

BS 8576:2013



BSI Standards Publication

Guidance on investigations for ground gas – Permanent gases and Volatile Organic Compounds (VOCs)

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Summary of pages

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Foreword

Publishing information

This British Standard is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 30 April 2013. It was prepared by Technical Committee EH/4, *Soil Quality*. A list of organizations represented on this committee can be obtained on request to its secretary.

Information about this document

This standard is intended to be read in conjunction with BS 10175, *Investigation of potentially contaminated sites – Code of practice*.

Test laboratory accreditation. Users of this British Standard are advised to consider the desirability of selecting test laboratories that are accredited to BS EN ISO/IEC 17025 by a national or international accreditation body.

Use of this document

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

Presentational conventions

The guidance in this standard is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is “should”.

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

Introduction

This standard, which is intended to be used in conjunction with BS 10175, provides guidance on the monitoring and sampling of ground gases. It covers volatile organic compounds (VOCs) and permanent gases such as carbon dioxide, methane and oxygen with particular reference to development sites and the risks posed by gassing sites to neighbouring land and developments. However, it is also relevant to investigations under Part 2A of the Environmental Protection Act 1990 [1] and under the Environmental Damage Regulations [2] (e.g. in respect of spills of oils, etc.).

A variety of gases might be present in the ground naturally, or as a result of contamination, or deposition of wastes. In addition to the main components found in air (nitrogen, oxygen, carbon dioxide), ground gas can contain other gases (methane, carbon monoxide, hydrogen sulfide, ammonia, helium, neon, argon, xenon, radon, etc.). It can also contain volatile organic compounds or inorganic vapours (mercury) which are of special interest in relation to the investigation of soil and groundwater contamination.

In order to complete an assessment of the risks posed by the presence of permanent and other ground gases, it is necessary to understand the potential sources of gas in and around a site. It is important to collect information on the other aspects of the site, including for example the history of the site, the natural and man-made geology of the site and surrounding areas, the hydrogeological regime, and the uses of the site and surrounding land. It is also useful to collect data on the nature of man-made soils including measurements of organic carbon content. These aspects are dealt with in BS 10175.

This information is used to develop a conceptual model of the site and surrounding area. The conceptual model is a description and/or representation of the site, incorporating what is known about the ground and groundwater conditions; the actual and potential contamination; the actual or potential presence of naturally occurring hazardous substances; the physical conditions and environmental setting; the receptors; and potential pathway linkages between contamination sources and receptors.

Development of the conceptual model requires an understanding of both the short-term (e.g. explosion or asphyxiation) and long-term hazards posed by the permanent gases and VOCs that might be present. Some relevant information is provided in Annex D of this standard.

Depending upon the objectives of the investigation, it could be relevant to consider new future receptors associated with the construction and completion of a new development, as well as existing receptors. Potential changes in the environmental setting (e.g. rising ground and surface water level) might also be relevant. The conceptual model leads to the formulation of contamination-related and other hypotheses, which the investigation process examines through the collection of relevant data.

The conceptual model is first formulated during the preliminary investigation (desk study and site reconnaissance) and informs subsequent investigations, if these are necessary, to meet the objectives of the overall investigation. One of the objectives will be reduction of uncertainty in the conceptual model. Consequently, the conceptual model is subject to regular review and updating as the work progresses.

Site investigation is an integral part of risk assessment (see CLR 11 [3]) and throughout this standard, the need for the information requirements for satisfactory risk assessment to inform the design of the site investigation programme is emphasized. However, there will be occasions where a risk assessment has been completed, and the primary purpose of the investigation is to collect additional information to aid design of protective measures, whilst of course, using the newly collected information to refine the risk assessment. Guidance is not provided on risk evaluation and characterization but guidance can be found in CIRIA C665 [4], CIRIA Report C682 [5], *Ground Gas Handbook* [6] and *Guidance on managing the risk of hazardous gases when drilling near coal* [7]. A hazard-fault/event-consequence probability analysis might be required when dealing with gas (see CIRIA report 152, *Risk assessment for methane and other gases in the ground* [8]). BS 8485, which is expected to be revised after publication of this standard (April 2013), gives recommendations and describes methods for the assessment of methane and carbon dioxide during new development of affected sites and appropriate protective measures for buildings. It does not consider ground gases other than methane and carbon dioxide. Guidance on protective measures has also been published by others (see references [9] to [13] in the Bibliography).

Carbon dioxide and methane are both powerful greenhouse gases and their uncontrolled release from landfills, etc. into the atmosphere is of concern in respect of their potential to contribute to climate change (in this sense the atmosphere is a receptor). The investigation of landfills, coal mines and other potential sources in order to design schemes for collection and/or beneficial use of gaseous emissions is outside the scope of this standard. Guidance on this has been published by the Environment Agency and others (see Bibliography for useful further reading).

The design of control measures (e.g. to prevent gas migration to adjacent land) and protective measures for buildings and other structures is outside the scope of this standard. However, when selecting such measures, it is advisable to consider the possible effects of the proposed measures on climate change in accordance with national policy.

As far as practical, the guidance on investigations for permanent gases and VOCs is provided together in an integrated text. Only where the approach required differs are they dealt with separately. It is important to consider them together rather than as separate issues because they commonly occur together. For example, petroleum hydrocarbons will degrade to form carbon dioxide under aerobic conditions and to form carbon dioxide and methane under anaerobic conditions. Indeed, the presence of carbon dioxide and/or methane is a powerful indicator that natural attenuation of hydrocarbons is taking place. Similarly, tipped wastes sometimes contain soil contaminated with VOCs and/or drums of VOCs. Radon could also be present in conjunction with other gases and VOCs.

BS 10175 advises early consultation with regulators when potentially contaminated sites are to be investigated. This advice applies equally to investigations for ground gas. Annex A describes the regulatory framework in the UK in March 2013 and the roles performed by different regulators. It is expected that Annex A of this standard will supersede BS 10175:2011, Annex I, when BS 10175 is amended to take account of the publication of this standard.

1 Scope

This British Standard provides guidance on the monitoring and sampling of ground gases. It covers volatile organic compounds (VOCs) and permanent gases such as carbon dioxide, methane and oxygen. It is intended to be read in conjunction with BS 10175.

Guidance is not provided on:

- risk evaluation and characterization;

NOTE 1 Guidance can be found in CLR 11 [3], CIRIA C665 [4], CIRIA C682 [5] and the Ground Gas Handbook [6].

- selection and design of protective measures;
- the verification of protective measures, although the site investigation methodologies described can be used when appropriate;
- the sampling of atmospheric gases;
- monitoring and sampling for radon.

NOTE 2 Radon occurs naturally at varying concentrations in large parts of the United Kingdom. It is commonly present in mine gas and can also be released from groundwater when it is extracted from the ground. It can also arise from deposited wastes such as those from the nuclear industry, phosphorus slags, and coal ash. Its importance lies in the fact that the risks associated with exposure to it are serious and its effects on the human condition are backed by extensive epidemiological information. There are established or draft International Standards for investigation and determination of radon in soils (BS ISO 18589 series) and in air (BS ISO 11665-1). The latter provides guidance on analysis of historic records, site reconnaissance, identification of preferential migration pathways, development of a sampling plan and how to measure radon in air once it has been emitted from the ground (see Annex B for further information). At the time of publication of this standard, the committee are not aware of any international standards or other authoritative guidance on the measurement and sampling of radon in the ground analogous to that provided in this standard for permanent gases and VOCs. The state-of-the-art is not sufficiently developed in the UK to provide such guidance as part of this standard but some preliminary guidance is provided for information in Annex B.

NOTE 3 The term "permanent gas" (3.10) is used rather than "bulk gas" as used in much UK guidance. The two are not synonyms. "Permanent gas" is an accepted international term in use for over 100 years. Its usage does not indicate any relationship between the proportion of a gas present and its properties in the way that the terms "bulk gas" and "trace gas" do. These terms were originally used in connection with "landfill gas". "Permanent gas" is considered more appropriate for the range of sources covered by this standard.

NOTE 4 "Ground gas" has the same meaning as "soil gas" as defined in BS ISO 11074, i.e. "gas and vapours in the pore spaces of soils".

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 5930, *Code of practice for site investigations*

BS 10175, *Investigation of potentially contaminated sites – Code of Practice* ¹⁾

¹⁾ BS 10175:2011 is also referenced in this standard informatively.

