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CL:AIRE research bulletins describe specific, practical aspects of research which have direct application to the characterisation, monitoring or remediation of contaminated soil or groundwater. This bulletin describes an alternative approach to ground gas risk assessment.

A Pragmatic Approach to Ground Gas Risk Assessment

ABSTRACT

Measurement of ground gas in monitoring wells does not always give a suitable indication of the likely hazard it may pose to developments. This is because the gas concentration, pressure and flow rate measured in a well headspace may not be representative of conditions in the surrounding formation. The number of gas monitoring wells on a site is also usually limited when compared to the total number of exploratory holes (trial pits, boreholes, etc).

A more robust assessment of the risk posed by the presence of ground gas (as opposed to landfill gas or mine gas) may be achieved by considering information and data that allows the likely gas generation from a source to be estimated. The proposed scope of gas protection is an important consideration in any risk assessment. Simple gas protection measures comprising an under floor venting system and gas resistant membrane have proven to be effective over a wide range of gas sources.

This Research Bulletin proposes a pragmatic approach to ground gas assessment using data that can be collected quickly and at low cost. The data is not subject to any significant external influences, unlike gas monitoring data. The approach can be used to identify where gas monitoring is required to help assess the risk posed to developments by landfill, mine or ground gas. On many sites, especially where gas protection will be provided, it will allow gas well installation and monitoring to be avoided, i.e. where soils of low organic content are present with low ground gas generation potential. It can also be used in conjunction with gas monitoring to reduce the period of monitoring required or to avoid extra gas monitoring where anomalous results are recorded.

The approach has been validated on a wide variety of sites and has been shown to provide an acceptable indication of the scope of gas protection that is required.

1. INTRODUCTION

Natural ground gases such as methane and carbon dioxide are found widely in soils and rocks, as they are an integral component of the geochemical cycle of the Earth. Methane and carbon dioxide can also occur due to the activities of man such as landfilling waste (landfill gas) and by mining (mine gas). The gases generally pose a risk to developments over or near them when the following occur:

1. An accumulation of large volumes of gas in the ground in or near buildings (source)
2. A pathway that allows gas to migrate through and/or out of the ground into a building or other structure sufficiently quickly to allow it to build up inside the building (pathway)
3. A confined space within the building or structure where gas can build up to unacceptable levels (receptor).

In other words there needs to be a source - pathway - receptor linkage for the gas hazard to pose a risk to any development. This requires a sufficient quantity of gas to pose a hazard and one or more pathways by which it may cause significant harm to people. Gas concentration in the ground (or monitoring well) should not be confused with volume of gas present. The two are very different and a small volume of gas can give rise to a high concentration in a monitoring well.

Landfills can generate large volumes of landfill gas and there are many instances where gas has migrated along a pathway and caused explosions or asphyxiation at a receptor (CIEH, 2008). Most recently this resulted in the evacuation of a housing estate in Australia (Brouwer, 2009). Similarly mine gas emissions from mine workings can be large and have caused deaths. As far as the authors are aware there are no recorded instances where ground gas from Made Ground or natural soils with a low organic content have caused gas emissions into above ground buildings.

Landfill waste with a high content of degradable organic material can be problematical where landfill gas forms in the pore spaces. The internal pressure of a gas bubble is inversely proportional to its radius so that it can remain in a stable condition in a discrete pore space at relatively high pressures up to a critical value. Above this critical value rupture of the soil skeleton surrounding the pore space will occur and a gas migration network will form (CIEH, 2008). Initial high pressures in sources such as landfills lead to coalescence of pores into a network that can cause large volume release of gas giving rise to potential risk to building development. Conversely in Made Ground and natural soils where ground gas generation is very low or has occurred in the geological past the ground gas pressure is much lower. The gas is now effectively trapped in the pore spaces of the soil or it is migrating out of the ground very slowly, for example estuarine alluvial deposits.

Buildings may often already require construction details that provide protection against ground gas ingress. If radon protection is required this will also give good resistance to ground gas ingress. Similarly the requirements for air tight construction lead to well sealed floor slabs. For this reason gas monitoring on low risk sites where small volumes of gas are likely to be present in the soil pores, or where radon protection or air tightness is already required, is not always necessary.

This bulletin proposes an alternative framework for the investigation and assessment of ground gas that takes into account the preceding considerations. It should allow gas well installation and monitoring to be avoided where appropriate. It can also be used in conjunction with gas monitoring to reduce the period of monitoring required or to avoid extra gas monitoring where anomalous results, particularly high borehole flow rates, are recorded.

The approach is based on principles described in the "*Local authority guide to ground gas*" published by the Chartered Institute of Environmental Health (CIEH,

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2008) and is compatible with the guidance in CIRIA Report C665 and British Standard BS 8485: 2007. The aim is to target resources effectively and separate out potential high risk situations such as large landfill sites from low risk sites where there is, typically only a thin layer of inert Made Ground or natural background sources of ground gas.

2. GAS MONITORING IN WELLS

Gas wells are an artificial construction in the ground that can in some specific instances cause high flow rates or gas concentrations from or in the well headspace that are not necessarily representative of sustained surface gas emissions. Factors that can have a significant influence on monitoring results are:

- Installation of simple standpipes with a single response zone to monitor ground gas, which means there is limited data on vertical variations in ground gas levels.
- Limited head space in the monitoring well so that small volumes of gas can cause high concentrations.
- Differential pressure recorded in a well with a response zone spanning different strata may be different to pressure recorded in discrete locations. This could create an artificial flow regime.. It is a particular problem where deep wells are installed for groundwater sampling and are then used for ground gas monitoring where no credible gas source is present. It also occurs where more permeable strata are confined by impermeable material such as clay over sand layers or clay over peat.
- The presence of organic material in groundwater that is standing in the well. This can degrade and produce small volumes of methane and carbon dioxide, resulting in high gas concentrations in the sealed headspace.
- Organic material in silt collecting in the base of a well can degrade and produce small volumes of methane and carbon dioxide, resulting in high gas concentrations in the sealed headspace.
- The presence of dissolved methane and carbon dioxide in groundwater that can come out of solution if changes in groundwater levels cause a drop in pressure in the headspace which does not occur in the surrounding ground.
- The presence of hydrocarbons collecting in the well that can degrade and produce methane and carbon dioxide. The degradation process and volume of hydrocarbon is generally small and will result in small volumes of methane and carbon dioxide giving high gas concentrations in the well head space. The chronic health risk posed by the hydrocarbons is in most cases more significant than the acute risks posed by methane and carbon dioxide. This will drive the type of gas/vapour resistant membrane that is required.
- The accumulation of methane displacing air due to buoyancy effects.
- The presence of the monitoring well creating an artificial mechanism by which gas can enter the headspace of the well (e.g. where the response zone intersects a layer of peat that is confined with more impermeable layers above and below it).

