CL:AIRE technical bulletins describe specific techniques, practices and methodologies currently being employed on sites in the UK. This bulletin evaluates over ten years-worth of continuous ground-gas monitoring experience and considers the extent to which the technique has provided a greater understanding of ground-gas behaviour, hazards and appropriate protection for both existing and new developments.

Continuous Ground-Gas Monitoring and the Lines of Evidence Approach to Risk Assessment

1. INTRODUCTION

Many guidance documents have been published on the topics of ground-gas generation, migration and associated hazards since the Loscoe event of 1986. The public inquiry held into this event identified the source-pathway-receptor model that is used today. It also identified migration drivers, such as falling atmospheric pressure, as a fourth factor that affects ground-gas contamination (Hooker and Bannon, 1993).

Since 1986 there has been a steady evolution in monitoring equipment, techniques and the understanding of ground-gas behaviour. However, as shown by the 2013-14 Gorebridge incident (Othieno, 2017), serious ground-gas contamination events still occur. The Gorebridge incident is believed to have involved carbon dioxide from abandoned mine workings affecting residents in a new housing estate and resulted in the demolition of 64 properties.

In 2006 continuous ground-gas monitoring was an esoteric research technique (Section 5.10, Wilson *et al.*, 2009). Today, it is more widely adopted and has been used on thousands of sites in the UK and elsewhere.

This bulletin evaluates over ten years-worth of continuous ground-gas monitoring experience and considers the extent to which the technique has provided a greater understanding of ground-gas behaviour, hazards and appropriate protection for both existing and new developments.

For the purposes of this bulletin the following definitions are used:

- 'Spot monitoring' – the discrete periodic monitoring usually carried out using hand-held equipment by suitably qualified technicians who visit a site to take monitoring well readings at prescribed intervals; usually weekly or less frequently.
- Continuous monitoring – monitoring carried out by *in situ* devices that record time-series data at a monitoring frequency that exceeds the frequency of change of the measured parameter. Typically, time-series data will need to be collected hourly or more frequently to be termed 'continuous'.

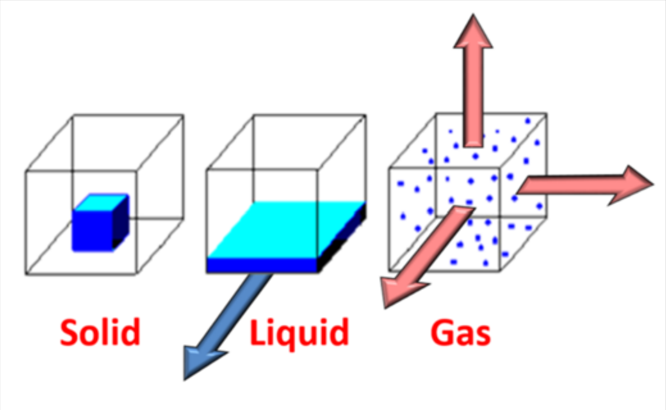

Figure 1. Properties of solid, liquid and gaseous contaminants.

2. GROUND-GAS BEHAVIOUR

Ground-gas contamination can provide significantly greater challenges for risk assessors than other forms of contamination. Solid contaminants, such as asbestos, if left undisturbed, will largely stay where they are placed; liquid contaminants will flow down-gradient, but ground-gases are fluids that expand and contract in response to changes in temperature and pressure and can flow in all directions (see Figure 1). Furthermore, the viscosity of gases is as much as two orders of magnitude lower than water which means gases can flow laterally faster and further in the unsaturated zone than liquid contaminants.

In addition, where gas is present below the water table, it may rapidly travel vertically by opening up conduits in saturated porous media which then remain open.

In consequence, while solid and liquid contaminants are relatively predictable, the mobility and flow of ground-gases are unpredictable and need a greater intensity of monitoring to characterise them compared to solid and liquid contaminants.

Ground-gases migrate by advection (i.e. pressure driven flow), diffusion and as dissolved gases in solution in groundwater and landfill leachate. These modes of migration are discussed in greater detail below.

Advective and diffusive flow occur in the unsaturated zone of permeable soils and rocks and are controlled by the permeability of these strata. Where the stratum is poorly graded, the permeability will be similar in all directions (see Figure 2). However, most sedimentary deposits have graded bedding (i.e. fining upwards sequences with coarse fractions at their base and finer fractions at their top) with associated permeability anisotropy i.e. the horizontal permeability is greater than the vertical (see Figure 2, top right). This also holds true for most anthropogenic deposits, such as engineered fill, made ground and landfill, which have been subjected to systematic deposition and compaction in layers.

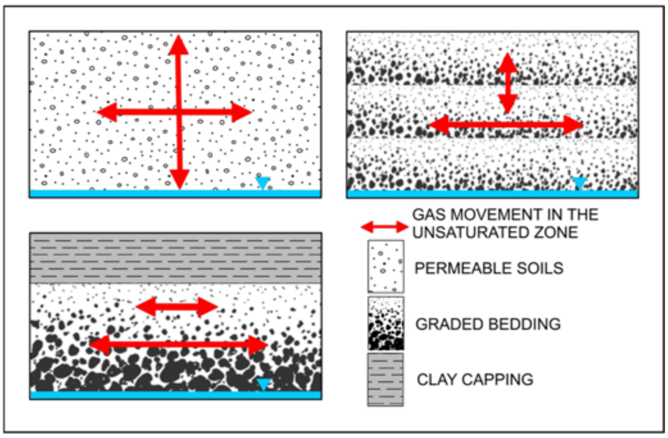

Figure 2. Permeability anisotropy. Top left, poorly graded bedding; Top right, normally graded bedding; Bottom left, capped graded bedding.

Often the horizontal permeability is greater than the vertical by a factor of 10 (Nowark and Gilbert, 2015) but where an upward fining sequence includes layers of silts and clays, the difference can be as great as a factor of 100 (Todd, 1980). This means that ground-gases will migrate laterally more easily than vertically in most geological settings.

Where the permeable stratum is trapped beneath a capping layer, gas migration will only be controlled by the horizontal permeability (see Figure 2, bottom left). This behaviour can have a profound effect on ground-gas monitoring results and is apparent in continuous monitoring based investigations.

Also, the effect of groundwater on a gas regime can be significant. Different gases have different solubilities. Methane will be saturated in water at 25 mg/l at standard temperature and pressure (STP) while carbon dioxide will be saturated in water at 1,450 mg/l at STP (Hooker and Bannon, 1993). Landfill gas (typically 60% methane, 40% carbon dioxide (Hooker and Bannon, 1993)) can be significantly modified by the carbon dioxide being preferentially 'stripped out' by going into solution when it passes through wet soils. The resulting percentage of methane left in the gas plume will be 'enriched' as the total must still add up to 100%.

A further process that frequently occurs in migrating methane and landfill gas plumes is oxidation. This can be progressive as methane migrates further away from a gassing source (Williams *et al*., 1999).

Also, changes in the depth to the groundwater table will affect the ground-gases in the unsaturated zone. If groundwater rises the ground-gases will be compressed and pressurised while if the groundwater falls the ground-gases will be put under suction. This behaviour is known as the 'piston effect' (Boyle and Witherington, 2007).

Before ground-gas monitoring is carried out it is important to understand the likely characteristics of a site and the interrelationships of possible source-pathway-receptor pollutant linkages (S-P-R). These should be included in a schematic Conceptual Site Model (CSM) (BS8576: 2013).

While the S-P-R model is well understood, the Loscoe event identified a driving mechanism as a fourth factor that profoundly affects ground-gas contamination. Pressure changes, groundwater fluctuations and concentration gradients are all significant ground-gas migration drivers given the right site conditions.

Due to geological complexity, permeability anisotropy, groundwater interactions and driver mechanisms, it is often difficult to interpret 'spot' monitoring data. In these circumstances continuous monitoring can provide additional 'lines of evidence' to help elucidate the ground-gas regime at both existing and new development sites.

3. BEST PRACTICE IN COLLECTING CONTINUOUS DATA

3.1 Monitoring well installation

The design and construction of monitoring wells has also evolved over time. The first ground-gas monitoring wells were described by Pecksen (1985). The current best practice is given in BS8576: 2013. The main elements must include; a discrete response zone (slotted pipe and filter pack) that vertically spans the unsaturated strata of interest, effective seals above and below that zone, and a sealed headspace (plain pipe section) in which to measure gas concentrations and borehole flow. Once constructed the quality of the installation is almost impossible to verify and the use of some form of construction quality assurance (CQA) is strongly recommended.