BS ISO 10381-3, *Soil quality – Sampling – Part 3: Guidance on safety*

BS ISO 11074, *Soil quality – Vocabulary*

BS EN ISO 14688-1, *Geotechnical investigation and testing – Identification and classification of soil – Part 1: Identification and description*

BS EN ISO 14688-2, *Geotechnical investigation and testing – Identification and classification of soil – Part 2: Principles for a classification*

BS EN ISO 14689-1, *Geotechnical investigation and testing – Identification and classification of rock – Part 1: Identification and description*

3 Terms and definitions

For the purposes of this British Standard, the terms and definitions given in BS 10175 and BS ISO 11074 and the following apply.

NOTE Where definitions differ between BS 10175 and BS ISO 11074, those from BS 10175 are to be used.

3.1 continuous monitoring

high-frequency monitoring at short intervals using automatically recording equipment

NOTE Intervals typically vary between a few minutes and a few hours but may be longer.

3.2 gas monitoring port

narrow diameter monitoring tube designed for sampling of ground gas

NOTE The tube is of short length and would typically extend only a short distance through a floor slab or similar slab.

3.3 grouped installation

a number of separate monitoring installations located close to one another

3.4 high-frequency monitoring

periodic monitoring in which the interval between monitoring events is short

NOTE 1 The underlying principal is that the time interval between monitoring events is less than the time that the conceptual model suggests important parameters are likely to vary.

NOTE 2 Intervals between monitoring events are typically measured in hours rather than days.

NOTE 3 Monitoring may be carried out manually or using automatically recording permanent in-well equipment.

NOTE 4 High-frequency monitoring is usually carried out over one or more comparatively short periods of time (see 9.5.2).

3.5 monitoring event

occasion on which ground gas data, other relevant information or samples are collected

NOTE Periodic monitoring, high-frequency monitoring and continuous monitoring typically comprise a number of monitoring events varying from a few to multitudinous.

3.6 multi-level installation

number of monitoring installations installed in one borehole with separate response zones

3.7 near-slab monitoring location

near-surface (sub-hardstanding) ground gas sampling location that is close to, but not under, the foundation of a building

NOTE Based on CIRIA Report C682 [5].

3.8 nested installation

number of monitoring installations installed in one borehole

3.9 periodic monitoring

spot monitoring carried out at intervals over an extended length of time

NOTE Monitoring is typically carried out weekly, fortnightly, monthly or quarterly with the time between monitoring events being extended as understanding of the ground gas regime develops.

3.10 permanent gas

element or compound that is a gas at all ambient temperatures likely to be encountered on the surface of the earth

NOTE 1 ISO DIS 11074:2011 defines permanent gas as: "Element or compound with a boiling point below 213 K at atmospheric pressure." This definition is not appropriate for use in this standard because the temperature of 213 K is arbitrary and excludes from the definition hydrogen sulfide and possibly some other gases (the boiling point of hydrogen sulphide is -60°C /213 K).

NOTE 2 Under extreme hot circumstances, some substances might become gases that would not otherwise be. These are not permanent gases.

3.11 response zone

section of the monitoring well or tube which allows the entry of ground gases into the monitoring point for subsequent sampling

NOTE The response zone is defined by the location of the granular annulus rather than just the slotted section of the tube.

3.12 single installation

monitoring well or similar means of enabling ground gas to be sampled from a single response zone

3.13 spot monitoring

collection of ground gas data at a point in time

3.14 sub-slab monitoring location

near-surface (sub-hardstanding) ground gas sampling location under the floor or foundation of a building or other structure

3.15 Volatile Organic Compound (VOC)

organic compound that is volatile under normal environmental/atmospheric conditions, although it can be found in the ground in the solid, liquid and dissolved phase form as well as in gaseous phase

NOTE 1 From CIRIA Report C682 [5].

NOTE 2 VOC can also be defined as an "organic compound which is liquid at 20°C and which generally has a boiling point below 180°C " (based on ISO DIS 11074:2011).

NOTE 3 Examples include single-ring aromatic hydrocarbons and other low boiling halogenated hydrocarbons, which are used as solvents or fuels, and some degradation products.

4 General

Toxic, asphyxiating and explosive gases can enter buildings and other structures and thus variously pose potential risks to occupants and users, and to the structures themselves (see Figure 4). Gases can also be injurious to plants and other components of natural ecosystems.

In order to complete an assessment of the risks posed by the presence of permanent and other ground gases, it is necessary to understand the potential sources of gas in and around a site. It is usually also necessary to collect information on other aspects of the site and the surrounding land, including for example the natural and man-made geology of the site and surrounding areas, the hydrogeological regime, and the current and historical uses of the site and surrounding land. These aspects are dealt with in BS 10175.

Methane and carbon dioxide can originate from land-filled wastes, degradable material present within the soil matrix of the made ground beneath a brownfield site, migrating landfill leachate, petroleum hydrocarbons, silt in docks and rivers, etc., coal deposits, peat, natural deposits (e.g. chalk and alluvial deposits), leaks of mains gas (natural gas) and sewer gas. Wherever biodegradable materials are present, microbial activity produces methane and/or carbon dioxide depending on whether conditions are aerobic or anaerobic. A number of additional trace gases can also be present.

NOTE 1 Properly designed and installed drainage systems are provided with vents to permit controlled release of gases and to permit entry of air so that the system operates at atmospheric pressure throughout. Thus there would not be sufficient pressure to drive sewer gas into the ground because it would be emitted through the vents provided. However, there could be occasions this might not be the case when the pipes or vents become blocked or damaged. For example, vents can sometimes become blocked by snow and ice. Under such circumstances, sewer gas might escape into the ground through any cracks or weaknesses in the system.

NOTE 2 Gas is likely to be generated if sewage leaks into the ground through a cracked pipe. The sewage can seed gas generation in materials it comes into contact with (e.g. old landfill material).

Permanent gases such as methane, carbon dioxide and carbon monoxide are also produced by coal measure strata and can emanate from old mine workings (see *Methane: its occurrence and hazards to construction* [14]). Burning coal measure strata, including waste in colliery spoil tips, can release carbon monoxide, as can smouldering domestic waste. Under some circumstances, sulfur rich deposits such as gypsum waste and some slags can release substantial quantities of hydrogen sulfide, for example, when sulfur-bearing wastes and domestic refuse are mixed.

Volatile organic compounds (VOCs) include, for example, halogenated hydrocarbons such as trichloroethene, non-halogenated hydrocarbons such as benzene, and organosulfur compounds such as thiols (mercaptans). They can occur as a component of ground gas originating from historically contaminated ground, spills and leaks from industry, commercial or residential properties (e.g. from pipelines, storage facilities, and at the point of use or dispensing), land-filled wastes and from naturally occurring sources.

NOTE 3 Some of these compounds are found in ambient air.

The choice of sampling and monitoring techniques should be based upon the conceptual model and be designed to achieve the objectives of the investigation, bearing in mind the requirements of any subsequent analytical procedures and the need to provide relevant data of sufficient quantity and quality. Consideration should also be given to the nature of ground under investigation, as well as the nature and distribution of contamination, the geology and the hydrogeology. Every effort should be made to avoid cross-contamination and at no point should underlying aquifers be put at risk.

NOTE 4 Information on the origins and properties of ground gases, factors governing their behaviour in the ground, and their entry into buildings and other structures is provided in Annex C and Annex D.

All exploratory holes should be properly decommissioned on the completion of investigation/monitoring works to prevent preferential gas and water pathways developing. This usually requires the holes to be pressure grouted.

NOTE 5 The Environment Agency has published guidance on the decommissioning of monitoring wells [15].

5 Health and safety

WARNING. Some persons are allergic/sensitive to traces of some gases and are liable to collapse and require assistance if affected. Although unlikely, the work should be conducted with this possibility in mind. This warning refers to work in the open and should not be confused with the requirements for work in enclosed spaces.

Health and safety issues should be considered at all times. BS ISO 10381-3, BS 10175, BS 5930 and industry guidance should be consulted for detailed guidance.

Before intrusive works begin, a comprehensive check should be made of the ground to ensure that no services or structures are at risk and no other hazards are present (see *Guidance for safe intrusive activities on contaminated or potentially contaminated land* [16]).

Training should be given to ensure that personnel understand the necessary precautions.

Personnel should be provided with suitable protective equipment, taking into account the potential toxicity and other hazards anticipated (assumed or measured).

Water flushing should be used when drilling in productive coal measures (see *Application for permission to enter or disturb coal authority mining interests* [17]).