Figure 1 shows how a number of these variables can affect flow rates.

In all these cases the gas concentration measured in a well headspace is not a good indicator of risk. If these effects are not fully understood and assessed when interpreting the monitoring results incorrect conclusions can be drawn about the gas regime in the ground below a site. A common response to anomalous results is to recommend ever more and frequent monitoring that does not solve the underlying problem. The approach proposed in this bulletin will also help to quickly resolve these situations.

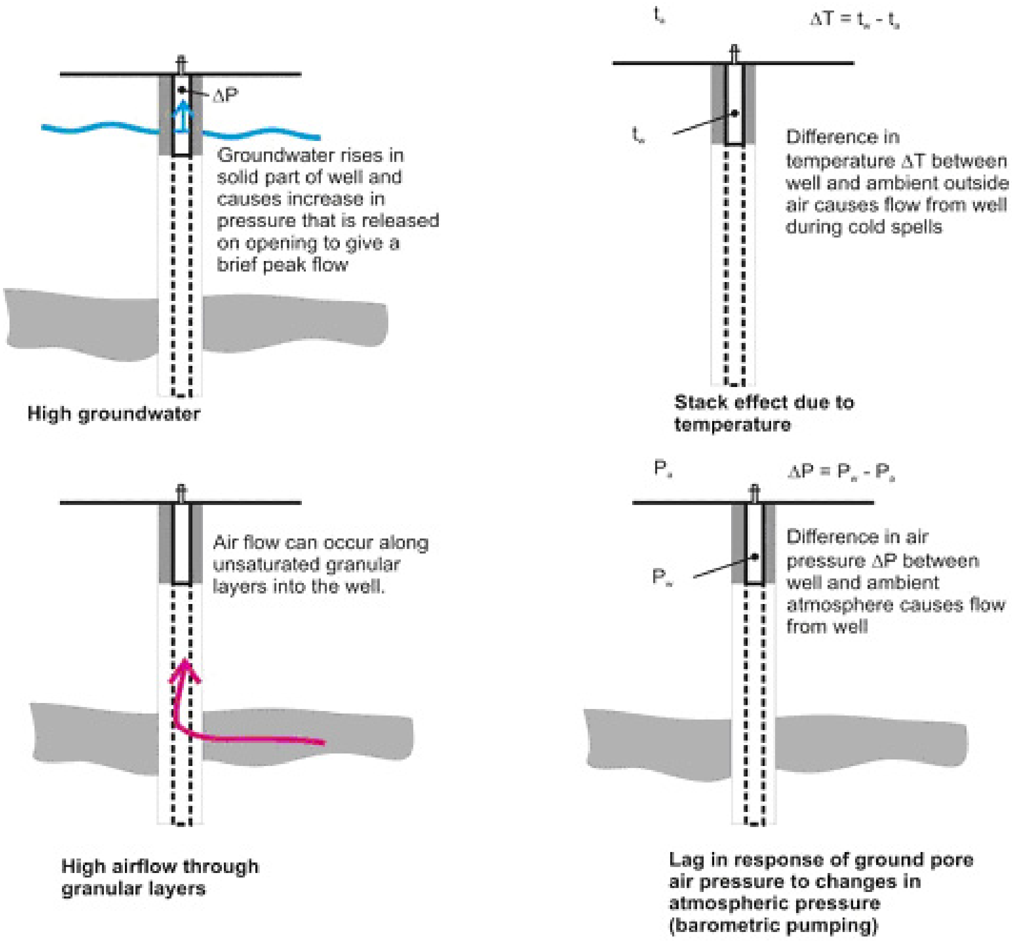


Figure 1: Factors that can affect flow rate measurements

Whilst the effects described above may also occur in the soil pores around the well they are magnified by the boreholes and are often not representative of normal conditions. They can also cause negative flow readings.

It is important that risk assessors recognise these issues and allow for them when interpreting results from gas monitoring data. This is because the screening process that is at the heart of UK guidance on ground gas risk (Wilson *et al.*, 2007; BSI, 2007) is based on limits that are derived using borehole concentration and flow rate. The Gas Screening Value (GSV) is the product of the borehole flow rate and gas concentration.

3. ALTERNATIVE APPROACH TO GAS MONITORING ON LOW RISK SITES

Given the uncertainty in the interpretation of measurement of gas concentrations and flow rates in monitoring wells that can sometimes occur, an alternative approach to ground gas assessment is proposed that removes the need for monitoring on low risk sites. These are defined as sites where the conceptual model has not identified any significant potential sources of ground gas or gas protection is to be provided on sites where small volumes of gas may be generated. The conceptual model will be based on sufficient supporting information as described later. The preliminary investigation and intrusive investigation should follow the guidance provided in BS 10175: 2011. Sites where routine gas monitoring is less likely to be required include the following:

1. Natural soils with a high carbonate content, e.g. Chalk, some Glacial Tills, etc
2. Natural soils that are known to contain methane, e.g. Alluvium, Peat, etc, providing pockets of trapped gas cannot be released quickly due to changes in groundwater level (which is rare and not likely on most sites).
3. Made Ground up to 5m depth with a low organic content (i.e. predominantly soil, ash or clinker with occasional pieces of wood, etc). Where Made Ground is greater than 5m depth there is a greater risk of unidentified degradable material with deeper deposits. One reason is because it is more difficult to investigate deeper than 5m with trial pits. If trial pits cannot reach 5m at the site under investigation, then the risk assessor will need to review the site history and variability of the Made Ground that is exposed, and decide whether borehole investigation to that depth will provide sufficiently robust information. The soil atmosphere is also more likely to be predominantly aerobic above 5m (USEPA, 2007). In some cases if there is consistently high groundwater within the Made Ground it could become anaerobic below the water table (this can be assessed by measuring dissolved oxygen in the water). Discrete perched water present in many sites will not cause anaerobic conditions to be widespread in Made Ground.
4. Areas of flooded mine workings or mine workings that were abandoned by the early 20th Century (gas emissions from these types of mine workings are not likely to pose a significant risk). The exception will be where buildings are within 20m of a mine opening (shaft or adit) or where shallow workings are very close to the surface and/or connected to deeper unflooded mines.