The response zone is where the ground-gases flow into a monitoring well. The sealed headspace is where the ground-gases collect and can be monitored. Where present, the depth to the groundwater should also be monitored as part of a ground-gas monitoring programme.

Given that ground-gas migration is frequently dominated by the horizontal permeability, it should be recognised that the gas encountered within a monitoring well will be also frequently dominated by the horizontal flow (see Figure 3). Monitoring wells that have a response zone from top to bottom were common in the 1980s and 1990s but where these cross two or more strata, it will be impossible to determine which stratum is the source or migration pathway for ground-gas. Monitoring wells with a slotted pipe section to the surface are effectively useless as fresh air can enter the well and will be monitored. Unfortunately, such wells are still occasionally installed.

3.2 Continuous monitoring

Continuous ground-gas concentration monitoring provides a wealth of data on the variation of concentration over time. Key characteristics of a gas regime, such as maximum and minimum concentrations can be determined at a particular location. However,

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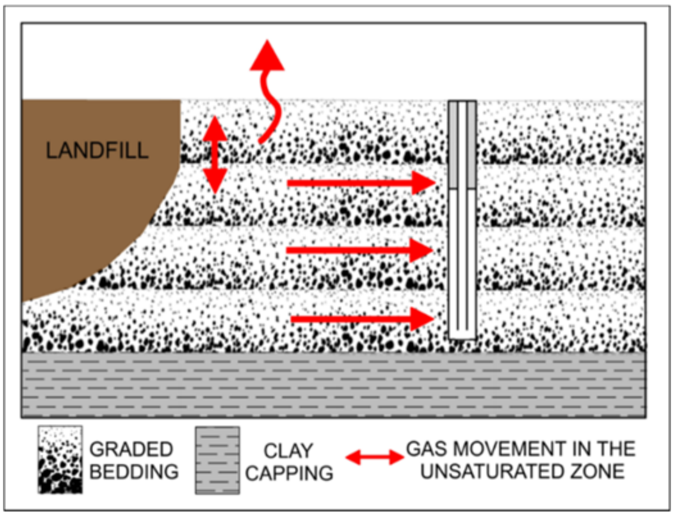

Figure 3. Horizontal permeability dominating monitoring well response.

the real value of the technique arises from identifying relevant environmental correlations that characterise a direct 'migration driver' effect on the gas regime. Correlations between variations in gas concentration and/or borehole flow and changes in atmospheric pressure, borehole pressure, temperature and groundwater fluctuations all provide valuable insights into the gas regime at a specific site.

To have confidence that a particular correlation is real it is important to demonstrate repeatability. Therefore, it is recommended that at least two cycles of the particular parameter are recorded i.e. two significant drops in atmospheric pressure or two cycles of rising groundwater (see Figure 4).

The UK's temperate maritime climate is dominated by weather systems blowing in from the Atlantic and a fall in atmospheric pressure is an important ground-gas driver on many sites. Specifically, it is the rate of fall of pressure and the duration of the fall that are the two factors considered most important (Wilson *et al.*, 2018). [The Loscoe event of 1986 resulted from a rapid drop of pressure of 29 mbar in 7 hours (King *et al.*, 1988)].

Wilson *et al.* (2018) propose these factors are used to define a 'worst-case zone' where atmospheric pressure drops are the main driver. This zone covers short duration high rate of pressure drop events of >8 mbar over 3 hours and longer duration pressure falls of >20 mb at a rate >1.15 mbar/hr.

A review of atmospheric pressure changes in Manchester over two years from 6 September 2016 to 20 September 2018 has been carried out. The largest recorded drop was 43 mbar over a 61 hour period (starting 23 December 2017) and the greatest rate of fall of pressure was 2.60 mbar/hr recorded over a 5 hour period (26 February 2017). With reference to the 'worst-case zone' (Wilson *et al.*, 2018), 138 continuous pressure falls >8 mbar occurred in the period while 25% of these events exceeded a 19 mbar fall. On average, a fall >8 mbar occurred every 1.3 weeks and a top quartile event, over 19 mbar, occurred every 3 weeks. It is suggested that in the UK, a 'significant' pressure drop event within the 'worst-case zone' will usually be captured within a four-week monitoring period.

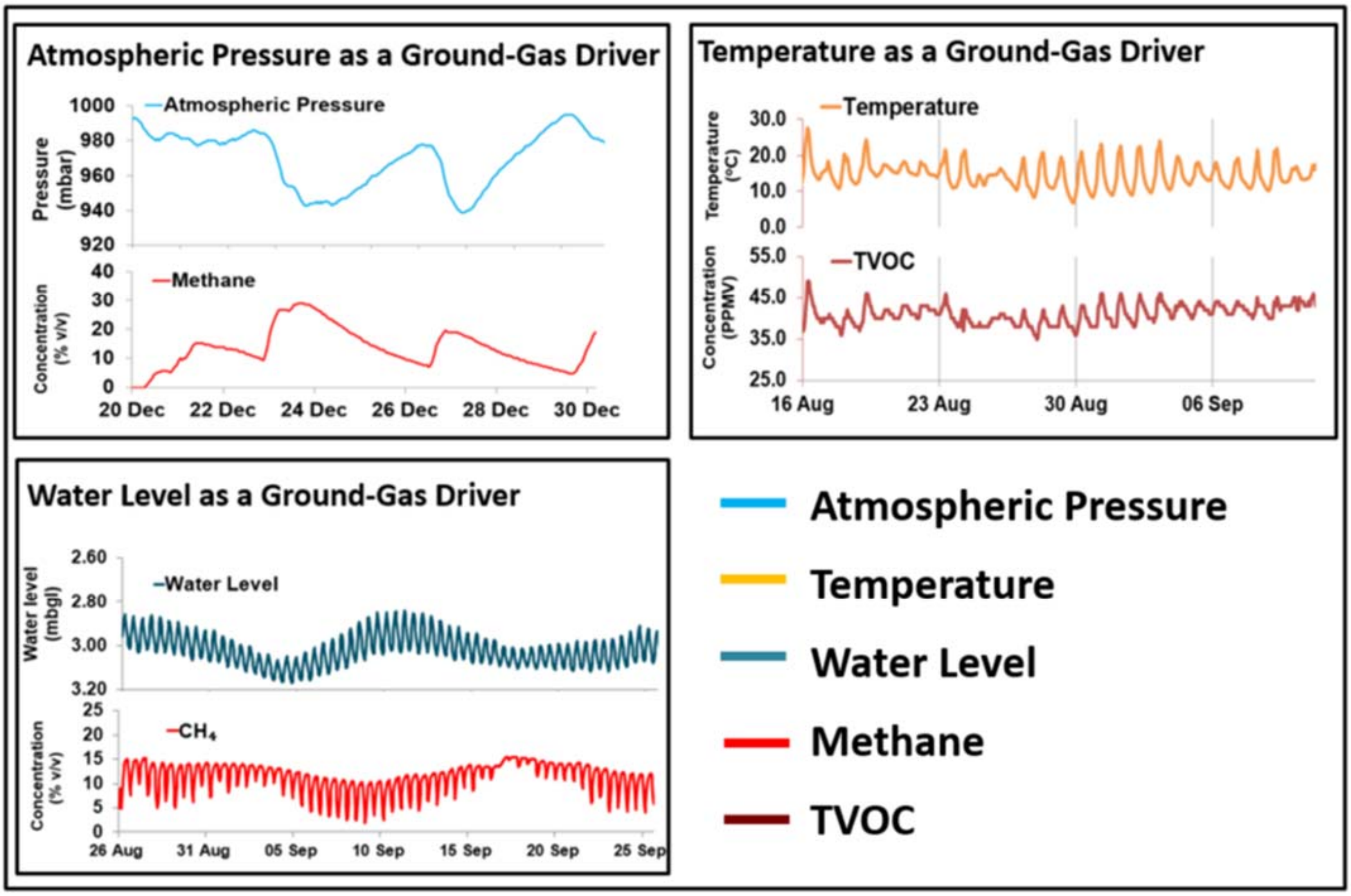

Figure 4. Key migration drivers; Top left, atmospheric pressure driver. Top right, temperature driver. Bottom left, tidal influence driver.

However, it should be noted that this approach represents only one line of evidence and other information needs to be considered before a final risk assessment is made.

It is recommended that continuous monitoring should ideally be undertaken to capture at least two of these 'significant' barometric events. Telemetry enabled continuous monitoring equipment has the advantage of allowing the monitoring to be stopped once sufficient data has been collected with the contingent cost savings.