The presence of asbestos fibres or asbestos-containing materials (e.g. fragments of asbestos cement sheeting) in the ground can present risks to health and requires particular care in the selection of appropriate sampling techniques and design of sampling procedures. Contingency plans should always be in place so that investigation personnel know how to proceed if any unexpected hazard, including asbestos, is encountered. (See *Site Investigation Asbestos Risk Assessment* [18].)

NOTE 1 Guidance on safe drilling and investigation practices is given in a number of industry documents (e.g. Reference 16).

NOTE 2 Carbon dioxide and some organic pollutants in the gas phase in soil and sub-soil can present toxicological risks of varying severity. Methane and some volatile organic compounds can form explosive mixtures with air. Large concentrations of carbon dioxide (in addition to being toxic) and methane can cause asphyxiation due to the associated reduction in oxygen concentrations. Nitrogen is an asphyxiant and is to be regarded as hazardous in the absence of sufficient oxygen, regardless of why this is the case. The properties and hazards posed by selected gases are described in Annex D.

NOTE 3 Injudicious choice of drilling method can cause risks to drillers due to gas coming out of boreholes. It can also cause risks to the public (e.g. the occupants and users of neighbouring buildings due to displacement of gas from the location where drilling is taking place – see HSE Position Statement, Carbon Monoxide [19] and Guidance on managing the risk of hazardous gases when drilling near coal [7]).

- a) A number of serious incidents have occurred as a result of surface emissions of toxic gases into houses during the investigation and treatment of nearby former coal mine workings. Of particular concern are incidents where carbon monoxide has been measured or inferred as entering houses from the mine workings below. Mine workings can also contain methane, hydrogen sulfide, carbon dioxide and oxygen-deficient air, all of which can be hazardous to health if emitted at the surface (see [7] and [19]). Reference 7 gives guidance on the general procedures to be adopted when drilling or piling into former coal mine workings (including mine entries) and unworked coal. Following the advice contained in the guidance is likely to reduce the risk of a dangerous incident happening.*
- b) Following a reported leak of petrol (over 60 000L) at the Bontddu Service Station in Autumn 1996, exploratory investigations were undertaken to assess the extent and severity of the associated contamination. The petrol vapours present in the subsurface had migrated beneath a neighbouring residential property, accumulated and ignited, resulting in an explosion. Later investigations into the incident suggested that the use of air-flush drilling techniques might have exacerbated the potential for the migration of the vapours and then explosion – see C682 [5] and Recommendations in the report into the Bontddu Petrol Incident [20].*

NOTE 4 Drilling in productive Coal Measures requires a permit from the Coal Authority (see Application for permission to enter or disturb coal authority mining interests [17]).

NOTE 5 Radon occurs naturally at varying concentrations in large parts of the United Kingdom. It is commonly present in mine gas and can also be released from groundwater when it is extracted from the ground. It might also arise from deposited wastes such as those from the nuclear industry, phosphorus slags, and coal ash. Appropriate safety precautions are required when it is considered that radon could be encountered at high enough levels and for sufficient duration to pose a hazard. Radon exposure in the open air around a small diameter borehole is not likely to be significant.

NOTE 6 It might sometimes be necessary to use electrical equipment and tools which are suitable for use in explosive atmospheres (www.hse.gov.uk/fireandexplosion).

NOTE 7 Fuel service stations can present particular health and safety problems, especially if they are operational. They require careful choice of equipment and operational procedures. There will often be areas around tanks, fuel lines and fuelling points in which investigation is not permitted. It is essential that the locations of old decommissioned tanks as well as operational tanks are established before any investigation is carried out. Records held by operators are seldom complete and it might be necessary to carry out detailed searches of planning records back to when the service station was first opened. The local Petroleum Officer might hold relevant records but these are often discarded once a service station has been closed. Geophysical investigation might be required to locate old tanks.

6 Development of preliminary conceptual model and preliminary risk assessment

In order to determine where and how to monitor, a preliminary conceptual model should be prepared prior to the investigation. This requires identification of:

- potential sources of hazardous gases based on a review of the current and previous uses of the site and neighbouring land, and the underlying natural and man-made geology and hydrogeology;
- potential human and other receptors (e.g. buildings and structures, flora, the atmosphere, ground water and surface water) both on-site and off-site;
- credible pathways of possible exposure of the receptors, taking into account what is known about the geology and hydrogeology, building construction and services layout, etc.;
- foreseeable events such as flooding, changes in groundwater level, global warming, extreme weather conditions, the closure of mines, and possible changes to the gas regime caused by future development.

If the ground gas investigation is to assess migration of gas outside a source, geological cross-sections should be provided showing credible migration pathways and sources of gas. Cross-sections should also be prepared if the investigation is to assess gas emissions to buildings or other receptors immediately above the source. The cross-sections should be used to decide where the response zones of monitoring wells are to be located.

The cross-section should preferably be to natural scale (i.e. the vertical scale should not be exaggerated), otherwise it can give an unrealistic picture of potential gas migration pathways. If an exaggerated scale is used for greater clarity, this should be highlighted to avoid giving an unrealistic impression of the site and potential migration pathways.

NOTE 1 Examples of conceptual model cross sections for permanent gases are provided in Figure 1 and Figure 2, and for VOCs in Figure 3. Figure 4 shows typical routes of entry of ground gas into buildings.

NOTE 2 Detailed guidance on preliminary site investigation including the preparation of a desk study, site reconnaissance and development of a preliminary conceptual model is provided in BS 10175.

NOTE 3 It is important to consult "as built" information on drainage layouts, foundations and floor structures (when relevant), and tank locations, etc. These are often available through the Building Control records, although the permission of the site or building owner is usually required to access these. Drainage records might be particularly important as revealing potential gas migration routes within sites and for migration onto and off sites.

The conceptual model is first formulated during the preliminary investigation (desk study and site reconnaissance) and informs subsequent investigations, if these are necessary, to meet the objectives of the overall investigation. It leads to the formulation of ground gas-related hypotheses, which the investigation process examines through the collection of relevant data. The conceptual model can also be used as the basis for a preliminary risk assessment and the design of the investigation for ground gases. It should be updated as necessary as the investigation progresses.

One of the objectives of an investigation for ground gas is reduction of uncertainty in the conceptual model by identifying other information required to enable a formal risk assessment to be prepared once the investigation for ground gases has been completed. The risk assessment should be updated as necessary as the investigation progresses.

NOTE 5 It is important to recognize that there might be several potential sources of gas in or around a site, e.g. marshland, buried sediments and landfills.

NOTE 6 Consideration of current uses includes the presence of services that might leak hazardous gas, such as gas supply pipes and other services which might provide effective pathways for the enhanced migration of gas via the granular material in which they are usually installed.

NOTE 7 As mentioned in BS 10175:2011, 6.2.1.2.1, Note 2, it is possible to purchase reports from a number of private companies that provide a collation of available information relevant to characterizing a site's history, geology, hydrogeology and environmental setting, etc. Although very helpful, these are seldom sufficient on their own to characterize a site in terms of the potential for hazardous ground gases to be present. It is important to cross-check information from various sources because there can be errors in the data banks from which they are derived (e.g. they might not be entirely up-to-date).