Providing the risk is adequately characterised and a robust conceptual model developed using the information described later in this bulletin gas monitoring is less likely to be required and will be focused on higher risk sites. These will include:

1. High risk sites where gas can be emitted from the ground in large volumes (domestic or industrial landfill sites with a high degradable content, Made Ground with a higher degradable content, mine workings where there is still a large gas reservoir and a vent to the ground surface such as a shaft or fractured rock).
2. Sites with Made Ground where maximum depth is greater than 5m or average depth greater than 3m.
3. Sites where migration from an off-site source with a credible migration pathway needs to be assessed.
4. Sites that exceed total organic carbon (TOC) limits provided in Table 1 later in this bulletin.

Even on these sites the data collected as part of this method (TOC, estimate of gas generation, etc) is vital to allow correct interpretation of monitoring results. It is also vital to measure the permeability of the ground when considering gas migration out of landfill sites.

Gas monitoring may also be chosen where it is thought the costs will be outweighed by cost reductions in the gas protection design (in this case wells may be installed as a precautionary measure during the site investigation and only monitored if the testing for organic carbon indicates it is necessary).

Gas monitoring will still often be required on sites being investigated under Part IIA of the Environmental Protection Act. This is because generally Part IIA sites involve investigating gas migration across site boundaries outside higher risk former landfill sites. In built resistance to gas in older housing stock cannot be assumed. However the principle of gas generation modelling does form an important element of these assessments.

The development of a conceptual model is important and this should be based on an understanding of the history of a site and the nature of the source material. It should identify and consider all the relevant aspects of gas generation and transport processes, including the source of gas, the site specific pathways of flow and transport and all of the potential receptors. Clear graphical presentation of the conceptual model is recommended (Environment Agency, 2001) and it is best achieved by drawing cross sections showing the geology, topography and proposed development.

The data required on the source material is quick and easy to obtain during an intrusive site investigation (TOC testing and forensic description). Gas moves in the ground and concentrations can be spatially and temporally variable. Gas monitoring results on some sites can be sensitive to external influences. This approach uses data that is not subject to temporal variations leading to a more robust risk assessment. Spatial coverage of the data used in the assessment should also be improved over that from gas monitoring in wells. This is because a greater number of test locations can be achieved compared to the number of gas monitoring wells that are normally installed in sites.

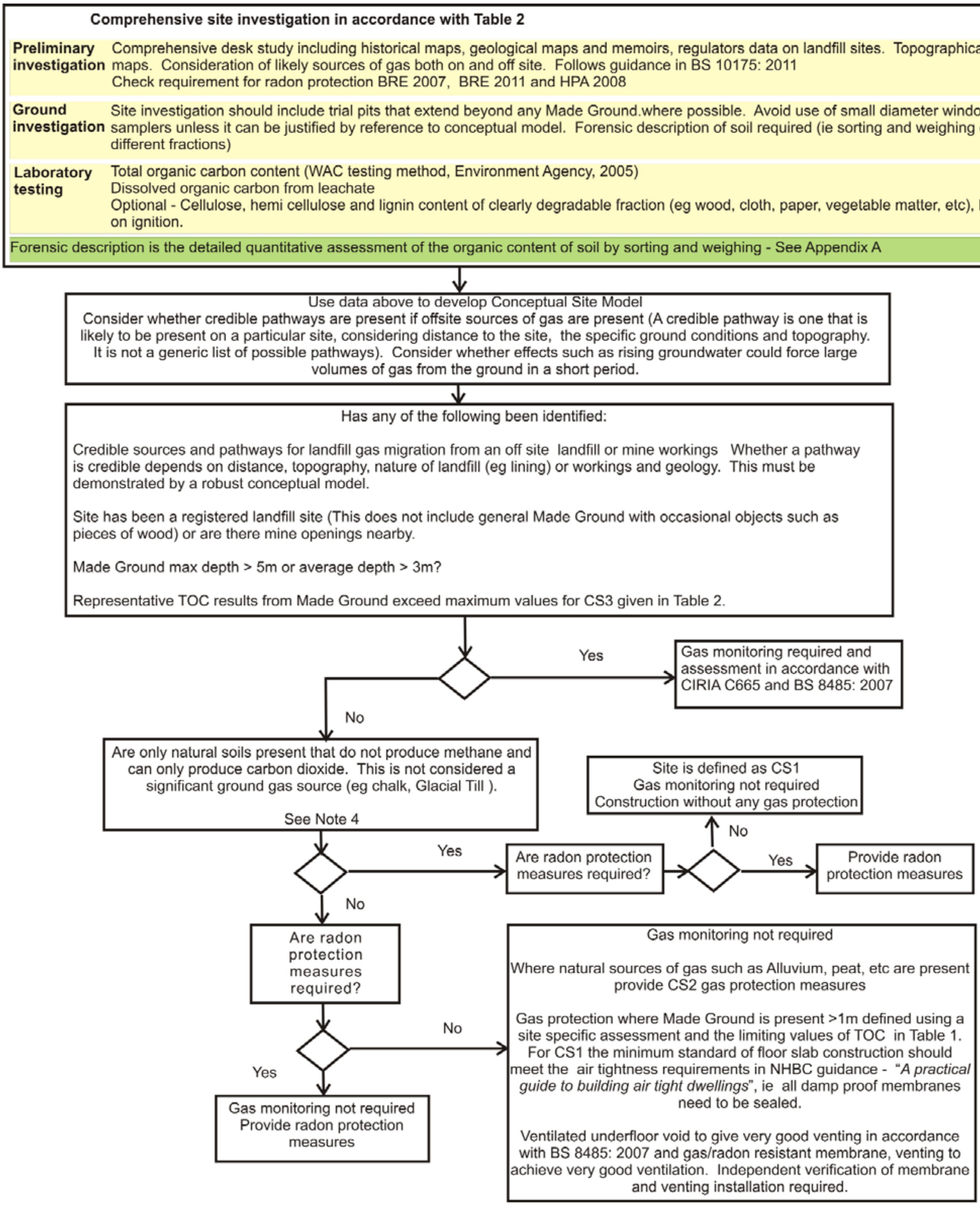
This alternative approach is based on an understanding of soil chemistry and gas generation processes and the volumes of gas produced from carbonate or organic degradable material that are cycled naturally in the environment. Such an understanding can remove the need to install costly monitoring wells. It can also be used in conjunction with gas monitoring to reduce the period of gas monitoring specified in CIRIA C665 (Wilson *et al.*, 2007) or avoid extended monitoring when anomalous results are recorded.