3.3 Concentration duration and percentage exceedances

'Spot monitoring' data-sets are partial in so far as they only record values at discrete moments in time. Continuous data-sets record the full variability of the monitored parameters through time. In consequence, a continuous data-set that has recorded a representative range of conditions can be replotted on a 0 to 100% of time scale. In this way hazardous gas concentrations can be expressed as a 'percentage time exceedance'. This is a useful additional line of evidence that can be considered in the risk assessment process (see Figure 5). In this example the concentration curve indicates that the lower explosive limit (5% v/v) is present for 15% of the time.

Concentration duration curves can also be split into different families that characterise different gas regime behaviours (see Section 4.2).

3.4 Differential pressure assessment

Most continuous ground-gas monitoring devices will have a pressure sensor linked to the sealed headspace within the monitoring well and a second pressure sensor linked to the atmosphere. These will separately record the borehole pressure (ground-gas pressure) and the atmospheric pressure. In permeable soils, where the ground-gases can freely 'breathe' in and out in response to changes in

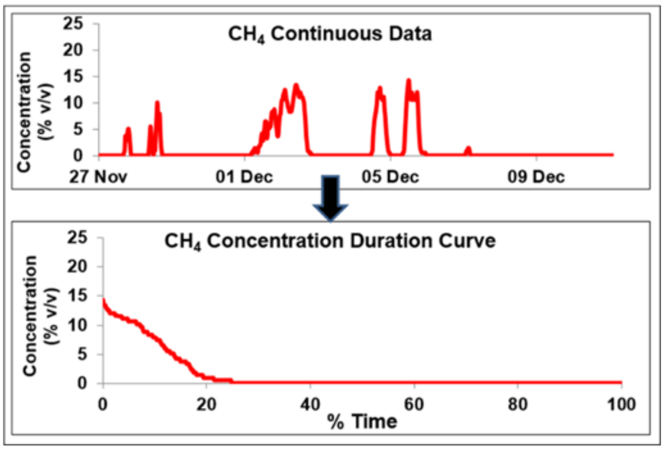

Figure 5. Conversion of time series data into a concentration duration curve.

atmospheric pressure, the borehole pressure will rapidly equalise with changes in atmospheric pressure resulting in both pressures recording the same. However, where the ground-surface is sealed, say by an area of hardstanding or impermeable capping layer, then the ground-gases are not able to 'breathe' and the ground-gas pressure will not equalise with atmospheric pressure. The result will be the development of a differential pressure.

In Figure 6 the atmospheric pressure can be seen to rise and fall between 950 and 990 mbar, while the borehole pressure only varies between 960 and 980 mbar and there is a time lag between the two. The resulting differential pressure reaches a maximum of 20 mbar and a positive pressure sustained over a period of 30 hours. When the atmospheric pressure is rising faster than the borehole pressure then the differential is positive and, if a spot reading was

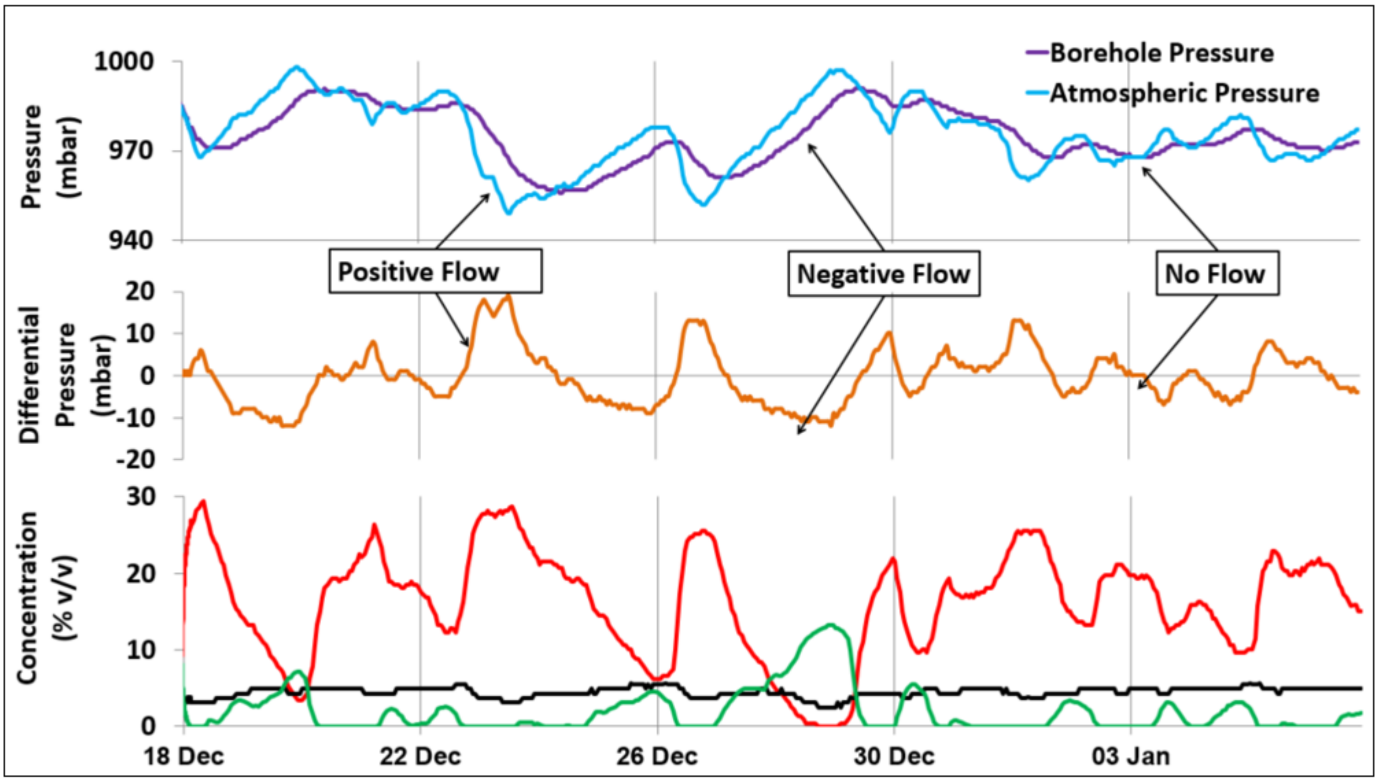

Figure 6. Relationship of differential pressure to gas concentrations.

taken at this point in the cycle, the flow would be out of the borehole (positive flow). When the atmospheric pressure is falling faster than the ground pressure then the differential is negative and a spot reading would record a flow into the borehole (negative flow). When both pressures are the same then there would be no flow. Where these flows are purely a function of the change in atmospheric pressure (i.e. there is no gas generation at source) this behaviour is termed 'barometric pumping' (Wyatt *et al*., 1995).

Any sustained differential pressure greater than 20 mbar is considered significant as it can lead to pressure-driven, advective ground-gas flow (lateral migration).

Differential pressure can also build up as a result of gas generation. This is illustrated in Figure 9 where the borehole pressure incrementally increases over time as ground-gases are generated and develop a differential pressure of 30 mbar.

Where significant differential pressures occur, the resulting advective flow will be the major migration driver and substantially more dominant than diffusion i.e. any local diffusion from a local source, say a hydrocarbon source, will be swept along within the advective flow of the bulk ground-gases that are present.

3.5 Purge and recovery test

This test is akin to a rising head permeability test carried out in aquifers and was first described by Godson and Witherington (1996). This test is only useful to carry out in monitoring wells that have steady gas concentrations that are not affected by changes in either ground-water level or atmospheric pressure.

The methodology for carrying out a purge and recovery test with a continuous monitoring device was described by Boult *et al.* (2011). If steady-state gas concentrations have been demonstrated, then the test is carried out by flushing out the ground-gases using an inert gas and measuring the exhaust gases at the surface. Once these fall to zero the monitoring well will be full of inert gas (care must be taken not to overfill the monitoring well to the point where inert gas is forced into the surrounding soil). When the gas concentrations drop to zero the supply of inert gas must be turned off. At this point a continuous monitoring device is installed in the well to monitor the ground-gas concentration recovery. The device needs to be set to monitor at a time interval of between 2 to 5 minutes to capture the initial re-bound. The resulting recovery profile is a function of the ground-gas flowing back into the well and gives direct information on the speed the ground-gas concentrations return to their steady-state conditions.