Figure 1 Example conceptual model cross section and targeted response zones for permanent gases

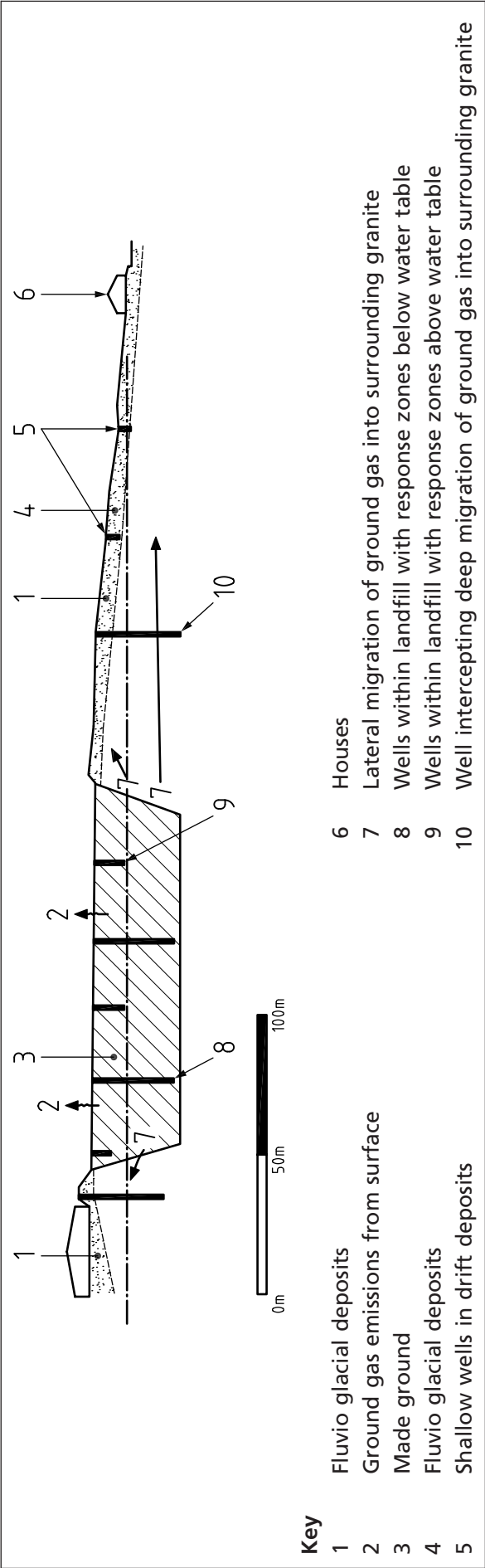


Figure 2 Example conceptual model cross section and targeted response zones for permanent gases

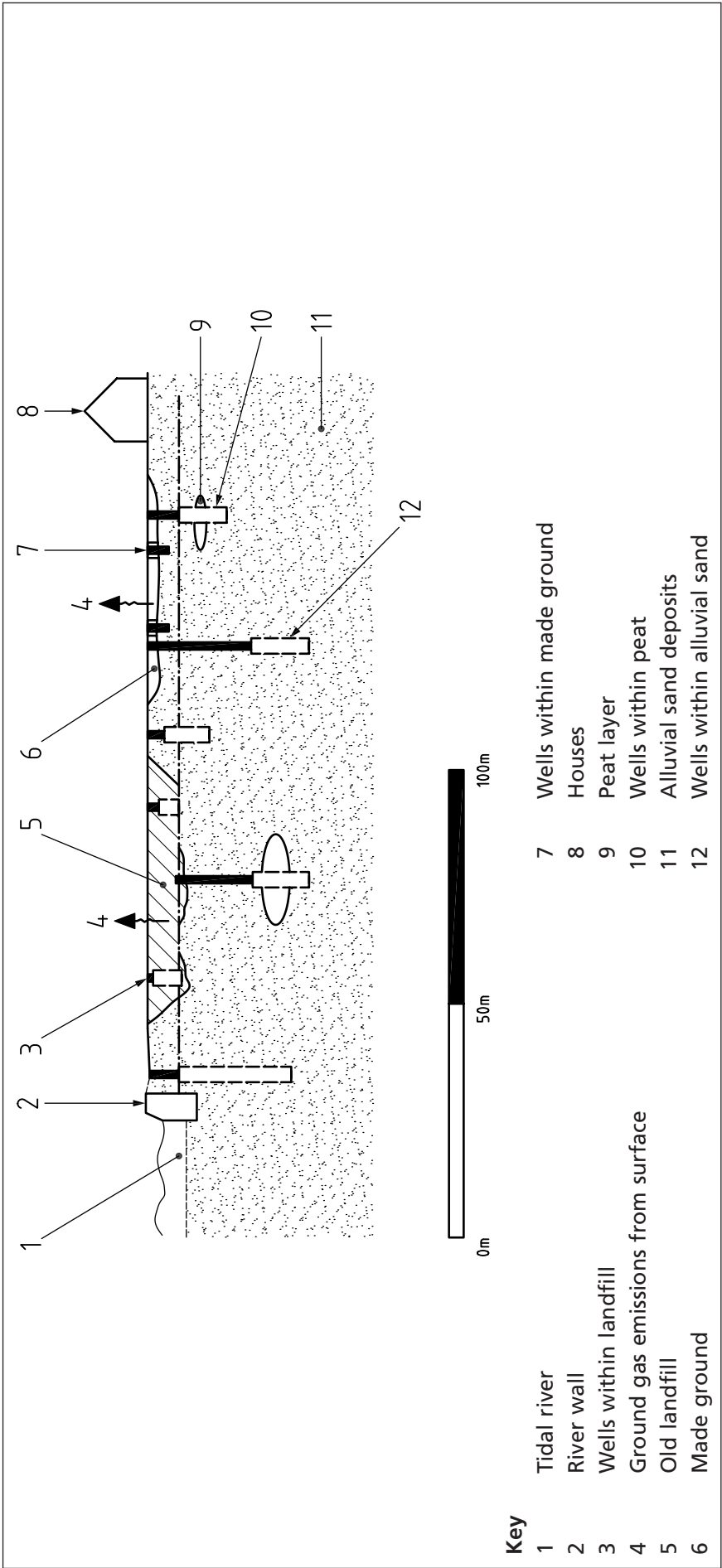


Figure 3 Example of conceptual model cross section and targeted response zones for VOCs