A flow chart showing the new approach and detailed requirements is provided in Figure 2.

4. NATURAL SOILS

Where there is no credible source of gas below a site or a pathway for gas to migrate from external sources gas monitoring is not considered to be necessary. An example would be where a site is underlain only by London Clay without any nearby landfills or similar. Sites where only Chalk is present that will give rise to small volumes of carbon dioxide would also fall into this classification. A summary of the more common ground conditions where this would apply is given in Appendix A.

Alluvial soils and buried peat can quite often give high concentrations of methane and carbon dioxide in monitoring wells, often methane concentrations can reach up to 90%. This is because the gas has been generated historically and is trapped in the pores due to limited transport (at low diffusion rates). The methane accumulates at increasing depth in peat columns, but this does not



Note 1

A registered landfill site is a site that was registered under waste management or control of pollution legislation, or shown as a refuse heap, tip or similar on old ordnance survey maps. It does not include areas where Made Ground has simply been placed to raise ground levels, fill old railway cuttings, etc or old ponds and similar features that have been infilled with general fill materials

Note 3

If a site investigation is not phased then developers/consultants may choose to install gas monitoring wells as part of the site investigation works, in case testing shows that gas monitoring is required. In this situation the alternative approach can be used to confirm the gas monitoring results and shorten the required period of monitoring. It will also remove the need for additional monitoring to deal with anomalous flow rates, etc.

Note 2

There are sites where infilled quarries or other features not specifically identified as landfills have been used to deposit domestic refuse. These sites will be dealt with further in the flow chart where TOC testing on the material will determine the gas risk.

Note 4

Made Ground deposits less than 1m thick such as general fill below roods and car parks or road construction sub-base, etc can be ignored for the purposes of this assessment. Infilled ponds do not generally pose a significant risk of lateral gas migration (CIEH, 2008)

Figure 2: Alternative approach to ground gas assessment on low risk sites

indicate high rates of production (Clymo and Bryant, 2008; Fritz *et al.*, 2011). There is no, or very little, current gas generation and the carbon dioxide has dissolved out of the gas trapped in the soil pores which causes a higher percentage of methane to be recorded.

Experience on many dockland and similar sites has shown that sites on Alluvial soils do not generate sufficient hazardous gas flows to exceed Characteristic Situation 2 as defined in BS 8485: 2007 (this has been demonstrated by monitoring under floor venting systems - Wilson and Card, 1999). Therefore if gas monitoring is not undertaken it is acceptable to simply install Characteristic Situation 2 protection on sites where Alluvial soils are present.

A similar approach is acceptable on sites with soils containing lignite or buried layers of peat (where the peat is well decomposed and the remaining material is predominantly woody material, i.e. lignin). In all these situations experience has shown that provision of passive venting or positive pressurisation below the floor slab combined with a gas resistant membrane (installed correctly and independently verified) is sufficient to mitigate the risk posed by the presence of gas in the ground. A table summarising some of the more common situations is provided in Table 4 at the end of this bulletin.

In many soils the pore space is made of small discrete voids such that the presence of ground gas represents a relatively small volume. In reality this does not generally pose a significant risk to buildings or development constructed over such soils.

Examples where ground gas is present and does not generally pose a risk include soils or rocks with low gas production, such as:

1. Made Ground and recycled soils
2. Carbonate soils (e.g. chalk or limestone).

Experience of gas monitoring on many city centre redevelopment sites has shown that Made Ground and/or recycled soils with a low organic content are present below many urban areas of the UK and there are low levels of gas in them. There are also areas with high natural methane content such as the Somerset Levels. These sites have had housing or other buildings over them for many years without any evidence that gas poses a significant hazard (Sladen *et al.*, 2001). The presence of methane and carbon dioxide in these soils was not really recognised until the past 15 to 20 years, because until this time gas monitoring was not a routine undertaking on development sites (Boyle and Witherington, 2007).

Now that gas monitoring wells are being installed on the majority of larger development sites ground gas is being found in many situations where it would not in the past have been considered an issue. This can cause problems with interpretation when it accumulates in gas monitoring wells at elevated concentrations. The result is that gas protection measures are specified on both greenfield and brownfield sites where small volumes/relatively low concentrations of gas do not actually pose a hazard or extended gas monitoring is undertaken when it is not required.

Carbon dioxide in wells is a particular problem and is not considered to be a good choice to regulate emissions through the ground from landfills because there are natural sources that are often present (C and P Environmental, 2011). The authors believe that carbon dioxide is also a poor indicator of risk to new developments, except those close to or over mine workings (although it is a very useful part of the conceptual site model).

The authors' experience of reviewing many hundreds of site investigation reports is that carbon dioxide in natural soils such as Glacial Deposits and Chalk can often be recorded at up to 15% in monitoring wells, but that this does not pose a risk to development. C and P Environmental (2011) indicate background levels of carbon dioxide around landfill sites have been recorded up to 18.5% and Chapelle (1993) refers to carbon dioxide concentrations up to 19% in unsaturated sediments.

5. TOTAL ORGANIC CARBON CONTENT OF MADE GROUND

Determination of the characteristic situation where Made Ground is present is based on the total organic carbon (TOC) content of the material. TOC is used as the defining parameter as this is a standard test requirement for waste acceptance classification (WAC) testing and therefore it can readily be carried out by commercial laboratories.