In addition, the test can provide quantitative information on the ground-gas flux within the response zone using the following equation:

$$Q = \frac{V \times \Delta c}{\Delta t}$$

Where:
Q = Gas Flux
V = Volume of the internal vadose zone of the borehole
Δc = Change in gas concentration expressed as a percentage
Δt = Change in time over which the change in concentration was measured

This lateral 'ground-gas flux' provides an additional line of evidence for use in risk assessment but it should be noted that the calculated value is different from, and should not be confused with, the measured 'borehole flow' from a gas tap in the top of a 50 mm diameter monitoring well that is used in the generic Gas Screening Value (GSV) discussed in the Modified Wilson and Card methodology (Wilson *et al*., 2007). The 'ground-gas flux' should not be used in GSV calculations but can provide information on gas generation rates within a gassing source.

Where the 'lateral ground-gas flux' is to be used in quantitative Tier 3 risk assessments it may be useful to repeat the purge and recovery test to demonstrate the test results are representative of the location. The repeatability of purge and recovery test results within gassing landfills was demonstrated in the ACUMEN research project[1]. In actively gassing sources, repeated purge and recovery tests produced similar response curves and lateral ground-gas flux values.

While in most cases advective, pressure driven flow appears to be the dominant migration process, diffuse flow will further enhance gas migration by 'feathering' the edge of a gas plume with a concentration gradient. As this gradient moves backwards and forwards past a monitoring well in response to changes in pressure, the observed concentrations will be seen to rise and fall.

3.6 Continuous flow monitoring

In the last few years continuous flow monitoring has become available and this provides a further line of evidence that can be used in ground-gas risk assessment. The latest monitoring devices replicate the 'spot monitoring' flow measurements taken via a monitoring well valve. However, these readings are taken at a high frequency, for example, hourly, to capture a continuous data set. In this way the 'borehole flow' can be correlated to the measured environmental parameters. In Figure 7 both the maximum gas concentrations and borehole flow can be seen to coincide with periods of falling atmospheric pressure.

Continuous flow monitoring is equivalent to 'spot monitoring' borehole flow and the values obtained can be used to calculate a 'Continuous GSV'.

4. SOURCE–PATHWAY–RECEPTOR (POLLUTANT LINKAGE) MODEL

4.1 Gas source behaviour

Ground-gases are ubiquitous in the environment occurring both naturally and from anthropogenic sources. The range of sources is well documented (Hooker and Bannon, 1993) but some of the greatest ground-gas hazards are associated with former landfills (Card *et al*., 2012).

The Environment Agency has estimated that there are approximately 1,600 closed licensed landfills and a further 23,000 historic landfills in England and Wales (Elliot, 2009) and, therefore, much effort has been expended on investigating and assessing the ground-gas risks to new and existing development located next to and, increasingly, overlying former landfills.

[1] https://www.gov.uk/government/groups/acumen-assessing-capturing-and-utilising-methane-from-expired-and-non-operational-landfills

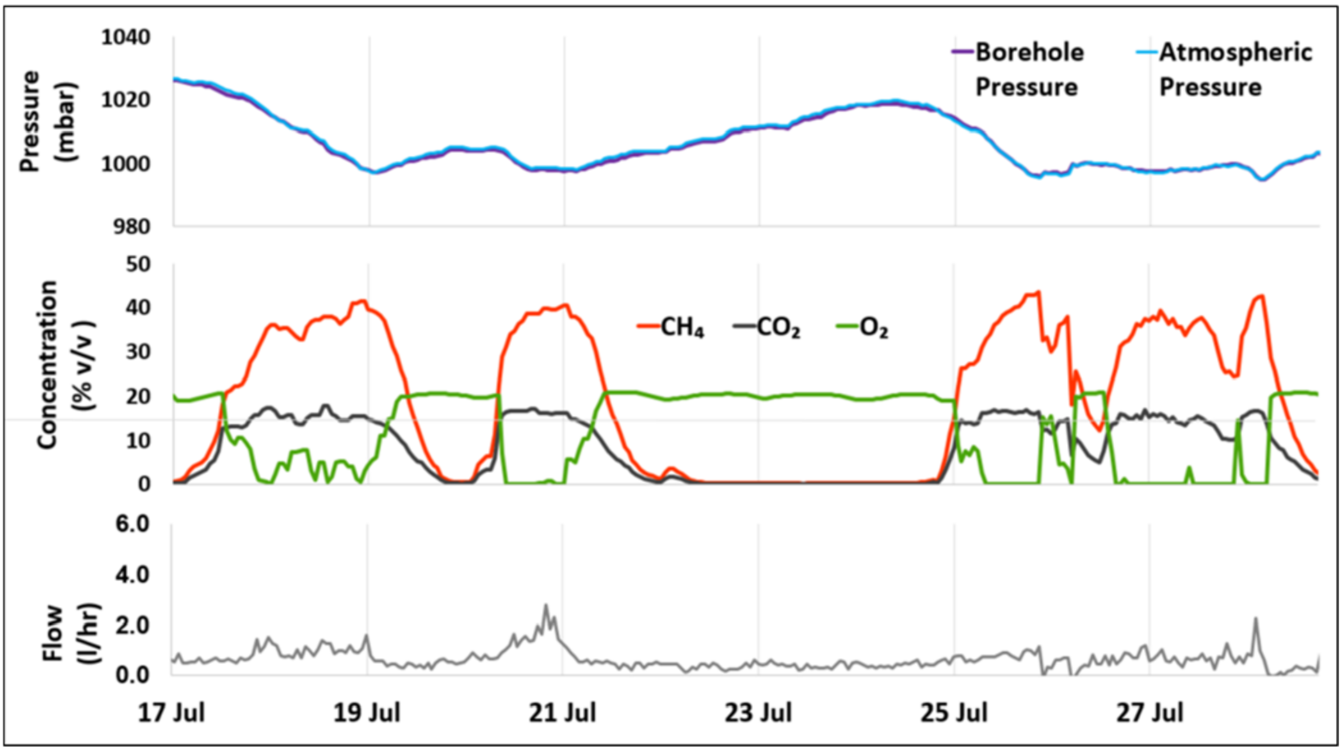

Figure 7. Relationship between pressure, continuous concentration and continuous flow.

The most significant landfill gas hazards are associated with landfills that were developed after the 1956 Clean Air Act, when the putrescible content of waste significantly increased and before the 1990 Environmental Protection Act which required containment systems to be used (Wilson *et al.*, 2009).

Continuous monitoring within an actively gassing former landfill will be characterised by consistent methane and carbon dioxide concentrations that are unaffected by changes in atmospheric pressure. Figure 8 shows three examples of such behaviour. Top left, mixed and household waste landfill tipped between 1952 and 1987; top right, private mixed waste landfill tipped between 1960s and