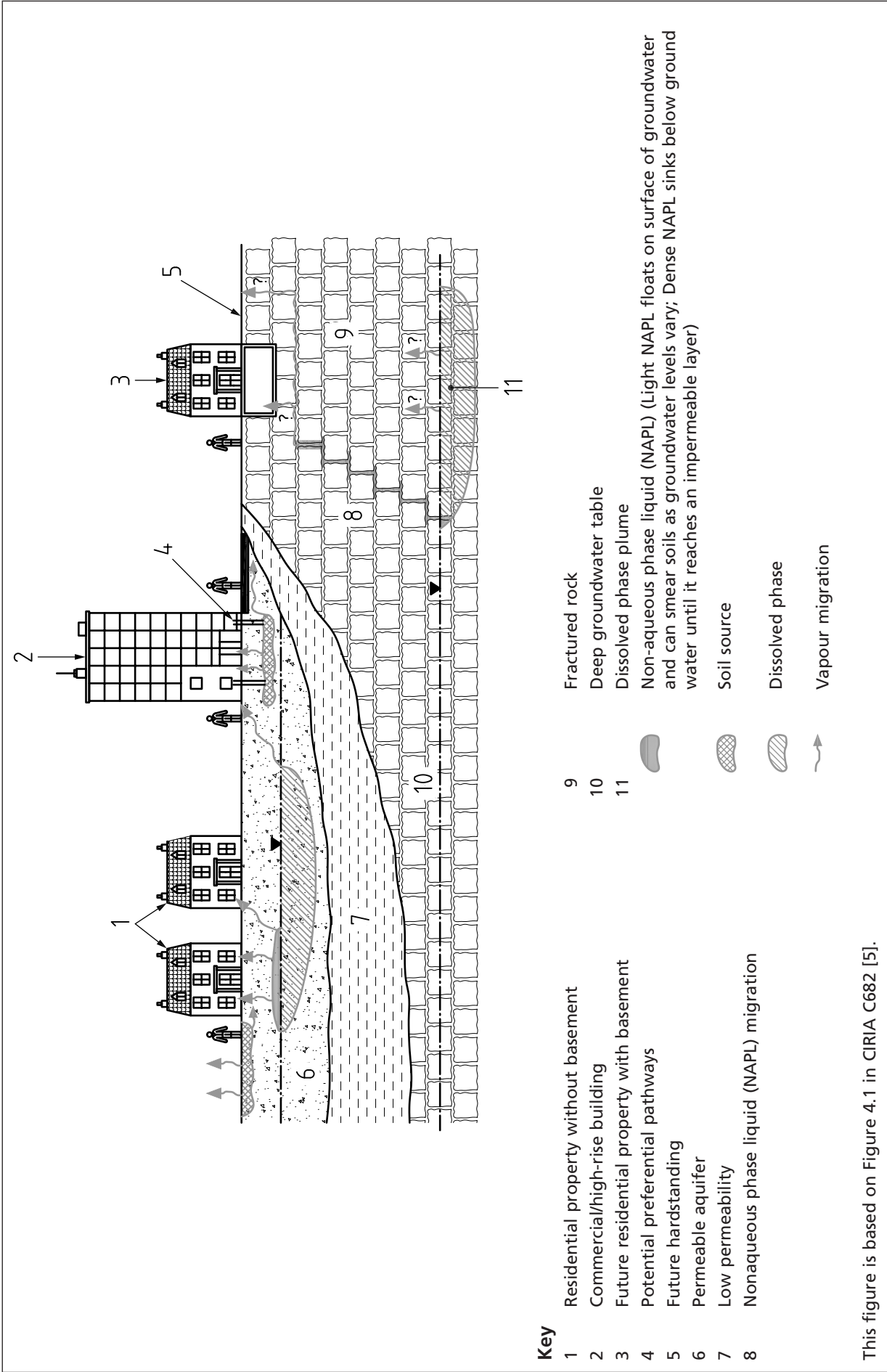
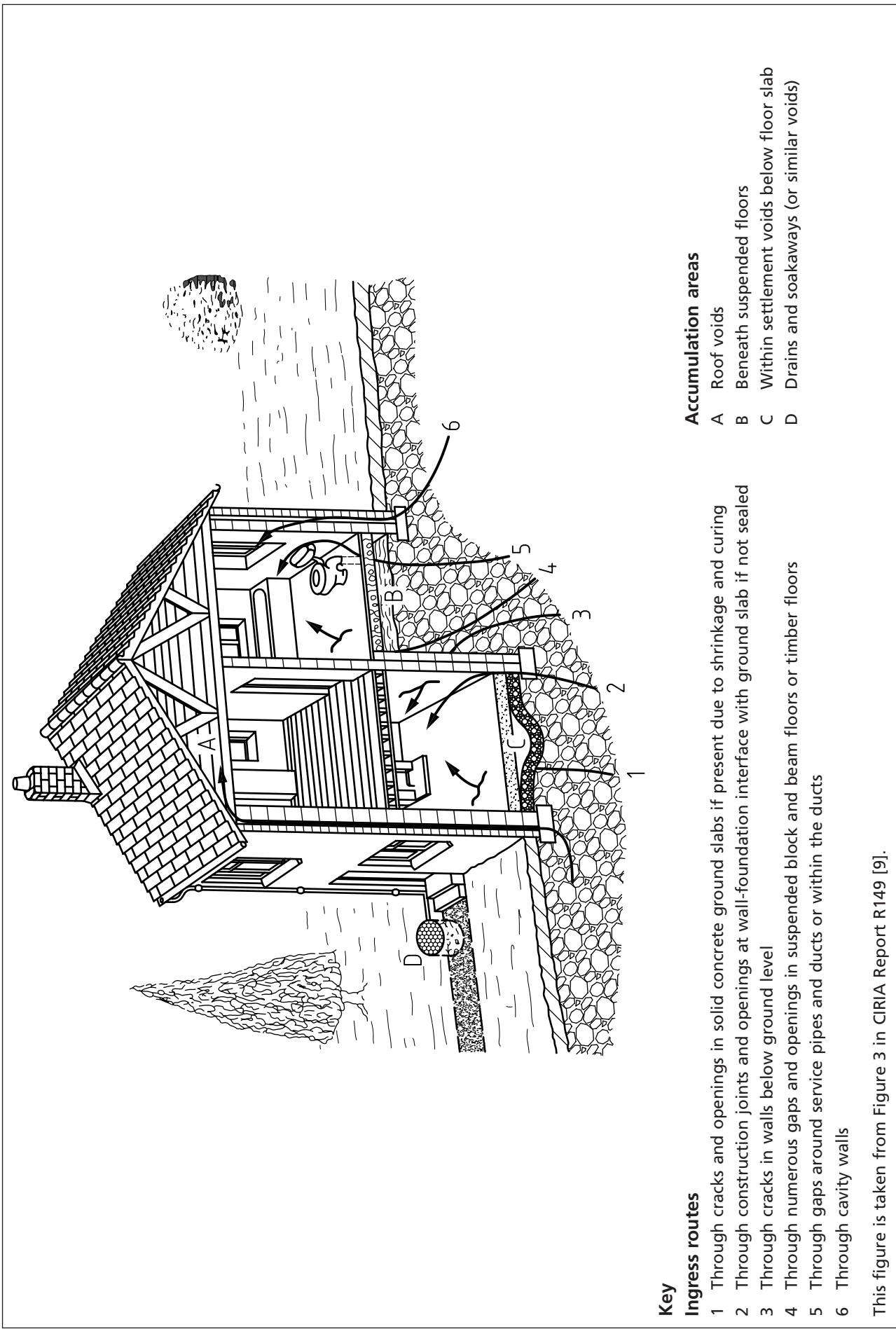


Figure 4 Key ground gas ingress routes and accumulation areas within buildings



7 Setting objectives

A preliminary investigation should be carried out in accordance with BS 10175 before setting the detailed objective(s) for an investigation for ground gas.

The principal objective of an investigation for ground gases is to provide the information necessary to:

- refine the conceptual model of the site;
- enable the potential risks to be assessed; and
- design appropriate remedial and protective measures, if required.

Objectives may also be to:

- determine possible reasons for plant growth inhibition;
- provide estimates of gas production potential and likely duration of gas production;
- detect underground combustion;
- assess emission of greenhouse gases with respect to climate change and its mitigation.

NOTE 1 This last objective is outside the scope of this standard but the methodologies described might be useful when making the requisite measurements.

NOTE 2 In order to achieve these objectives, it is usually necessary (see Clause 8) to monitor:

- *ground gas composition;*
- *flow rates and pressure (for permanent gases);*
- *concentrations, etc. at different locations on a site;*
- *gas concentrations and generation changes which accommodate pertinent temporal variations and/or other site specific influences which could affect gas concentrations and generation (see 8.6);*
- *for an appropriate period of time and frequency, taking into account the expected periodicity of any variations and site-specific factors that might affect gas concentrations and generation rates (see 8.5).*

NOTE 3 Guidance on the selection and design of protective measures for sites where ground gases are present is outside of this standard but can be found in BS 8485 and References [5], [6] and [9]–[13]. They might include:

- *protective measures for buildings and other structures;*
- *site-wide gas control or collection measures;*
- *measures to control migration of ground gas off-site, on to the site, or within the site;*
- *management control systems; and*
- *source reduction or management for VOCs.*

8 Developing the investigation strategy

8.1 General considerations

The investigation strategy should take into account:

- the objectives of the investigation;
- the possibility of zoning the site;
- the conceptual model developed to date;

- site-specific factors (for example, the site size and topography, physical obstructions, physical permeable pathways);
- current and varying groundwater levels and the direction of groundwater flow;
- the location of buried services, etc.;
- potential heterogeneity of distribution of ground gas;
- the need to avoid creating routes for migration of either gas or (contaminated) groundwater;
- protection of health and safety and the environment;
- temporal effects and the significance of such effects on the results of the investigation;
- locations and extent of proposed buildings and infrastructure;
- off-site considerations;
- how data and other information are to be analysed and presented so as to inform the risk assessment and aid understanding of the data.

NOTE 1 Rising and falling groundwater can cause positive or negative pressures/flows.

Zoning of sites should only be done with caution and should not be based solely on gas monitoring data from earlier investigations.

Development of the investigation strategy should include decisions about:

- phasing of the investigation;
- the location, pattern and number of monitoring points required for the site as a whole or for individual zones (see 8.4 and 8.5);
- the design of monitoring wells or monitoring points including the response zone(s) (see 8.5);
- what on-site measurements are to be made and how these are to be made (choice of instruments, etc.) (see 9.3, 9.4, 9.5, 10.5, 10.6 and 10.7);
- the frequency and timing of monitoring and the period over which monitoring is to be carried out (see 8.6);
- the type and number of samples to be collected for laboratory analysis (9.6 and 10.8);
- the methodology by which samples for laboratory analysis should be collected, transported, stored and preserved (see 9.7 and 10.9);
- the laboratory analyses required;
- any safety measures needed to protect the personnel or the environment (see Clause 5);
- what quality assurance measures are required (see Clause 12).

To understand site conditions as well as is practicable and to be able to prepare a sound risk assessment, parameters other than gas monitoring data should be recorded, such as weather conditions, state of ground surface, dewatering nearby excavations, etc. (further details for permanent gases and VOCs are provided in Clause 9 and Clause 10 respectively).

Before on-site measurements are made, the following should be taken into account (9.3 and 10.5):

- the need to understand exactly what is to be measured in order to ensure that the correct techniques and equipment are used;

- the limitations associated with the usage of the equipment chosen;
- whether the very act of setting up and making the measurement might affect the distribution equilibrium between the solid phase and the gas phase and hence affect the measurements taken;
- whether portable or in-situ gas monitoring equipment is sufficient or whether off-site analysis is required.