There are various methods of testing for TOC, each with its own advantages and disadvantages. The method adopted for consistency and practicality is that specified by the Environment Agency in their guidance on WAC testing (Environment Agency, 2005).

Further information on the organic carbon content of soils and how it is used to model gas generation is provided in Appendix B.

The limiting values of TOC in Table 1 should be determined from a combination of forensic description and laboratory testing on the soil fraction of the Made Ground. For example if Made Ground contains 30% discrete material at 20% TOC and the remaining 70% of the soil fraction has a TOC of 0.5% the overall TOC will be 6.4%. Guidance on the organic carbon content of various waste fractions is provided in references such as Andreottola and Cossu (1998).

Care is needed where Made Ground includes organic materials that are not degradable. Ash, clinker and coal can give high TOC results that do not represent the risk of gas emissions from such material (it is generally not degradable so cannot produce methane or carbon dioxide). For example coke breeze can contain up to 51% TOC but only 4% dissolved organic carbon (DOC) (Analytik Jena, 2011). In this case the assessor must estimate what proportion of the TOC will be degradable and apply a reduction factor to the results. This can be assessed by looking at published data (for example Eleazer *et al.*, 1997) or determining the proportion of lignin, cellulose and hemicellulose in the sample (Zheng *et al.*, 2007).

Discrete layers of highly degradable material should be assessed separately from other Made Ground (for example a layer of rotting vegetation or highly organic sediment at the base of infilled ponds).

Experience over the past 10 years suggests that the majority of sites, where the main source of gas is Made Ground with a low degradable content, will be classified as Characteristic Situation 2 or 3. Therefore the approach is currently limited to a maximum of Characteristic Situation 3. If the requirements in Table 1 for Characteristic Situation 3 are exceeded gas monitoring will be required to define the protection measures for a site.

6. INHERENT GAS PROTECTION INCORPORATED INTO BUILDINGS

The flow chart (Figure 2) takes account of the fact that many developments may already incorporate some inherent gas protection in the building construction. Many areas of the UK require radon protection measures to be installed in accordance with BRE Guide BR211 (2007) without any data from site specific monitoring. The main form of protection for new buildings is to provide a radon barrier in the floor slab construction and ventilation below using the approaches described by Scivyer (2009). In commercial buildings positive pressurisation and a membrane may be used.

These are the same methods used to protect against the ingress of other ground gases such as methane or carbon dioxide (Wilson *et al.*, 2007; Boyle and Witherington, 2007). Therefore it seems unreasonable to mandate gas monitoring in such situations, where gas protection is already to be provided unless there is reason to suspect that higher levels of protection may be required.

The requirements of Part L of the building regulations relating to the air tightness of buildings also leads to the need for a well sealed floor slab (NHBC Foundation, 2009). Standards are intended to become more stringent with time

Table 1: Limiting values of organic content

Characteristic situation (BS 8485 and CIRIA C665)	Thickness of Made Ground (m)	Maximum total organic carbon content of Made Ground - TOC (%)$^{\text{see note 1, 2 and 3}}$		Comments
		Made Ground	Made Ground in place for > 20 years	
CS1	Maximum 5m Average < 3m	≤1.0	≤1.0	Limiting values based on reported soil organic matter (SOM) content of natural soils up to about 1%
CS2	Maximum 5m Average < 3m	≤1.5	≤3	Limiting values based on gas generation modelling assuming slow degradation Equilibrium methane concentration in building above <0.01%
CS3	Maximum 5m Average < 3m	≤4	≤6	Limiting values based on gas generation modelling assuming slow degradation Equilibrium methane concentration in building above <0.01%
This method can only be used to define characteristic situations up to 3.	Gas monitoring required where TOC is greater than 4% (or 6% in old Made Ground). Gas monitoring results will show whether the high TOC is available and conditions are suitable to generate ground gas.			

Note 1: TOC = DOC x 1.33 (Hesse, 1971).
Note 2: TOC of soil tested in accordance with the method described in "*Guidance on sampling and testing of wastes to meet landfill waste acceptance procedures*," Environment Agency (2005) and combined with estimate of discrete organic material from forensic description (Appendix C).
Note 3: Where TOC of soil is not representative of degradability (e.g. where it is predominantly ash or clinker) the TOC value used in the assessment should be reduced based on the fraction of degradable organic carbon.

so there will be an increasing need for all penetrations through floor slabs to be well sealed, both between pipes and the floor structure and the damp proof membrane using top hat details (Figure 3). Again these are the same measures required for protection against the ingress of ground gases.

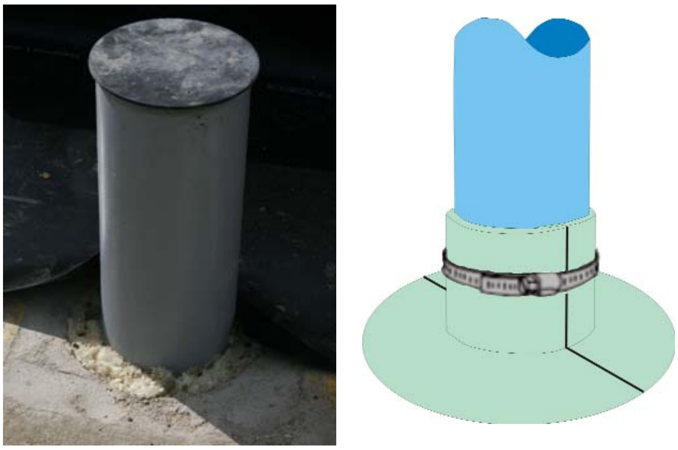


Figure 3: (Left) Good sealing between a pipe and the floor structure using expanding foam. (Right) Example of a top hat detail. A seal is achieved around the pipe and the flange is sealed to the barrier (1200g membrane).