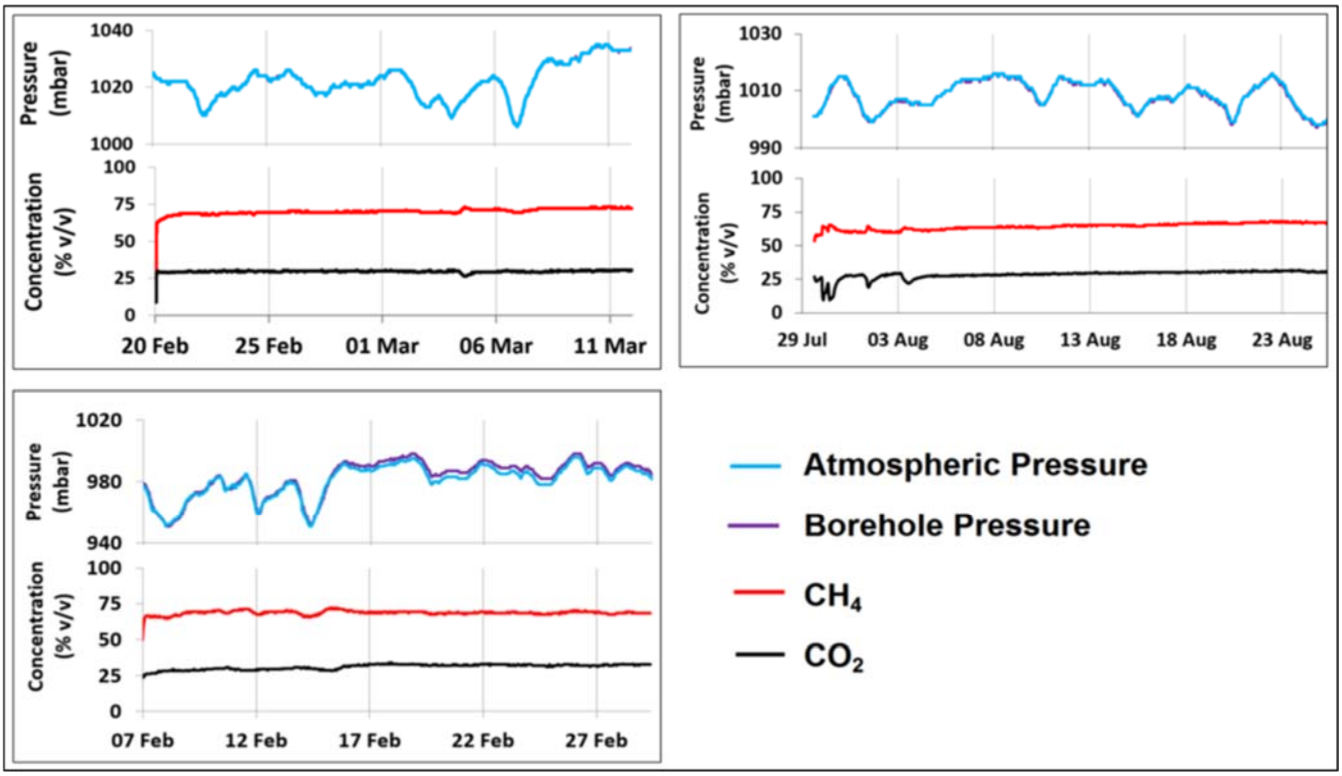

Figure 8. Top left, household waste tipped between 1952 and 1987; Top right, mixed waste tipped between 1960s and 1970s; Bottom left, inert and industrial waste tipped between 1903 and 1991.

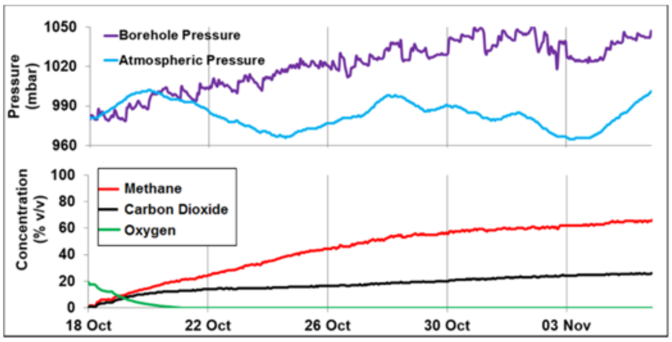

Figure 9. Landfill gas stabilisation period in an older landfill.

1970s; bottom left, local authority inert and industrial waste landfill tipped between 1903 and 1991. All three graphs are characterised by methane flat-lining at 70% and carbon dioxide flat-lining at 30% as a result of active landfill gas generation. These concentrations are unaffected by changes in atmospheric pressure as the monitoring wells are located within the gas generation source.

The 70/30 methane to carbon dioxide ratio which is commonly observed is higher than quoted as the typical landfill gas composition of 60/40 (Hooker and Bannon, 1993) and may be due to a degree of methane enrichment due to some carbon dioxide dissolving in leachate. [Note that the concentration scale is from 0 to 100% on these graphs]. Oxygen is consistently absent indicating an anaerobic gas regime.

Where a gassing source has been demonstrated by constant gas concentrations a purge and recovery test can be used to provide an indication of the lateral ground-gas flux and the gas generation rate.

As an alternative to a purge and recovery test it may be possible to directly observe the gas generation rate as a gas monitoring well achieves 'stabilisation'. In Figure 9 a monitoring well in an older actively gassing landfill is seen to take almost two weeks to move from atmospheric conditions to 70/30 methane to carbon dioxide ratio typical of landfill gas generation. At the start of the monitoring period (borehole open to atmosphere) the oxygen concentration is at 20% while methane and carbon dioxide are both zero. Note how the borehole pressure progressively diverges from the atmospheric pressure as the landfill gas concentration builds.

Pre-1956 landfills are dominated by ashy waste with low biodegradable content. Continuous ground-gas monitoring indicates that these sites are characterised by low carbon dioxide gas generation, very low or absent methane and variable concentrations of oxygen. Typically, these sites have aerobic gas regimes.

Other sources of ground-gas include, peat deposits, organic rich soils, coal measures and made ground.

Figure 10 shows continuous monitoring from, top left, domestic landfill deposited from 1935 to 1953; top right, housing development site on peat; bottom left, housing development site on 6 m of demolition rubble made-ground beneath a clay cap.

In both the pre-1953 domestic landfill site and housing development site underlain by peat, the ground-gases stabilise at a constant concentration after an initial period irrespective and independent of changes in the atmospheric pressure (and temperature - not shown). This indicates that the monitoring well is located in a gassing source. This is not true of the housing development site with 6 m of made ground. Despite having a clay cap, the carbon dioxide concentration is mostly constant at around 5% while the methane concentration is rising and falling in direct response to changes in atmospheric pressure. This suggests that while carbon dioxide is generated within the made ground, the methane is migrating to the monitoring well from elsewhere and is not being locally generated within the made ground. The behaviour of ground-gases within a migration pathway is discussed below.

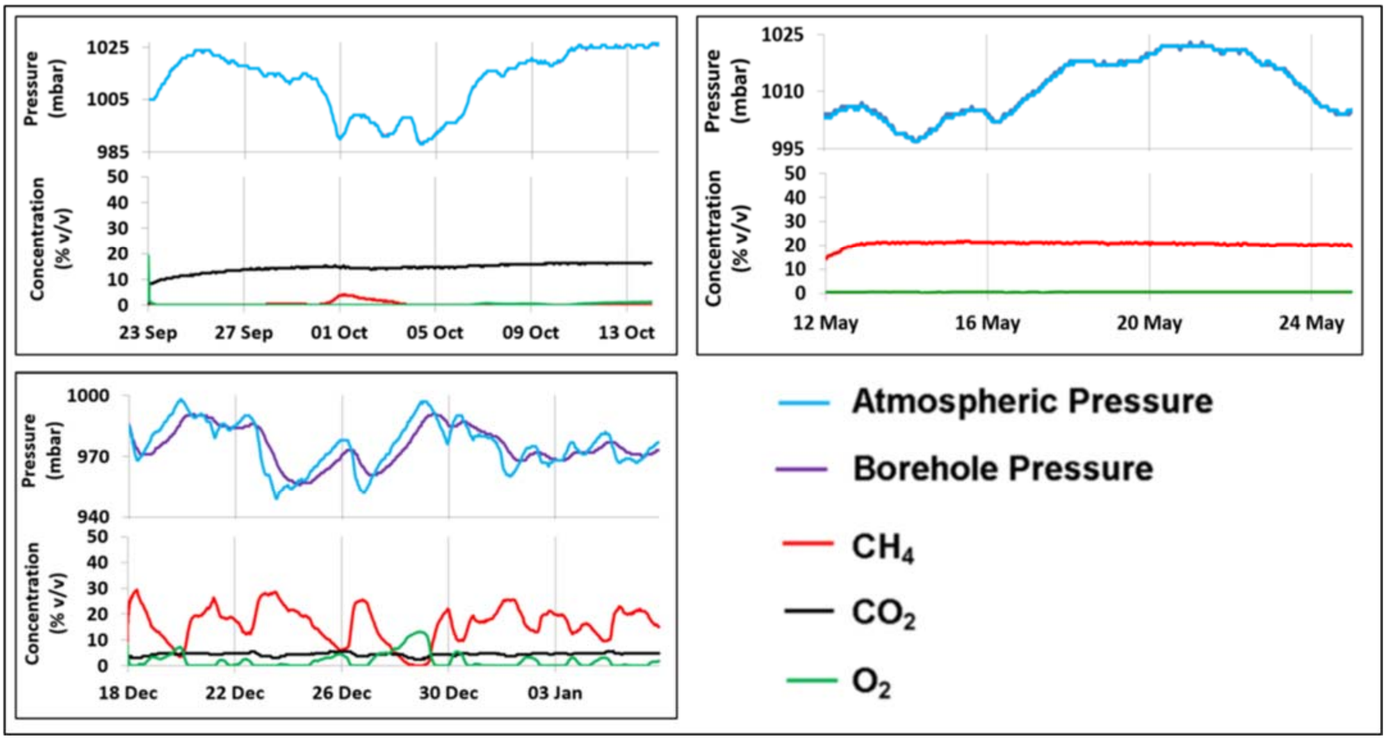

Figure 10. Top left, domestic landfill tipped between 1935 and 1953; Top right, 2010 housing development on peat; Bottom left, 2012 housing development on 6 m of made ground beneath a clay cap. [Note that the concentrations scales are from 0 to 50% on these graphs].