NOTE 2 Gas concentration measurements may be taken using portable or in-situ equipment (see 8.2, 9.1, 10.5 and 10.7) or samples may be taken for off-site laboratory analysis (see 9.6 and 10.8). It is usually advisable to collect gas samples, to be submitted for confirmatory analysis in a laboratory, in order to verify the on-site monitoring results.

NOTE 3 Ground gas samples can usually be taken to be representative of a large zone, although ground gases can migrate in all directions within the ground and they might find a preferential route leading to uneven distributions.

NOTE 4 The composition of ground gas changes as it migrates through the ground, for example, due to differing solubilities, differential adsorption and microbial degradation. For example, methane is at least 50 times less soluble than CO₂ at Standard Temperature and Pressure (STP). In consequence, migrating ground gas can become enriched with methane. A high pH enhances the solubility of the CO₂, temperature increase leads to gases being less soluble, etc.

NOTE 5 Oxidative processes in shallow soils can also result in changes in the relative proportions of methane and carbon dioxide, e.g. methane can be oxidized to carbon dioxide.

When the results of successive monitoring and sampling exercises over a period of time are to be compared, the technique used should be consistent to ensure comparable results including between different operators especially when monitoring from standpipes.

NOTE 6 There might be more than one type of well installation on a site. It is important when assessing changes in the results between monitoring events to be aware of the type of well installation because different well types, including those with different response zones at different depths, might respond differently to changing conditions.

8.2 Preparation of monitoring and sampling plan

Once the investigation strategy has been developed as described in 8.1, a monitoring and sampling plan should be drawn up. This should set out:

- the objectives;
- what is to be done;
- how it is to be done;
- when it is to be done, including how often and over what period of time; and
- who is to do it.

It should link to the Safety Plan and other documentation that those carrying out the work should be aware of (e.g. the conceptual model).

It should include provisions governing when and how the plan may be deviated from and by whom (e.g. whoever is supervising placement and formation of monitoring installations).

Any changes to the plan should be recorded and reported together with an explanation of why the changes were made, e.g. adverse weather conditions.

A sampling protocol and checklists to ensure that key activities are not overlooked should be developed for use whenever monitoring is undertaken to ensure that the techniques used by different operators are consistent and to reduce uncertainties in data quality.

NOTE Example protocols for recording site information for permanent gas monitoring and sampling are provided in Annex E. Activities can be omitted or added depending upon the site and the requirements of the investigation.

8.3 Installation options

Ground gas can be monitored and/or sampled using:

- driven probes;
- permanent gas-monitoring wells, ports or sampling probes;
- flux chambers.

Although each technique has its uses, in situations where a detailed, long-term understanding of the site is required, monitoring wells or sampling probes installed in boreholes should be used.

If gas concentration measurements are required at different depths, grouped, nested or multi-level installations should be used. The use of a number of wells (>15 mm diameter) in a single borehole is not recommended because of the difficulty forming effective seals between the response zones.

Selection of the installation(s) to be used should take into account health and safety and potential environmental impacts, and where known, the geology.

NOTE 1 Health and Safety considerations might hinder the use of some techniques. For example, it might be necessary to hand-dig pits to locate services before beginning to drill which can be difficult under some circumstances. Some techniques also preclude the collection of soil samples for examination.

Spot monitoring using spike holes should not be carried out to sample permanent gases but may be carried out to sample VOCs in ground gases provided the limitations associated with their use is understood and accepted (see Table 6).

Surface surveys can be used to measure emissions from cracks in the ground surface, e.g. using flame ionization detectors.

All lubricants used should be such that they will not interfere with the measurements to be made, either whilst the work is in progress or during later monitoring (e.g. it might be preferable to use vegetable rather than mineral oils as lubricants when VOCs are to be monitored). Similarly, care should be taken during storage and handling of lubricants, fuels and hydraulic fluids for drillings rigs, etc. that they do not leak into the ground.

NOTE 2 Measurements of soil-gas atmosphere in spike holes are subject to significant variation depending upon the porosity of the ground, the nature of the soil (e.g. is it likely to smear thereby sealing the hole?) and the weather conditions. Consequently, the results of the measurements from spiking need to be interpreted with caution. A negative result does not necessarily mean the absence of a problem, as gas or volatiles could be present at greater depths. Concentrations can also build up when ground gases are confined, for example in wet ground conditions when the soil pores become blocked at the ground surface. Spike holes for gas monitoring are formed by inserting a solid rod (spike) into the ground and then removing it to leave a hole that can be monitored for gas. Obviously, spike holes can only be formed when the ground is sufficiently cohesive to remain open when the rod is removed, which means that smearing of the sides, reducing permeability, can occur. The depth of the hole will depend on the nature of the ground but is typically only about 0.5 m. Spiking might not penetrate a low-permeability surface layer, e.g. compacted ground or a deliberately placed cap on a landfill site.

NOTE 3 Options for detecting and measuring permanent gas are listed in Table 1.

NOTE 4 Any invasive activity can affect migration patterns and act as a pathway for the gas.

NOTE 5 Gas monitoring boreholes can also be useful for obtaining hydrogeological, geotechnical and contamination information if this has not been otherwise obtained. It might be possible to obtain the same data from gas monitoring wells designed for sampling of VOCs in ground gas, recognizing that the progression of narrow diameter boreholes is preferable, which might limit the ability to collect additional geoenvironmental samples.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
Hand auger	Many designs available for different soil types, conditions, and sampling requirements. Preferred forms take a core sample. The auger is used to form a "borehole" of suitable diameter into which a suitably formed sampling pipe can be placed, the annulus filled with granular material to the required depth, and the top of the annulus sealed, generally as described in 9.2.3 and 10.2.3.	Cheap and easy to use. Deeper than spiking/shallow probes depending on ground conditions. Allows examination of soil profile and collection of samples at pre-set depths. Easier to use in fine or sandy soils, i.e. where there are no obstructions such as stones. Portable and useful for locations with poor access.	Equipment can be physically difficult to operate. Only limited depths can be achieved if obstructions present, e.g. stones. Ease of use very dependent on soil type.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
Driven probes	(1) Driven probe with lost cone. Hollow tube with solid nose cone. Mechanically driven into the ground with a hydraulic or pneumatic hammer. Monitoring pipe installed inside tube. Tube extracted leaving behind nose cone. (2) Driven probe with retractable nose cone. Hollow tube with a solid and retractable nose cone. Mechanically driven into the ground with a hydraulic or pneumatic hammer. Monitoring pipe installed inside tube. Tube partially extracted liberating a sampling chamber above the nose cone. (3) Driven probe with screened tube. Hollow tube with plain part of at least 1 m, and with strained part of at least 50 mm. The tube is mechanically driven into the ground with a hydraulic or pneumatic hammer. Monitoring pipe installed inside the tube to capture the air from the strained part of the tube.	Minimal ground disturbance. Easily portable thus access problems unlikely. Can reach a depth of 10 m or sometimes more. Allows soil-gas profile through the ground to be determined.	Will not penetrate obstructions. Can cause smearing in clayey soils which restricts gas ingress into the probe hole, although this is minimized by the use of an oversize nose cone.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
Boreholes (without flushing device)			
(1) Use of cable percussion rigs	Cased borehole is sunk by cable percussion techniques. Consists of a tripod derrick with a winch driven by a diesel engine. The cutting tool, which forms the borehole by gravity percussion, is attached to the winch via a steel cable. Steel casing can be used to support the borehole. Perforated standpipe is installed in the borehole. The pipe is surrounded with gravel, and the casing withdrawn.	Can install several standpipes in one borehole to measure at different depths (i.e. a nested installation). Can take samples of strata at different depths during drilling. Allows groundwater to be monitored. Allows soil-gas profile through the ground to be determined. Allows greater sampling depth than with hand augers. Can penetrate most soil types. Minimal surface disturbance.	Might have access problems. Brings contaminated material to the surface. More costly and time-consuming than hand augers. Waste from boreholes requires disposal and can cause surface contamination where groundwater or liquid contamination is present. Potential for contamination of underlying aquifers and groundwater flow between strata within an aquifer unless properly cased.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
(2) Use of percussive window and windowless drilling rigs	Borehole is sunk using percussive windowless or window sampling technique. Cylindrical steel tubes (often with an internal plastic sleeve) are driven into the ground by a percussive hammer. Hammers are usually mounted on small wheeled or tracked rigs, but can also be hand-portable. (Some dynamic sampling rigs are also capable of rotary drilling.) A perforated standpipe is installed and surrounded with gravel. If a casing has been used, this is then withdrawn.	Minimal disturbance to ground. Substantially faster than cable percussion. Very compact rigs are available which can be used inside buildings or where space is limited. Portable equipment available for use in poor and limited access areas. Allows soil-gas profile through the ground to be determined. Less potential for adverse effects on health and safety and above-ground environment than boreholes. Can be used either for shallow sampling or at depths down to 10 m with appropriately sized equipment.	Care is needed to avoid enabling contamination of an underlying aquifer. Depending on the weight of the hammer, might be unable to penetrate some obstructions (except where the drilling rig has a dual percussive and rotary capability). Can cause smearing of hole walls in some strata. Causes compression of some strata, e.g. peat. Holes, if not cased, could open up migration pathways. Depth of penetration might be more limited than for other types of drilling equipment, especially when small rigs are used, but heavier rigs can reach 10 m or more, depending on the strata to be penetrated. A percussive hammer is noisy. Could be unsuitable in certain locations where noise is an issue. Casing can be inserted during drilling where the rig has adequate power and a removal system.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
(3) Borehole formed using continuous flight auger	Borehole formed using continuous flight auger with hollow central shaft. Withdrawing centre bit and plug allows access down the stem for sampling. A perforated standpipe is installed and surrounded with gravel. If a casing has been used, this is then withdrawn.	Usually more rapid than cable percussion. Great depths attainable. Minimal disturbance to ground. Can install several standpipes in one borehole to measure at different depths (i.e. a nested installation). Allows soil-gas profile through the ground to be determined.	Can have access problems. Brings contaminated material to the surface. Care is needed to avoid enabling contamination of an underlying aquifer. Less amenable to visual inspection of strata than cable percussion boreholes. Less suitable for deeper boreholes than cable percussion unless large rigs used.
Boreholes (with flushing device)	Similar to borehole without flushing device, but the hole is drilled by a rotary tool and flushed with air or water or other fluid to aid rock penetration.	As for "boreholes without flushing device" but: • quicker than cable percussion; • penetrates and samples all soil types and rock; • relatively mobile rig; • permits recovery of rock cores for description of rock and jointing/bedding. This is often necessary for gas migration assessments.	As for "boreholes without flushing device" but: • not intrinsically safe, sparks might be a hazard on a gassing site; • water flush can spread contamination; • air flush can cause migration of ground gas. Care is needed to avoid enabling contamination of an underlying aquifer. Does not allow determination of soil-gas profile due to the effects of the flush. Flush requires containment and disposal.