Many housing developments have block and beam suspended floor slabs with a ventilated underfloor void (these are the preferred type of construction for geotechnical and/or cost reasons in many areas). The void provides good protection against ground gas ingress and when designed and constructed correctly it dilutes any gas being emitted from the ground to acceptable levels. The minimum level of ventilation required to deal with condensation is capable of dealing with quite onerous ground gas regimes. For a typical residential property up to 8m wide the minimum ventilation to the void of 1500mm^2/metre of wall will provide adequate dilution of gas (equilibrium concentration of 0.25% v/v) up to a Gas Screening Value of 3.5l/h (Wilson and Card - Characteristic Situation 3 or NHBC - Amber 2). This has been demonstrated by monitoring of voids below completed buildings for many years (Wilson and Card, 1999; Pecksen, 1986). Good construction also requires the cavity wall below ground level to be filled with concrete, again limiting the potential for gas ingress. Thus many buildings will already have an inherent level of gas protection provided in their construction and this can be taken into account when determining whether gas monitoring is likely to be required during a site investigation.

Uncontrolled buildings such as sheds, greenhouses, etc are not covered by such levels of protection. However, natural ventilation rates will usually be much higher in these types of structure, therefore reducing the potential for gas accumulation within them.

7. DATA REQUIREMENTS

One of the key elements of this approach is the collection of robust desk study information combined with rigorous interpretation of that data. This allows the development of a sound conceptual site model that includes cross sections in and outside the site (to natural scales if practicable, i.e. the vertical scale is not exaggerated).

This is possible on most sites even if only rudimentary data are available from ordnance survey maps and observations made during a walkover survey (e.g. spot levels taken using a hand held GPS). At this stage potential credible gas sources and pathways should be identified for the specific site being considered.

The data requirements to enable the new approach to be used are summarised in Table 2.

The intrusive site investigation will require sufficient coverage to give a robust indication of the nature of any potential gas source. It is recommended that forensic description (see Appendix C) of Made Ground is carried out on at least one bulk (10 to 15kg) sample from each trial pit. This can be done on site or in a laboratory. The sample should be representative of the source material. Often more than one sample will be required, for example where there are significantly different horizons within Made Ground or there is variability across a site. The overriding requirement of the sampling is that the source is adequately characterised in terms of how much ground gas can be generated and small variations that will not influence this are not important. The forensic description should be combined with TOC tests on the soil fraction from the Made Ground.

Table 2: Requirement for site investigation

Element of site investigation	Requirements
Preliminary investigation	Comprehensive desk study including historical maps, geological maps and memoirs, regulators data on landfill sites. Follows guidance in BS 10175: 2011. Topographical maps (and aerial photographs?) Consideration of likely sources of gas both on and off site. Check requirement for radon protection in BR211 (BRE, 2007), "*Radon: guidance on protective measures for new buildings,*" "*Radon in the Workplace*" (BRE, 2011) and "*Radon in Dwellings in Scotland*" (HPA, 2008)
Ground investigation	Where possible the site investigation should include trial pits that extend beyond the base of any Made Ground. Forensic description of soil required (detailed quantitative assessment of the organic content of soil by sorting and weighing different fractions: fine soil (organic and inorganic), coarse soil (such as clinker, gravel, concrete, etc), wood, vegetable matter, cloth/leather, other non degradable materials (metal, glass, ceramics, etc), paper and card, other degradable material). See Appendix A. Care should be taken when relying on information from small diameter window sampler holes. The requirement for more robust methods of investigation will be determined by the preliminary conceptual model and risk assessment and on ground conditions encountered.
Laboratory testing	Total organic carbon content (carried out on the fine soil fraction only). Test in accordance with Environment Agency "*Guidance for waste destined for disposal in landfills*" (Environment Agency, 2006) and "*Guidance on sampling and testing of wastes to meet landfill waste acceptance procedures*" (Environment Agency, 2005). Dissolved organic carbon in leachate. Optional - Cellulose, hemicellulose and lignin content of clearly degradable fraction (e.g. wood, cloth, paper, vegetable matter, etc) using Neutral Detergent Fibre, Acid Detergent Fibre and Acid Digestible Lignin test methods (Richards *et al.*, 2005), loss on ignition.

8. EXAMPLES

The approach has been used on many development sites and sites being assessed under Part IIA of the Environmental Protection Act 1990 in the past few years to confirm the Gas Screening Values obtained from gas monitoring results. Sites assessed using this new approach also include moderate to high risk gassing sites to demonstrate and verify upper limit criteria on TOC content. Summaries from a selection of these projects are provided in Table 3.

The summaries show that in general the approach gives a similar assessment of gas risk to existing approaches when the anomalous or natural background readings of gas concentrations from gas monitoring are discounted. Thus it is as reliable and robust as the standard required approach.

The approach and its application to various common scenarios is summarised in Appendix A.

9. CONCLUSION

The alternative approach to ground gas assessment will provide a rapid and more reliable indicator of ground gas risk on appropriate development sites. It will remove the need for gas protection on sites located over natural ground where low levels of carbon dioxide are ubiquitous. It will also reduce the need for gas monitoring wells on low gassing sites and should give a more reliable and rapid indicator of the ground gas risk than current approaches that rely on periods of gas monitoring.

Table 3: Summary of application to various developments

Development	Nature of gas source	Gas concentrations and flow rates used to calculate GSV	GSV / Characteristic situation - gas monitoring data and BS 8485	Estimated GSV from site specific gas generation modelling / Characteristic situation	TOC content / Characteristic situation from Table 1	Comments
TOC content / Characteristic situation from Table 1	Made Ground average depth 4.4m	54% CH_4 14% CO_2 0.6l/h	0.3l/h / CS2 but with occasional higher values in one well up to 0.5l/h	0.1l/h / CS2	1.7% / CS3	Recently placed Made Ground
School in SE Manchester	Made Ground average depth 0.5m	0.1% CH_4 12% CO_2 15l/h	2.2l/h / CS3 due to occasional high flow rates, typically 0.01l/h / CS2 (due to concentration)	0.2l/h / CS2	1.3% / CS2	Made Ground placed over 50 years ago
Warehouse development in Liverpool	Made Ground average depth 2.5m	69% CH_4 12% CO_2 0.4l/h	0.3l/h / CS2	0.7l/h / CS2	1.3% / CS2	Made Ground placed over 10 years ago
Apartments, west London	Made Ground average depth 1.2m	0.1% CH_4 3.2% CO_2 1.4l/h	0.04l/h / CS1	0.2l/h / CS2	0.5% / CS1	Made Ground placed over 90 years ago
Housing in Northwest England	Made Ground average depth 2m	1.6% CH_4 8.9% CO_2 0.8l/h	0.07l/h / CS1	0.1l/h / CS2 (close to limiting value for CS1/CS2)	0.7% / CS1	Made Ground placed over 40 years ago
Housing in Southeast England	Old landfill average depth 10m	38% CH_4 12% CO_2	12.5l/h / CS4	4.75l/h / CS4	5.3% >CS3	Placed over 45 years ago

Where the assessment shows that gas protection is required developers and their consultants may still choose to install gas monitoring wells if they consider it will reduce the characteristic situation and there is a cost benefit. However on many smaller sites this will not be the case.