4.2 Migration pathway

As stated earlier, in poorly graded (single sized particle distribution) deposits, exposed at the ground surface, ground-gases can freely 'breathe' in and out and interchange with atmospheric gases in response to changes in atmospheric pressure. Lateral migration will only occur if the rate of gas generation is greater than the vertical emission rate to atmosphere. In deposits that have permeability anisotropy, ground-gas migration will be controlled to a greater or lesser extent by a combination of the gas generation rate and the horizontal to vertical permeability ratio.

Where the permeable strata is capped at the surface by, say, concrete hard standing, clay layer or saturated top-soil layer, the ground-gases will have a lateral migration pathway controlled by the gas generation rate in the source, the horizontal permeability and the differential pressure between the ground and a distant point where the strata 'day-lights' with the atmosphere. This behaviour is thought to have been responsible for the Loscoe event (Hooker and Bannon, 1993).

Massmann and Farrier (1992) carried out a two-dimensional finite element analysis of a capped permeable layer. They found that a 48 hour, 25 mbar atmospheric pressure rise and fall induced a lateral migration event of 45 m when the layer had a permeability (k) of 10^{-6} cm^2 (e.g. medium sand).

However, as the gas travels further away from the source there will be increased potential for modification to its composition due to the processes of differential solubility and/or methane oxidation.

A ground-gas plume migrating through a pathway will be characterised by a source of gas at one end and a leading edge that travels back and forth in direct response to any additional differential pressure driver that occurs due to atmospheric pressure changes at the location the strata 'day-lights' or to any groundwater level changes. Occasionally, as reported by Williams *et al.* (1999), landfill gas will have a methane leading edge that lags behind a carbon dioxide leading edge due to the progressive oxidation of the methane to carbon dioxide (see Figure 11).

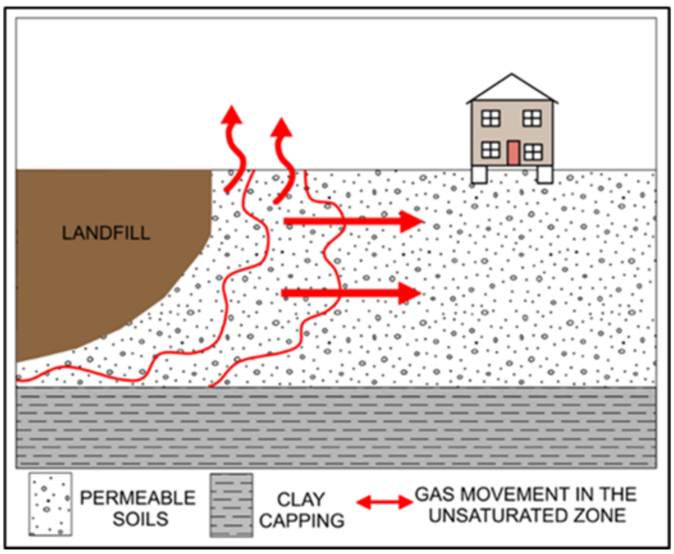

Figure 11. A ground-gas migration plume within a pathway with a source and a leading edge(s).

Where the strata 'day-lights' it is connected to atmosphere and the ground-gases can vent and atmospheric air is able to enter the pathway. This also occurs at poorly constructed monitoring wells which do not have adequate surface seals.

Continuous monitoring of wells located within the migration pathway will observe the lateral flux of ground-gases and interchange with atmospheric air conditions. The closer to the source of gas the less modification will occur with less evidence of atmospheric air. Conversely, the further away from a gassing source the greater the effects of gas modification and greater evidence of normal soil conditions and atmospheric air ingress. In addition, the observed duration of hazardous gas within a monitoring well will be related to its distance from a gassing source. Close to the source, the gas will be consistently present in the monitoring well. At a distance from the source the gas will be sometimes there and sometimes not. At a further distance, at the extremity of a migration pathway, the gas will only occasionally 'spike'. This behaviour can be characterised by families of concentration duration curves (see Figure 12).

4.3 Receptor

While permeability anisotropy may not usually be an issue for contaminated groundwater risk assessment, it should be carefully considered when assessing monitoring data and the risk from ground-gas hazards. As discussed earlier, the horizontal flow of ground-gas is measured within monitoring wells not the vertical flow. Most development is built on the ground surface and, in theory, will be only affected by ground-gases that migrate vertically to the structure. However, the near surface soils will be frequently altered by earthworks, site levelling and the construction of access roads and parking areas etc. after the monitoring period and the ground-gas risk assessment is finished. The development and associated works can significantly alter the ground-gas regime at a site.

Generally, for buildings with shallow foundations where the ground-gas hazard or migration pathway is in deeper strata, the effect of permeability anisotropy will result in the ground-gas risk being over-estimated, even though the ground-gas regime may have been altered.

An important exception to this will be where the ground-gas bearing strata is intercepted by man-made migration pathways such as; deep foundations, service trenches and, perhaps most often overlooked, site investigation boreholes and monitoring wells.

The 2013-14 Gorebridge incident may have been exacerbated by the presence of open grout holes, site investigation boreholes and vibro-stone columns beneath the footprint of the affected homes. Such features could have provided a direct pathway from carbon dioxide present in near-surface abandoned mine-workings to immediately beneath the building envelope (Othieno, 2017). Following the evacuation of the residents the affected buildings were closely monitored. Continuous monitoring carried out in the under-stairs cupboard in one of the houses recorded concentrations of carbon dioxide, up to 25% v/v, associated with periods of falling atmospheric pressure.

Wherever possible, site investigation boreholes and monitoring wells should not be located directly beneath the footprint of proposed buildings. Where this is unavoidable they should be properly backfilled and sealed. On occasion this may require monitoring wells to be over-drilled and backfilled with grout tremied to their bases.