Table 1 Methods of intrusive investigation that can also be used for sampling of permanent gases

Method	Description	Advantages in relation to sampling of permanent gas	Disadvantages in relation to sampling of permanent gas
Sonic drilling	Two types of rig are generally available: sonic and rota-sonic. Both use high-frequency energy which shears and displaces the soil particles. Rota-sonic combines rotary and sonic drilling capabilities in the same rig.	Permits at or near 100% core recovery in the majority of ground conditions. Faster drilling progress is possible where conditions permit compared with cable percussion boreholes. Permits recovery of intact samples. The use of drilling flush is not always necessary. Rota-sonic drilling can penetrate all soil types and also hard rock, concrete and other obstructions (sonic drilling can be subject to refusal).	Some rigs do not have the ability to insert casing, which could result in the creation of migration pathways. Dry drilling (without flush) can result in heat being generated by the drill rod, which causes loss of volatiles. This can be reduced by changing the drilling process. Sonic drilling in weak rock can result in drilling-induced fracturing of the intact samples, which could be of concern if an integrated investigation is required. Difficulties in measuring water strikes, particularly where water is used during drilling. Drilling flush requires containment and disposal. Some rigs have inbuilt waste water management systems.
Sub-slab	Drilling a hole in the hardstanding or foundation slab through which the sampling port can be installed.	Permits the atmosphere immediately below the slab to be monitored (e.g. in granular fill that permits accumulation and migration of gas). Cheap and easy to form, possibly using hand-held drill, so numerous holes can be inserted with minimal disturbance in occupied buildings or facilities.	Damages any underlying damp proof or gas control membrane (this applies to all through slab exploration).

NOTE Dry drilling (without flush) can result in heat being generated by the drill rod, which causes loss of volatiles. This could also increase the risk of explosion where methane is present. This can be reduced by changing the drilling process.

8.4 Location of monitoring installations

The locations of monitoring wells and other in-ground installations should take into account:

- the investigation objectives;
- the conceptual model, including:
 - geology and hydrogeology;
 - the location and number of potential on- and off-site sources;
 - migration pathways such as more permeable zones of soil or rock and close to service ducts and trenches;
 - permeability of the ground (which affects the zone of influence of the wells);
 - locations of underground services, etc.;
 - the locations of existing buildings (including location, form and depth of foundations) and other structures;
 - the locations of proposed buildings and services;
 - the extent of proposed excavations and other earthworks;
- health and safety;
- accessibility;
- the sensitivity of the (proposed) end use; and
- the need to assess potential off-site migration.

Each well should be designed after consideration of the field records of that hole.

In areas where chemical contamination is thought to be severe, the drilling of boreholes can produce preferential pathways for liquid contaminants or contaminated groundwater and as a result, information should be sought on specialist drilling precautions.

Monitoring installations locations may be targeted in locations such as the following:

- a particular area of a site or stratum that is suspected of generating permanent gases;
- a particular area of a site or stratum where it is suspected that VOCs might be present;
- zones of permeable geology that could provide a migration pathway from a potential ground gas source;
- at the closest point to an existing, adjacent or proposed potential receptor such as housing;
- in areas of low risk, to enable collection of background concentration data;
- at locations and depths to assess attenuation/emission potential through overlying lower permeability strata;
- where there is a potential off-site source, close to the site boundary, and possibly off-site.

The spacing of wells located on the site boundary should take into account the proximity of the potential source and the nature of the ground through which the gas might migrate (e.g. the extent of fissuring, if any). Service trenches might provide a pathway for gas migration and these should therefore be separately monitored.

NOTE 1 It is often useful to place wells at different distances on a section along a migration pathway to observe variations in gas concentrations and flows as distance from the source increases. This is often referred to as transect monitoring.

NOTE 2 It might be necessary to locate monitoring installations where there is existing low-permeability ground cover such as a foundation or floor slab. Consideration can also be given to the location of monitoring installations close to the edges of such slabs (i.e. to form near-slab installations) to capture gas emanating from below the slab but forced to migrate laterally by the slab.

NOTE 3 Table 7.1 of Waste Management Paper 27 [21] suggests a spacing of 5 m to 20 m on the boundary in fissured strata when development adjoins a landfill site, depending on the amount of fissuring.

Monitoring installation locations may also be non-targeted, for example, where:

- potential permanent-gas generating soils are present across the whole site (such as a site underlain by alluvium);
- it is considered that VOCs might be present across a wide area of a site with little prior information as to where they might be concentrated;
- the conceptual model is poorly developed so that there is only weak evidence for targeting the investigation (in this case, consideration should be given to installing gas wells in later phases of the overall site investigation once the sources and migration pathways are understood more clearly).

Subsequent monitoring wells should be positioned on the basis of the information obtained from the initial site investigation or gas well installations.

NOTE 4 Examples of monitoring well construction for permanent gases and for VOCs in ground gas are given in Clause 9 and Clause 10 respectively.

NOTE 5 Where monitoring locations for groundwater and permanent gases are coincident, it is not always possible to install a combined monitoring well. In some cases, it is undesirable to monitor gas in groundwater monitoring wells, for example, where very deep groundwater wells are installed with a small response length in a deep aquifer. Such a situation can cause unrepresentative flow rates and concentrations to be recorded. Unrepresentative flows and concentrations can be recorded because of partitioning of gas from groundwater into the headspace and because the deep well acts as a chimney to promote gas flow which would not occur through the soil if the well was not present.

NOTE 6 It is not generally advisable to install a combined groundwater and ground gas monitoring well where ground gas samples are intended to be sampled for VOCs and the results used in a quantitative risk evaluation. Data on VOCs obtained from such wells is best considered as mainly qualitative, e.g. indicating what compounds are present and/or relative concentrations.