The approach can also be used alongside gas monitoring as a separate line of evidence in the risk assessment. This would allow the period of monitoring to be reduced from that specified in CIRIA C665 or help to avoid extended monitoring where anomalous results are obtained that are not consistent with the site conceptual model.

Where chemical test data indicates a TOC greater than the limiting value for CS3 in Table 1, or there is a credible gas migration risk from off site, gas monitoring in accordance with CIRIA C665 and BS 8485: 2007 will be required to verify the gas regime and characteristic situation.

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APPENDIX A

Table A1: Application of approach to common scenarios

Scenario and source of ground gas	Gas monitoring?	Gas protection?
Natural soils with no Made Ground. E.g. London Clay, Mercia Mudstone, Lias Clay, Chalk, Gault Clay, Glacial Till	X	X
Natural soils with No Made Ground - in an area where radon protection is required.	X	✓ Gas/radon protection required
Natural soils with low organic content - less than 1m of Made Ground that comprises general infill and car park construction materials. E.g. Made Ground over London Clay, Mercia Mudstone, Lias Clay, Chalk, Gault Clay, Glacial Till	X	X
Natural soils with high organic content and less than 1m of Made Ground that comprises general infill and car park construction. E.g. Alluvium, Peat over natural soils such as London Clay, Mercia Mudstone, Lias Clay, Chalk, Gault Clay or Glacial Till	X	✓ CS3 gas protection provided
Natural soils with low organic content and 1m to 5m of Made Ground (average <3m) that comprises general infill and car park construction materials TOC less than 6%. E.g. Made Ground over London Clay, Mercia Mudstone, Lias Clay, Chalk, Gault Clay, Glacial Till	X	? Determine gas protection using TOC content of Made Ground and Table 2
Old landfill with 6m of older refuse material. Identified as old landfill on historical maps	✓ Determine TOC content and use gas generation modelling to assist with interpretation of results	? To be determined from gas monitoring data
Old mineworkings that were abandoned before the early 20th Century	? To be determined based on preliminary conceptual model using desk study data	?
Glacial Drift deposits over Coal Measures strata with no former mine workings.	X	X

APPENDIX B

TOTAL ORGANIC CARBON

Natural soils in the UK can contain up to 1% organic material and pose no hazard with respect to ground gas generation. For example siliciclastic mudrocks can contain 1% organic matter (Reeves *et al.*, 2006). Even bentonite used to form seals in monitoring wells can contain 4% to 6% organic matter (Herzog *et al.*, 1991) which may contribute to ground gas in wells if it is not in a cement:bentonite mixture (the cement will increase the pH of the mixture and inhibit any degradation).

When organic matter has been present in the soil for years at a suitable moisture content the remaining organic matter comprises large complex compounds that few microbes present in the soil can degrade. The material that is hard to decompose is called stabilised organic matter and can comprise between one third and half of the total organic matter in soil (University of Minnesota, 2011). Other compounds become bound inside the soil structure where they cannot be reached by microbes. When drilling boreholes the exposure of soils to atmospheric aerobic conditions can allow microbes to reach this material and is possibly one reason why initially high concentrations of methane can often be detected in wells installed in low generation potential material shortly after installation. After a period of time the concentrations subsequently decrease to negligible values (CIEH, 2008) as shown typically in Figure 4.

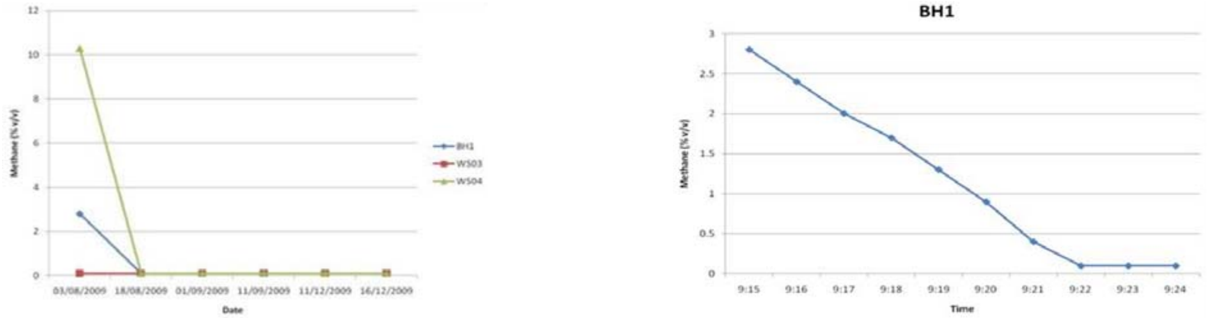

Figure 4: Initial peak methane results in gas well installed into Made Ground

The figure shows that initial high frequency data using a portable hand held gas monitor identified the reduction in gas concentration that has subsequently been confirmed by spot monitoring. Another reason for these initial peaks may be the release of small volumes of methane trapped in the soil pore spaces that is not replenished.

LIMITING VALUES IN NATURAL SOILS

Therefore the assumption made in the new classification system is that Made Ground with a soil organic matter content less than 1% does not require gas protection measures (i.e. they meet the requirements of Characteristic Situation 1). Cresser *et al*., (1993) indicate that arable soils can typically generate 90 litres of methane/m^2/year (0.01l/h/m^2). This is equivalent to a borehole flow rates of 0.1 l/h (if the Pecksen correlation between flow rate and surface emission is used) which is the same order of magnitude as the limiting Gas Screening Value for Characteristic Situation 1 in CIRIA C665 (0.07l/h).

