Soil-gas monitoring: soil-gas well designs and soil-gas sampling techniques

Investing in Opportunities
This project has received European Regional Development Funding through INTERREG IV B.
INTERREG IVB

Summary

Gas transfer from volatile pollution sources (located in the satured or unsaturated zone) to ambient air (especially indoors) is significant and has to be characterized and monitored. Therefore, soil-gas sampling is an important aspect in the frame of polluted site characterization and monitoring as well as in risk assessment. That is why soil-gas sampling installations have to be well designed and soil-gas sampling techniques well mastered. Reliable results cannot be obtained if these two conditions are not reached.

Indeed, geared to the measurements carried out, soil-gas investigation can match three different points: source screening, gas plumes delineation as well as soil-gas assessment and monitoring. Nowadays, different sampling installations, sampling methods and analysis exist, in order to satisfy the different needs of the approaches mentioned previously. Investigators must assume the most appropriate soil-gas sampling installation and technique selection depending on site specificities and the investigation objectives. Successful selection of an appropriate soil-gas sampling system depends on the level of understanding of the whole site specificities like vadose zone characteristics, contaminants properties, chemical and biological vadose zone processes as well as soil-gas sampling systems applicability.

Many studies were carried out on soil-gas sampling and some official reports expressed practical recommendations. Few guidelines dedicated to soil-gas well installations and soil-gas sampling methods have been published, especially in Europe. Among them, some have not been updated since several years. In England, a new standard is currently in progress and should be published during 2013. The European standard (ISO 10381-7) is also under review. CityChlor feedback contributes to the improvement and enhancement of current practices.

Soil-gas well construction should follow some specific recommendations concerning the drilling method used, its design as well as the implementation of some tests prior sampling.

Concerning the drilling method, INERIS recommends the use of percussion hammer with percussion gouges and in case of appropriate lithology conditions, a core sampler with a synthetic sampling tube (percussion hammer method). It is also recommended to establish PID vertical profiles thanks to these soil cores in order to get information on lithology as well as contaminants concentration and depth.

Concerning soil-gas well design, it is made of a closed tube and screened interval threadedly assembled. The screened interval should be located in a sand pack. This filter bed is placed all along the screened interval with two barriers against atmospheric air intrusion (sealing rings) at the bottom of the screened tube (“bottom cap”) and above the screened interval respectively. The screened interval should be located at least 50 cm below the ground surface and more than 50 cm above the water table in order to secure the soil-gas well from the potential water table variations. Shallower soil-gas wells could be considered if weatherproof conditions are reached (especially

towards ambient air). Screened interval length depends on lithology, investigations objectives as well as the contaminants. It is strongly recommended against installing a screened interval along two different sorts of lithology.

Concerning multi-depth sampling, European documents (ISO 10381-7, VDI 3865-2) do not mention any specific recommendation. Since, when multi-depth sampling is needed, several conventional soil-gas wells are installed closely but far enough, not being in each well radius of influence.

According to the results obtained in the frame of CityChlor project (5 sampling campaigns), two soil-gas well designs can be recommended for multi-depth sampling: multi-depth nested wells and soil-gas wells installed in different but similar boreholes. Multi-depth nested wells should be more relevant than soil-gas wells installed in different but similar boreholes, when lithology varies at low distances Nevertheless, soil-gas wells installed in different but similar boreholes required more common construction procedures (similar to conventional soil-gas well), whereas design 2 remains more delicate and complex to implement. Finally, soil-gas well with two screened intervals should be considered only if packer airproof could be well-mastered.

When the soil-gas well is properly installed, some precautions should be taken before sampling: re-equilibration period, leakage as well as recharge and recirculation tests are recommended to implement.

For each type of sampling installations, several sampling techniques can be used. Some are active samplers with mechanic or natural pumping, others passive. All are complementary devices which enable an improved soil-gas characterization.

Prior to sampling, the soil-gas installation should be purged. Two purging strategies can be considered. The first one is based on the volume of gas pumped. Indeed the volume of soil-gas extracted by pumping from the soil-gas well has to match 3 to 5 times soil-gas well volume. The second strategy is based on the stabilization of monitored physical chemistry parameters. Purging a soil-gas well using a PID (whose pump has been calibrated previously), seems to be an appropriate system which combines both purging strategies.