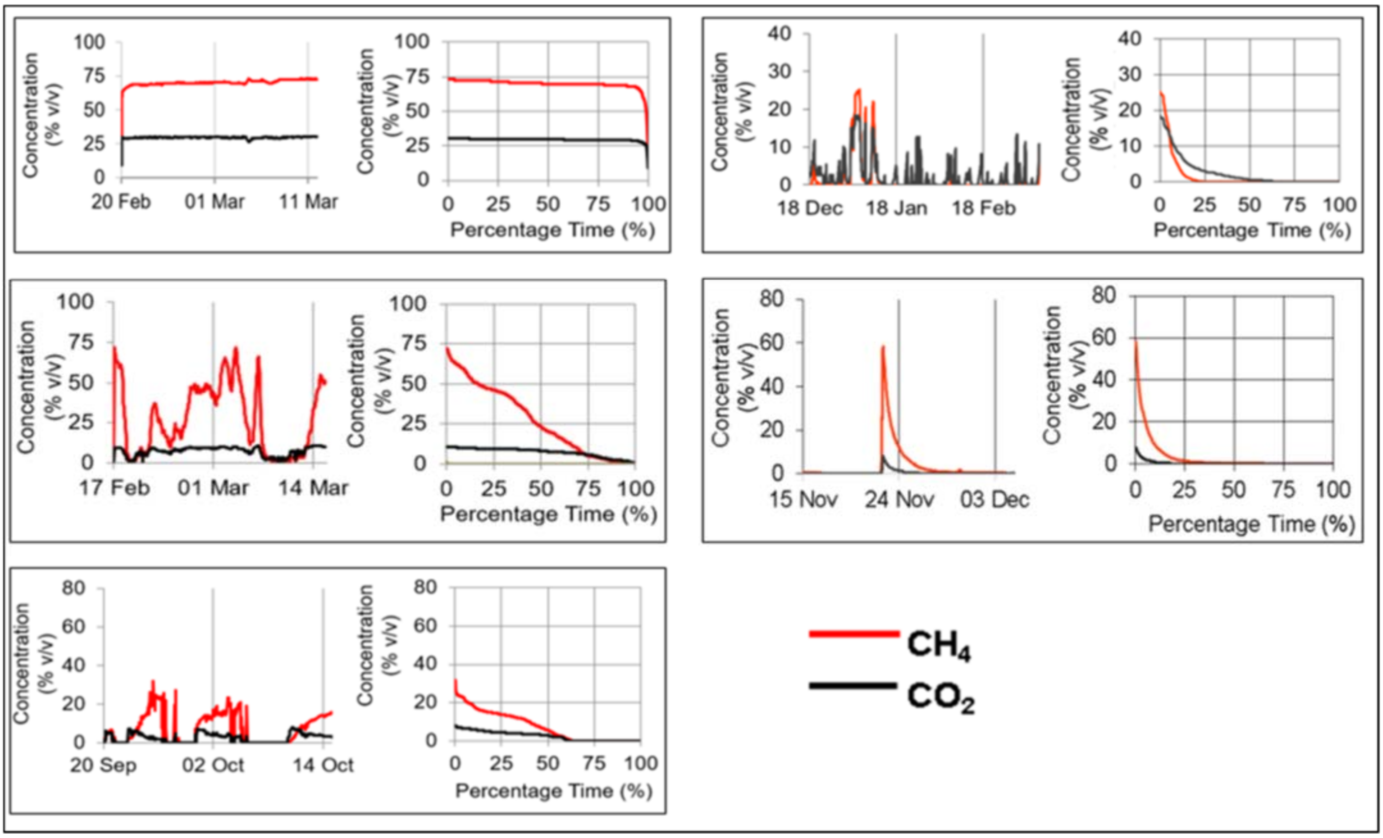

Figure 12: Families of methane (CH_4) and carbon dioxide (CO_2) concentration duration curves characterising position on the migration pathway from near source (top left) to extremity (middle right).

Piled foundations are commonly adopted for carrying development loads to firmer bearing capacity strata located at depth. Where these piles intercept ground-gas bearing strata it is recommended that cast *in situ* piles are adopted wherever possible (Wilson and Mortimer, 2017). Driven piles can form vertical open annuli around the upper portion of the pile through 'whiplash' vibrations during the driving process. Vibro-stone columns, by their nature, will introduce a high permeability pathway to immediately under the future buildings.

If there is concern that the gas regime at a site has been significantly altered, then post-construction continuous monitoring of sub-floor voids and inside sensitive building locations, such as service entries, can be a valuable tool to confirm that the ground-gas risks have been effectively managed. One technique of sub-floor continuous monitoring is discussed in CL:AIRE Technical Bulletin 16 (Wilson *et al*., 2017).

5. CONTINUOUS MONITORING DEPLOYMENT STRATEGIES

Continuous ground-gas monitoring provides additional lines of evidence that can be useful in a range of situations, namely; when traditional 'spot monitoring' data still leaves uncertainty as to the gas regime or when time is short.

A common approach is to collect continuous data from the monitoring well identified from 'spot' data to have the highest gas concentrations and flows to further 'calibrate' the risk assessment for a site. On larger sites greater confidence can be obtained by selecting a proportion of the monitoring wells for continuous monitoring to supplement the 'spot' monitoring data.

Where a site has been zoned, for example into a 1940s landfill area and a 1960s landfill area, it can be useful to select a representative monitoring well in each zone for continuous monitoring to provide greater confidence in the acquired data. Such zoning may be vertical where different strata are present e.g. a layer of made ground and demolition rubble overlying an organic rich silt.

Where high quality evidence is needed for a legal determination of a pollutant linkage e.g. for a Part 2A determination, continuous transect monitoring can be useful. In this circumstance continuous monitoring is carried out concurrently within the source, the pathway and at the receptor. In this way a gas migration plume can be tracked through time from the source to the receptor during identified different conditions e.g. during a significant fall in atmospheric pressure.

6. DISSOLVED GAS AND FREE GAS INTERACTIONS

Further to the discussion of ground-gas compositional modification during migration due to preferential solution or oxidation of specific gases (Section 2), continuous data can capture groundwater and ground-gas interactions which may not be observed in 'spot monitoring' data.

Where a monitoring well response zone is submerged the only gas that can accumulate within the head space will be those gases that come out of solution from the groundwater. The amount of gas that comes out of solution will be in direct response to pressure changes within the headspace in line with Henry's Law and the partitioning of the gases from the dissolved to free gas states. In addition, temperature also affects solubility with carbon dioxide solubility increasing with decreasing temperature (Crovetto, 1991). Where the groundwater has risen in the surrounding strata the headspace will be pressurised by the difference in the water level within the monitoring well and in the surrounding strata. A flow reading taken in this circumstance will be directly related to the pressure differential due to this hydrostatic head. Furthermore, as the pressure in the monitoring well begins to drop, the change in pressure will cause the dissolved gases to come out of solution. In this way artificially high flow rates and gas concentrations may be recorded that are artefacts of the monitoring well construction and are not representative of the true gas regime at a site.

Where dissolved gases come out of solution the continuous data often describe a distinctive 'saw-tooth' pattern (see Figure 13). These patterns are typical of a diffusive process and indicates the free gas returning to the dissolved phase as pressure increases although other processes may also be at work where the response zone is not completely submerged.

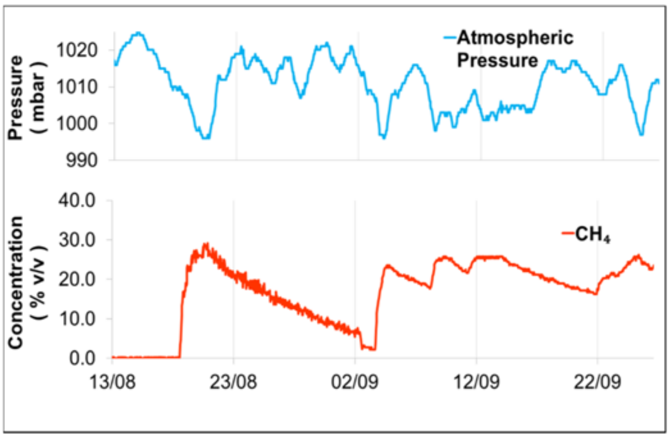

Figure 13. Continuous data depicting typical methane de-gassing behaviour.

7. RISK ASSESSMENT USING CONTINUOUS DATA

7.1 Tier 1 Risk assessment and conceptual site model lines of evidence

At its simplest a Tier 1 risk assessment is gathering the evidence to demonstrate whether there is a 'credible' pollutant linkage. This will largely be answered by a good quality desk study and a preliminary CSM accompanied by a schematic diagram demonstrating the relationship between the various elements that make up the S-P-R model.

Where limited published data exists then borehole or trial pit data may be required to determine the characteristics of potential gas sources and migration pathways. CL:AIRE Research Bulletin 17 (Card *et al.*, 2012) provides useful guidance on whether the site data provides sufficient evidence of a credible pollutant linkage that would justify ground-gas monitoring and a Tier 2 risk assessment.

7.2 Tier 2 Generic risk assessment lines of evidence

When a credible pollutant linkage exists, sufficient ground-gas monitoring data will need to be collected to confirm and characterise the linkage. As discussed above, where 'spot monitoring' data is insufficient to fully characterise the ground-gas regime then continuous monitoring can be used to obtain high quality data within a relatively short period of time. Not only will the full variability in gas concentrations and gas flow be obtained but the following additional lines of evidence can be used to further characterise the gas regime and inform the generic risk assessment:

- Environmental correlations
- Concentration duration curves
- Differential pressure assessments
- Purge and recovery tests
- Dissolved gas analysis

The modified Wilson and Card generic Gas Screening Value (GSV) and associated Characteristic Situation (CS) is widely used and is included within CIRIA C665 (Wilson *et al.*, 2007). Continuous data can be particularly helpful in selecting the most appropriate parameters to feed into the GSV calculation.

In line with BS8485: 2015 the 'worst possible' GSV approach is calculated from the worst gas concentration measured for a site and multiplying it by the worst gas flow measured for the site. This approach is only appropriate if the character of the site geology is reasonably uniform and cannot be zoned and instantaneous peak flows are discounted.

The 'worst credible' approach is to take the maximum GSV calculated from all the individual wells across the site. This can be automated, as demonstrated in Figure 14 which shows continuous flow monitoring allowing a 'continuous GSV' to be presented.

Professional judgement must be used in selecting an appropriate GSV and all decisions must be justified. At the Figure 14 site the highest continuous GSV exceeds the CS3 threshold for only a few minutes during the monitoring period. A lines of evidence approach can be used to inform the judgement whether the gas protection measures to be adopted should be to CS2 or to CS3.

7.3 Tier 3 Site specific quantitative risk assessment

Where there is a legal (e.g. Part 2A investigation) or a financial imperative (e.g. where further assessment could demonstrate that gas protection is not required), a more detailed, Tier 3 quantitative risk assessment can be carried out. In these circumstances the 'Fault Tree Analysis' is the most common numerical tool used to calculate site specific ground-gas risks. This technique is described in detail in CIRIA 152 (O'Riordan *et al.*, 1995) and discussed further in Wilson *et al.* (2009).