LIMITING VALUE FOR MADE GROUND

The determination of limiting values of TOC for higher characteristic situations is based on analysis of gas generation modelling. This has used the equations from the Environment Agency report "*Guidance on the management of landfill gas*" (Environment Agency, 2004) The rate of gas generation at any time after deposition is given by:

$$\alpha_t = \Sigma 1.0846.A.C_i.k.e^{-k.t}$$

Where:
α_t = gas formation rate at time t (m^3/year)
A = mass of waste (tonnes)
C_i = DOC content (kg/tonne), degradable organic carbon content. This is related to total organic carbon (TOC) by the approximate equation
DOC = TOC ÷ 1.33
and to soil organic matter (SOM) by
DOC = SOM ÷ 2.29
k = rate constant (year^{-1})
t = time elapsed since deposit (years) - for recently placed Made Ground this is taken as one year and for Made Ground older than 20 years is taken as 21 years. The latter can be a very conservative assumption depending on the site.

The analysis has been undertaken based on the estimated degradable carbon content of the ground gas source at the time of the site investigation (from correlations with TOC identified earlier). It is assumed that 65% of the organic material in Made Ground is readily available for degradation. This is reasonable because the main type of degradable material in Made Ground will be wood, textiles, newspapers, etc that do not fully degrade and 65% is consistent with information provided by the Environment Agency (2004) and DEFRA (2003). It is also slightly precautionary when compared to the values of percentage decomposition for various waste fractions quoted in the references.

It is also assumed that all gas generated can reach the surface. In reality this is not the case, for the reasons discussed previously and the fact that some gas becomes trapped in pore spaces. The gas generation estimates are the peak values that will occur in the first few years after placement of the material. They will often reduce significantly in later years where the conditions are suitable (where there is sufficient moisture, etc). Thus the analysis gives a worst case scenario. In addition where the gas source is less than 5m deep a large proportion of the material may be much more aerobic (DEFRA, 2003; USEPA, 2007). The USEPA guidance suggests a methane correction factor for shallow unmanaged disposal sites of 0.4 (i.e. methane generation will only be 40% of that indicated by the models). Thus decomposition will generate more carbon dioxide in the aerobic zones and overall methane generation will be lower or may be absent altogether. The generation equations were developed for domestic landfill material and are known to be conservative when applied to more inert materials.

SURFACE EMISSION RATE CONVERSION

The estimated gas generation is then converted to a surface emission rate. As the gas migrates through the soils to the surface from most low generation sites there is significant oxidation of methane in the upper 1m of soil. To be conservative this has been ignored although it is likely to occur on most sites, even below buildings. The surface emission rate is converted to an equivalent borehole flow rate using the Pecksen correlation (multiply surface emission rate by a factor of 10) and compared to the limiting values in CIRIA C665 and BS 8485 (BSI, 2007).

EQUILIBRIUM CONCENTRATION IN BUILDINGS

As a check the gas generation rate estimated using the procedures described above is used to determine the equilibrium gas concentration in a house built over the source. A limiting value of 0.05% is considered acceptable where gas protection will be provided to meet the requirements of Characteristic Situations CS2 and CS3 as defined in BS 8485: 2007. Again this is a very conservative approach as any resistance to gas flow provided by the ground or floor construction (that will include a membrane or robust floor slab and underfloor venting) is ignored in the assessment.

ROUNDING UP

Finally the limiting TOC values are rounded up to the nearest 0.5% to reflect the nature of the analysis (in reality this will make no difference to the risk on any site because the calculated surface emission rate would not vary significantly from this rounding up).

APPENDIX C

FORENSIC DESCRIPTION OF MADE GROUND FOR PURPOSES OF GAS GENERATION ESTIMATION

1. SCOPE

This document specifies the test method for determining the amount of degradable material in Made Ground.

This is intended as a test from which the degradable organic content can be estimated for use in gas generation assessments that are used to assess the risk from old landfill sites in accordance with the "*Local authority guide to ground gas*" (CIEH, 2008).

2. TERMS AND DEFINITIONS

For the purposes of this document the following terms and definitions apply.

Made Ground - soil or other material that has been placed in the ground by man.

3. PRINCIPLE

A sample of Made Ground is taken and the main constituents are divided into separate batches. The batches are weighed to determine the proportion of each in the sample.

4. APPARATUS

Weighing scales with a readability of 0.02% of maximum capacity (up to a maximum of 2g).

Weighing scales with a maximum capacity of at least 15kg.

5. SAMPLES

Bulk sample Made Ground with a weight of 10 to 15kg (for size comparison cat litter is normally supplied in 10kg bags).

6. PROCEDURE

Take the bulk sample and spread it out on a suitable surface (e.g. plastic bag or sheet).

Divide the sample into the following fractions:

- Fine including gravel less than 10mm (divide this into organic and inorganic)
- Coarse inert particles including clinker, gravel, concrete, brick, etc greater than 10mm
- Wood, trees, branches, etc
- Vegetable matter, etc
- Cloth, leather
- Metal, glass, ceramics and other inert material
- Paper and card
- Other degradable material

Weigh each fraction and record the result.

Determine total organic carbon content of the fine soil fraction in accordance with the method described in "*Guidance on sampling and testing of wastes to meet landfill waste acceptance procedures*" (Environment Agency, 2005).

7. TEST REPORT

The test report shall include the following information.

- Site reference
- Sample reference
- Sample location and depth
- Date of sampling
- % by weight of each of the following fractions in the sample
    - o Fine soil including gravel less than 10mm
    - o Coarse inert particles including gravel, concrete, brick, etc greater than 10mm
    - o Wood, trees, branches, etc
    - o Green vegetation, grass, food waste, etc
    - o Cloth, leather
    - o Metal, glass, ceramics and other inert material
    - o Paper and card
    - o Other degradable material
- TOC content of fine soil fraction.

ADVISORY NOTE

Note the most practical way to carry out this test is to complete it on site as samples are taken. This avoids having to transport and dispose of large volumes of sample material. Alternatively it may be completed at a geotechnical or chemical test laboratory.