As a result, depending on the objectives of the investigations and site specific constraints, several sampling techniques can be considered. Choice should be managed according to the targeted substances, the different levels of contamination depending on the compounds and the appropriate limit of quantification required for each of them. Sorbent tube is the most used but Summa-canister® could also be considered. All the materials used in the frame of sampling have to be calibrated and free of contaminant.

In order to provide better data interpretations, trip blank and field blank are strongly recommended. Finally, for each site, several investigations should be carried out in order to value the variations due to the weather (seasonal investigations).

As meteorological conditions have an important impact on contaminants transfer, it is strongly recommended to monitor pressure (soil-gas, indoor and barometric pressure), temperature (indoor and outdoor buildings), wind speed and rainfall during the whole sampling campaign, even some few days before and after. Humidity and temperature inside the soil-gas well installations are also relevant parameters. Their measurements are recommended at least, at the beginning and at the end of each investigation. Also, the operator should verify the absence of water downhole. Moreover, it is recommended to avoid soil-gas sampling campaigns in case of rain events, frost and snow when soil-gas installations are outdoor.

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1 Introduction

1.1 CityChlor and the integrated approach

Space is scarce in Europe. Even in the subsurface it is getting busier. Large-scale soil and groundwater contamination with chlorinated solvents are often an obstruction for urban developments. The traditional way of dealing with polluted soil and groundwater does not work in all cases and is not economically and sustainable feasible. In urban environments multiple contaminations with chlorinated solvents are often mixed with each other and spread underneath buildings. This not only leads to technical problems for remediation, but also to liability and financial discussions and hence has an impact on society. An integrated approach and area-oriented approach is needed to tackle the problems. The CityChlor project has demonstrated that remediation and sustainable development can evolve on a parallel timescale.

An integrated approach combines all aspects that are relevant to tackle the problems that pollution with VOC in urban environment causes. Depending on area, site and context different aspects together or parallel to each other can be used. Not only technical solutions are included, but also socio-economical aspects as urban development, communication, financial and legal aspects, time, space, environment and actors (active & passive) have to be handled.

CityChlor did not remain at single case remediation, but looked at the area as a whole in a bigger context: the area-oriented approach. A technical approach that makes it possible to remediate, monitor and control multiple groundwater sources and plumes within a fixed area.

1.2 CityChlor and technical innovations

The managing of knowledge and technical innovations are one of the key to achieve a sustainable city development. A development project has to cope with loads of information coming from different disciplines in different (technical) languages and with different uncertainties. With chlorinated solvents, the knowledge about the pollution will always have a certain uncertainty that can have an impact on the course and the costs of the remediation. An efficient 'managing of knowledge' will try to decrease this degree of uncertainty.

CityChlor therefore also worked on the technical aspects of characterization and remediation. The conventional techniques that are applied for investigation and remediation have their limitations dealing with chlorinated solvents. Promising innovative techniques exist, but do not easily find their way to current application. This barrier is often caused by lack of knowledge on different levels. Experts and contractors do not always have the means to invest in experiments with new techniques, authorities are reluctant to accept techniques of which the results may be uncertain and clients aren't eager to pay for experimental techniques.

Dissemination of knowledge can break this deadlock. CityChlor therefore collected experiences from field application of innovative techniques and implemented itself a number of techniques in pilot projects. For the detailed outcomes, the reader is referred to the specific reports.

2 Introduction to soil-gas monitoring

Soil-gas sampling is an important aspect for contaminated site management, especially in case of volatile pollution like chlorinated solvents. In this case, gas transfer from the soil sources to ambient air (especially indoors) is significant and has to be characterized and monitored. That is why soil-gas sampling installations and soil-gas sampling techniques have to be designed and well mastered to give reliable results for polluted site characterization, monitoring and risk assessment. Indeed, geared to the measurements carried out, soil-gas investigation can match three different points: source screening, gas plumes delineation as well as soil-gas assessment and monitoring. Source screening and gas plumes delineation are qualitative approaches whereas soil-gas assessment and monitoring are quantitative approaches. Then, they do not match the same sampling objectives but bring complementary information.

