthworks were undertaken with suitable validation works throughout.

The remedial works were carried out over a number of phases across the site with earthworks undertaken to provide a development platform on which subsequent construction works could be undertaken by others.

The works comprised a mass cut and fill of more than 1 million m3 soils, which were sorted for re-use in accordance with the Specification for Highway Works (SHW), with removal of deleterious materials, including those with degradable content, followed by analysis of the soils to a specific forensic TOC (fTOC) percentage (established by emissions calculations as part of the assessment). The soils were placed to form an engineered cap which was subject to surcharge.

Validation was carried out throughout the earthworks with the lines of evidence for verification being:

- Drum tests measuring ground gas from the processed waste;
- Forensic assessment of TOC content prior to re-use;

- Walkover surface emission surveys following excavation with laser diode flame ionisation detector (with confirmatory surveys occasionally carried out following deposition of the fill and prior to surcharge);
- Flux box tests carried out at the same time as the surface emission surveys; and,
- A limited amount of borehole monitoring was carried out on completion of each phase of the earthworks. Although this was not included as part of the original remediation specification it was subsequently agreed with the regulators (both contaminated land officer and warranty provider) that this would be undertaken given that the proposed lines of evidence approach (drum tests, fTOC, surface emissions, etc.) was novel and relatively untested at that time (the first phase was carried out in 2016 and since then it has been used on several sites). During the subsequent validation works for each of the phases it became clear that the lines of evidence approach was far more reliable than reliance on post construction monitoring.

APPENDIX 2

Total Organic Carbon Testing

CL:AIRE Research Bulletin RB17 (Nov 2012) *A Pragmatic Approach to Ground Gas Risk Assessment*, discussed the information and data that allows the likely gas generation from a source to be estimated. For an engineered fill this approach allows the ground gas generation potential of the fill material to be assessed by its organic content and its likelihood to become anoxic once placed.

Methanogenesis is highly inefficient in terms of chemical entropy and thus only very simple organic compounds, such as short chain (typically less than C7) alcohols, aldehydes, carboxylic acids and amines, together with the simple organic compounds that can be hydrolysed down to them, can degrade to produce methane. More complex organic compounds such as lignin, cutin, humic acids and fulvic acids cannot be degraded by methanogenesis and thus remain preserved in anoxic environments, allowing peat deposits to build up and bog oaks, timbers, leather and bodies to be preserved. No commercial analysis method is currently available for assessing only the simple organic compounds likely to be involved in methanogenesis. Therefore, all the commercially available methods of measuring the total organic carbon (TOC) content of a soil sample, can only provide a very approximate and very conservative estimate of the methanogenic potential of a soil.

Laboratory TOC methods vary considerably and some employ far harsher extraction methods than others, so will produce dramatically different results on the same soil. In general TOC measurement methods can be split in to; wet digestion and dry combustion methods, but whatever method is adopted, the initial stage of sample preparation usually involves air drying and crushing the soil and acidifying it to remove inorganic carbon such as carbonates. This process is likely to remove or degrade many of the simple organic compounds, which could undergo methanogenesis. The wet digestion methods involve the oxidation of the organic matter using potassium dichromate (Walkley and Black method and Photometric method), whilst the dry combustion methods involve heating the dried soil to combust the organic matter at 400°C to 975°C and either measuring the weight loss (Gravimetric- loss on ignition method) or the carbon dioxide generated using infra-red absorption (Combustion instrumentation method). In a recent CONTEST (laboratory proficiency test) round, laboratories using the Walkley and Black method measured an average TOC content of 3.2% whilst on the same soil, the average TOC content measured by the instrumentation method was 9.6%. Therefore, the TOC measurements from different laboratories are not necessarily comparable and a single TOC value cannot be adopted as a definitive indicator of the methanogenic potential of the soil. It is, however, probable that TOC assessed using the Walkley and Black method will provide a

better indication of the methanogenic potential of the soil, as the TOC value produced will include fewer of the complex organic compounds that will not degrade under anoxic conditions. However, it is noted that only a limited number of commercial labs offer TOC measurement using the Walkley and Black method.

If the origin of an engineered fill is known, TOC testing (using the Walkley and Black method) can provide a very conservative validation of the absence of a methanogenic potential if enough tests have been completed to adequately characterise the material, especially if the soil is to be placed above groundwater level and will remain aerobic. However, a moderate or high TOC content, especially if measured using the combustion instrumentation methods, does not indicate that the soil has a high methanogenic potential, as the result may simply indicate the presence of complex organic compounds, such as timber or coal fragments, which could not undergo methanogenic degradation, even under anoxic conditions.