8.5 Response zones (monitoring depths)

The selection of response zones should take into account:

- the objectives of the investigation;
- the conceptual model;
- geology and hydrogeology;
- the possible influence of underground mine workings and/or services;
- the potential for migration;
- likely depth of emissions.

Multiple wells formed to different depths (grouped installation) or nested wells (nested installation) may be used to monitor gas concentrations at different depths, though the former provide more reliable data if nested wells are not installed correctly. Where nested wells are used, the installation should be closely supervised to ensure gas-tight seals are achieved within the borehole. It is preferable to have a minimum of 2 m long bentonite seals that are either tremied into place, or if pellets are used, that are well hydrated in the hole and compacted down. Response zones should be relatively short.

NOTE 1 Information on concentrations at different depths is useful as it allows for a better understanding of the propensity for the gas to migrate.

NOTE 2 Monitoring the ground gas profile during the formation of boreholes can provide useful information on the vertical distribution of gas components and concentrations. Monitoring during installation can also give important safety information (e.g. the potential for explosive atmospheres to be present).

NOTE 3 Where the response zone extends below the water table, gas present in the groundwater will tend to produce an equilibrium concentration in the well headspace. This applies to both permanent gases and VOCs but can be particularly misleading in the latter case. Testing for dissolved gases in groundwater is useful to help interpret monitoring results in such a situation. Similarly, any VOCs in a floating non-aqueous hydrocarbon layer will produce an equilibrium concentration in the well headspace.

NOTE 4 Where nested wells are installed, the range of monitoring techniques might be limited to portable devices. If in-situ high-frequency or continuous monitoring is required, additional care is necessary in the design and construction of headworks.

8.6 Timing and frequency of monitoring of permanent gases

Monitoring should be carried out starting from shortly after installation of the monitoring equipment for a period commensurate with the objectives of the investigation.

Monitoring should be sufficient to allow prediction of worst case conditions. Justification should be provided for the monitoring period and frequency that is adopted. This should be based on the preliminary conceptual model. Factors that should be taken into account in the decision process include periods of rising, falling and stable barometric pressure and the need to be able to predict the nature and timing of worst case conditions (see Note 3). A guide to the decision process for permanent gases is provided in 8.7 (see also Annex F).

Gas monitoring does not necessarily need to be carried out under worst case conditions. It does not necessarily need to be at low or falling atmospheric pressure, but rather should be continued until it is unlikely that additional data will change the interpretation of the data, the outcome of the risk assessment and proposed remedial actions. This requires continued assessment of data as the monitoring progresses. One of the main considerations is to assess whether gas flow rates or concentrations could possibly increase and thereby affect the risk assessment and hence the choice of protective measures.

High-frequency monitoring (see Note 4) might be especially useful in assessing gas emissions around mineshafts to more recently closed workings or around landfill sites where large volumes of gas can be emitted through cracks in the surrounding ground in response to atmospheric pressure or other variations. The risk of this occurring and the need for high-frequency monitoring can be assessed using the conceptual model and depends on the management of the landfill, treatment of the shaft and the geology. On lower risk sites, high-frequency monitoring might be useful in some cases where spot monitoring indicates a higher gas regime than expected from the conceptual model, if there are time constraints to conduct longer monitoring programmes, or if surety is needed for sensitive receptors.

NOTE 1 Gas emission rates are likely to be at their highest when there are sharp falls in atmospheric pressure. Where prolonged sealing events occur (e.g. surface freezing or water logging), ground gas can often become trapped, which can result in differing gas emission points or might cause an increase in gas pressure which when removed might cause rapid gas release.

NOTE 2 The generation of carbon dioxide, methane and other ground gases is not affected by atmospheric pressure. However, their migration, and hence concentrations at particular locations away from the source, might be. For example, within fissures connecting to the atmosphere and in near-surface strata subject to "atmospheric pumping", i.e. air being forced into the ground as atmospheric pressure increases or drawn from the ground as atmospheric pressure decreases. High wind speeds might also cause air to be drawn from the ground. The depth over which atmospheric pumping has an effect depends on the permeability of the surface, the permeability of near-surface strata and whether fissures or other connections to the atmosphere are present. If the well is not leaking significant air exchange between the well and the soil will not take place in homogeneous ground with hydraulic conductivity less than about 1×10^{-6} m/s. In homogeneous ground conditions the maximum depth over which atmospheric pumping might have an effect is often considered to be approximately 1 m but effects at depths of up to 5 m have been recorded, and can feasibly occur at any depth where more permeable strata are confined below impermeable layers and are connected to the atmosphere.

If gas concentrations in a ground gas monitoring well are responsive to changes in atmospheric pressure it needs to be in continuity with the atmosphere. This could be for a number of reasons. It could be because of poor well construction, i.e. there is a leak around the cap/bung or there is a leak down the side of the installation. It could also be because the well is in continuity with the surrounding soil which is affected by atmospheric pumping. At times of high atmospheric pressure gas concentrations might be lower because air is forced into the well diluting the methane present, for example. There is often a misconception that this is not a valid result and is lower than it should be. This is incorrect and it is a valid result if it reflects the dilution that is also occurring in the surrounding soil (i.e. the well is not leaking).

There is also a misconception that under these circumstances flow rates and pressure measurements will also be unreliable. This is not correct unless the well is leaking, because the flow rates might represent what is happening in the surrounding ground. If the well is leaking sufficiently to have an impact on the conclusions drawn from the monitoring then making measurements at times of low atmospheric pressure and falling atmospheric pressure might help to overcome the deficiencies of a poorly constructed well. This needs to be based on an assessment of the results and the site conceptual model. There are often circumstances in which it is desirable to measure gas concentrations within the zone affected by atmospheric pumping as this can have a significant influence on the gas risk assessment.

NOTE 3 Suggested monitoring periods and frequency of monitoring for permanent gases can be found in CIRIA Report C665 [4]. The suggested monitoring periods and frequency of monitoring are dependent on the generation potential of the ground gas source and the sensitivity of the development. The overall philosophy that is adopted in determining the periods and frequency of monitoring is based on:

- *likelihood of gas being present in large volumes in the ground;*
- *nature of the gas source – the lower the gas generation potential, the fewer readings are usually required;*
- *potential migration pathways;*
- *the use of the data (trying to prove the absence of gas migration from off-site might require more readings than proving it is happening);*
- *the impact of collecting extra data on any risk assessment – will it make any difference or increase confidence? If not, extra data is not required;*

- *sensitivity of development – the more sensitive the development, the more data are required;*
- *the level of gas protection that is present or to be provided. (Will extra data increase the requirements? If it is not likely to do so, the extra data are not necessary);*
- *is the gas source to be removed during development? If so, gas monitoring might not be necessary.*

NOTE 4 Where a more comprehensive characterization of a ground gas regime is required, for example, to improve a risk assessment, the collection of data at a higher frequency may be considered. This type of monitoring is not necessary on all sites. It can be achieved in a number of ways using either well head or in-hole monitors programmed to sample at regular intervals. This can enable valuable information to be recorded for later downloading and analysis or for the information to be sent by telemetry for real-time assessment. The benefit of higher frequency data should be considered against the period of time over which it is collected. A longer period of individual results might span a greater range of atmospheric, climatic and groundwater conditions and give greater confidence than a short period of higher frequency data that only covers limited variations in conditions in limited wells [(see Figure 5a)]. On the other hand, where the conceptual model suggests that the gas regime might fluctuate due to, for example tidal influences, frequent monitoring over a period of only a day might be helpful. High-frequency monitoring using hand held meters over a few days at hourly intervals during the day can help to assess the volume of gas in a well headspace. One of the advantages with high-frequency/continuous monitoring is its ability to log concentrations with changes in environmental variables including atmospheric and borehole pressure, water level and temperature, to provide insights into the gas migration drivers and correlations. Other parameters can also be monitored and logged where required to develop the conceptual model further. Figure 5b) shows the variation of methane with atmospheric pressure in a well. If considered necessary, high-frequency monitoring can be carried out for a number of shorter periods of, for example, six weeks at three or four different times of year, to gather more detailed information on responses to environmental factors in different seasons.

NOTE 5 In order to assess the level of confidence that can be placed in short periods of high-frequency data versus longer periods of spot data, it is useful to plot all the data on a single graph. This also allows a comparison of both data sets to help make decision about whether further data are required [(see Figure 5a)]. The lines between the individual periodic results are to help visual interpretation of the graphs and do not imply that a straight line relationship occurs in reality.