Nowadays, different sampling installations, sampling techniques and analysis methods exist, in order to satisfy the different needs of the approaches mentioned previously. Some installations are highly versatile for numerous applications whereas others are dedicated to more limited or specific applications. Most of them are complementary installations. Generally, soil-gas sampling is used to get results thanks to cost-effective and easy-to-use sampling techniques. Most often it is performed on site with a range of sensors and analyzers or devices more or less specific to a family of compounds and/or a detection threshold. Investigators must assume the most appropriate soil-gas sampling technique selection depending on site specificities and the objectives of the investigation. Successful selection of an appropriate soil-gas sampling system depends on the level of understanding of the whole site specificities like vadose zone characteristics, contaminants properties, chemical and biological vadose zone processes and soil-gas sampling systems applicability.

Many studies were carried out on soil-gas sampling and some official reports expressed practical recommendations. Few guidelines dedicated to soil-gas well installations and soil-gas sampling methods have been published. Among them, some have not been updated since several years In England, a new standard is currently in progress and should be published during 2013. The European standard (ISO 10381-7) is also under review. Then, current practices do not fit the best measurement protocols. Moreover, these different sampling installations and sampling techniques are characterized by some limits that may cause problems of representativeness (soil characteristics, underground networks and humidity, depression influence, sampling duration respectively).

This report reviews the main soil-gas sampling installations and sampling methods. It compares some of them thanks to field measurements in the frame of CityChlor. And finally, it uses this feedback to provide guidance to people on their own choice**.**

First, the soil-gas sampling installations are reviewed. Two different sampling strategies are used in European countries. They have to be clearly distinguished: surface flux sampling and soil-gas sampling. These two strategies do not have the same applications as they do not measure the same gas matrix. Both can be carried out using several sampling installations, presented below.

For each type of sampling installations, several sampling techniques can be used. Then, the second topic of this report concerns sampling techniques. Some are active samplers with mechanic or natural pumping, others passive. All are complementary tools which enable an improved soil-gas characterization.

3 State of the art of subsurface installations for soil-gas flux measurement

Surface flux sampling measures soil-gas transfer from the non-saturated zone to the ambient air (flux measurement) using flux chambers. These devices are used to assess the flow of volatiles compounds generated for a given period of measurement. Because of preferential pathways, bioattenuation, mitigation, diffusive transfers (outside air) and convective-diffusive transfers (indoor air), surface flow measurement represents plumes of gas present in the vadose zone. It does not properly measure soil-gas but value the gas diffusion or diffusion and convection at the interface soil/outdoor air or soil/indoor air. Soil-gas surface flux measurements can be used as tools to assess the timing fraction of soil-gas emitted into the atmosphere during the migration of these contaminants. They are reflective of all the subsurface state and transport processes that are most of the time hard to model. They are usually used in the frame of contaminated sites, landfill sites, land treatment and water treatment ponds.

Surface flux sampling is useful for specific applications. Surface flux measurement can provide an approximate order of magnitude of the soil gas flux. Indeed, this soil gas flux could be under or over estimated because of a lack of pressure-induced advective flow created by heating or ventilation systems, or no building foundation respectively. Surface flux sampling is usually used for screening as well as determining the optimum monitoring wells[1] location if soil-gas sampling is necessary in a next step of investigations. It may be used to monitor contaminant emissions from soil or groundwater, providing data necessary to settle parameters in gas transfer models (01) as well as to assess the health hazards risk to exposed people (ASTM D 5314-92; 011).

Surface flux chamber is set up to enclose a known surface area. It is placed directly on the surface (ground, floor) for a known time period (generally from few minutes up to few hours, using dynamic scanning chambers). It should be well-sealed against the surface. If good sealing could not be performed, surface flux measurements may be not appropriate and avoid, especially in case of flux measurement longer than a couple of minutes and/or using an important sampling flow.