Continuous monitoring data, and the additional lines of evidence discussed above, provide greater confidence on the characterisation of the gas regime at a site and hence the choice and justification of the parameters chosen to be used in the calculations.

A fault tree analysis should be accompanied by a sensitivity analysis to demonstrate the range of risk results that would arise if different parameters were chosen. Again, the continuous monitoring data, and associated lines of evidence, can inform the upper and lower bounds of the parameters to be used in the sensitivity analysis.

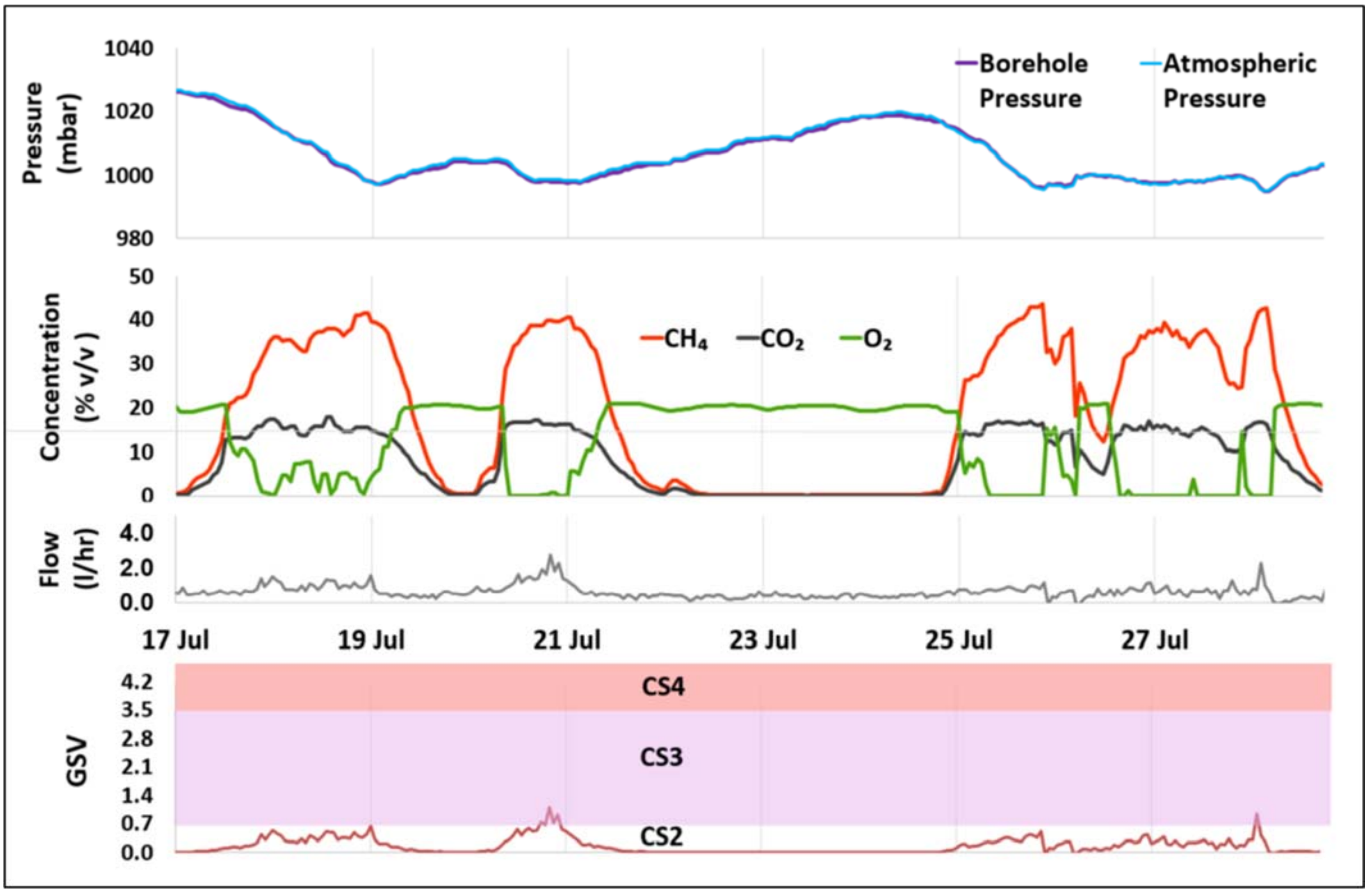

Figure 14. Graphical presentation of continuous GSV data produced from continuous concentration and flow monitoring.

7.4 Tier 4 Risk assessment - receptor monitoring including sub-floor void monitoring

With the advent of continuous monitoring there has been an increase in demand for receptor monitoring. Where a gas protection design has not been followed or has not been verified in line with good practice (Mallett *et al.*, 2014) then receptor monitoring can provide the evidence that a development is safe. This technique can be used as a useful tool to satisfy a verification planning condition for new developments and for assessing existing properties that may be affected by ground-gas contamination as was the case at Gorebridge.

If receptor monitoring is required a systematic approach should be adopted. The first stage should be a full internal survey of the ground-floor and/or basement of the property using a high resolution hand-held monitoring device at ppm level, with particular attention taken around all service entries and confined spaces. This should be carried out during a falling atmospheric pressure event. The results of the survey will inform the choice of locations for subsequent internal continuous monitoring. Usually these will be at service entry points and smaller rooms or cupboards with reduced air changes. Continuous monitoring equipment should be installed with appropriate high resolution sensors i.e. 0.05% on a 0 to 5.0% scale for methane and carbon dioxide where these are the contaminants of concern. Continuous monitoring should then continue to capture two significant driver events that approach worst case conditions.

A continuous sub-floor monitoring approach is discussed in CL:AIRE TB16 (Wilson *et al.*, 2017). Alternatively, sub-floor void exhaust vent continuous monitoring can be carried out to demonstrate the efficiency of the dilution of ground-gases within the void. Such monitoring can only be effective on the leeward (down-wind) side of a building and should be accompanied by appropriate local weather information that demonstrates the wind direction and speed during the monitoring period. It is also important that any sampling line to the void is not kinked or blocked and it is recommended that a semi-rigid tube is used for this purpose.

8. CONCLUSIONS

This bulletin describes the use and development of continuous ground-gas monitoring as a technique to measure and assess ground-gas emissions and for the purposes of selecting gas protection measures. As stated in BS8576: 2013 "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 migration drivers and correlations".

Such correlations can also be used to predict the impact on the ground-gas regime due to climate change, for example groundwater rise or extreme climatic changes. Flood and drainage design routinely accounts for the effects of climate change in the design of the built environment. Similarly, data from continuous monitoring allows site specific correlations to be established that can be used to predict the effects of climate change when evaluating the gas regime and migration drivers over the design life of new and existing building development.

As stated in Section 7.3, continuous monitoring is particularly useful for undertaking Tier 3 site specific risk assessments in accordance with CIRIA Report 152 as it can provide the appropriate gas data with environmental variables to derive the statistical probabilities for a fault tree analysis, for example the probabilities for:

- Presence of ground-gas;
- Ground-gas exceeding concentration criteria (in the case of methane exceeding the 5% lower explosive limit);
- Frequency of atmospheric pressure drops.

Whilst such probabilities can also be developed from spot monitoring data the outcome might be less reliable because, by its very nature, spot monitoring introduces operator and equipment variability with time. Discrete readings with time can miss important trends unless a large data set of readings is made. CIRIA C665 indicates that up to two-years' worth of readings might be needed on a highly gassing site for sensitive residential development. Thus, spot monitoring can be a long and expensive technique for the purposes of undertaking a Tier 3 risk assessment.

The ability to correlate gas regime and gas migration to environmental variables means that Tier 3 site specific risk assessments can be developed to predict the long-term effects, such as climate change or rising groundwater levels on gassing regimes. This will lead to more robust design and specification of gas protection measures for new building development and infrastructure.

Another key role is the use of continuous gas monitoring to investigate and evaluate existing building development or infrastructure affected by ground-gas. As described in Section 7.4, receptor monitoring may be required because the development either has inadequate or no gas protection measures and ground-gas may already be affecting internal air quality and human health. In such circumstances retro-fitting gas protection measures to existing development cannot be selected based on the scoring system set out in BS8485. Instead specific design and specification is required based on a Tier 3 risk assessment approach. Continuous gas monitoring can provide the comprehensive data needed in an economic and timely manner.

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