Several surface flux chambers have been designed. All of these chambers are expected to create the best mixing and sampling conditions, minimizing the disturbance of the gas emission. They can be used with online tracking by direct analysis of gas, a monitoring of integrative carrier or a

[1] more often permanent wells at this stage of investigations

combination of the two devices. A large broad of volatile compounds can be monitored by surface flux measurements, just like VOCs, mercury, methane, carbon dioxide, NO_x, sulfur compounds...

These sampling results are strongly sensitive to soil characteristics. High water saturation, clay, organic matter and slab, for example, limit soil-gas transfer at near surface horizon. Then, they induce a decrease of the flux of contaminants coming from subsurface and entering the surface flux system. Indeed, these parameters influence soil-gas transfer from the soil to the ambient air but do not induce a bias in the measurement depending on the sampling technique used.
On the contrary, soil humidity, soil temperature, barometric pressure and wind speed which also strongly control the vapour phase contaminant migration, should be taken in order to adapt the sampling techniques and the sampling duration in accordance with the objectives of the investigation. The impact of these parameters variations cannot be clearly quantified from site to site because of site specificities.

This method yields the current flux of the contaminant out of the ground, which eliminates some of the assumptions required when calculating the flux with a model. However, this technique is not as fast or easy to implement. It is also subject to near-surface effects and gives us no idea of what may be "hiding below".

This state of the art tackles the two main installations used for soil-gas flux measurement.

3.1 Static surface flux chamber

Static flux chamber is a simple device. The chamber looks like a container constructed of an inert and non-adsorbing material. It also holds sampling ports in order to connect the appropriate sampling system to the soil-gas flux chamber.
The static-flux chamber follows the evolution of the gas concentration in the chamber after sealing the chamber to the floor (when needed) without introduction of any gas into the chamber.
Contaminant flux and thus, concentration increase over the sampling period. Discrete samples should be withdrawn at regular intervals during the whole sampling period. Continuous sampling could also be considered, using on-line analyzers, inducing a continuous slight depression due to pumping.

Figure 1: Static-flux-chamber with PID monitoring *(source: INERIS)*

Static chamber could also use gas recirculation. This system (Pokryszka and al. 1999) is based upon a principle of accumulation chamber connected with an analyzer. The accumulation chamber is equipped with an external low flow recirculation, which enables on-line analysis. Gases emitted from the site within an elementary surface are pumped, sent to the analyzer and re-injected into the chamber, creating a recirculation flow. In that way, the atmosphere enclosed in the chamber is enriched with contaminant compounds, until it reaches an asymptote in equilibrium with ambient air concentration. The local flow can be deduced from the measurement of the atmosphere enrichment, the sampling time and the chamber geometry. The on-line analyser may be replaced by an adsorbent tube: in this case, clean air is injected in the chamber and the concentration continuously increases in the chamber.

Static flux chamber measurement lasts from some minutes (using PID or FID) to one hour or less (using sorbet tubes for example). Sampling equipments and protocols are easy to implement and handiness. Around ten to twenty measurement per day could be considered, depending on the sampling techniques and the sampling duration. Costs are usually rational. Then, multi soil-gas flux measurements could be easily considered, giving a better view of the gas emissions of the investigated site.

3.2 Scanning surface flux chamber

“Dynamic scanning-chambers” (Pokryszka & al. 1995) are more complex. These chambers are connected to an inert gas supply system and an exit fitted out with measurement points. The system gathers contaminant gas emitted from soil within the inert gas flow. Before sampling, it is necessary to reach the stabilization of the flow regime of inert carrier gas into a chamber in contact with the ground. Therefore the measured parameters (concentrations and outgoing air-flows) allow to quantify the flow of emitted vapours outgoing from the chamber, and thus to deduce the flow released through the concrete slab or the ground.

Figure 2: Scanning flux chamber with PID monitoring *(Source: INERIS)*

This surface flux chamber needs a longer period of equilibration due to its size and the gas injection. Flux measurement lasts around three or four hours. It is also a less handiness surface flux installation than the static-chamber. Then, it has more limited applications. However, this chamber is very relevant in case of low flux: thanks to the longer sampling duration, lower quantification limits (than using static flux chamber) can be reached.

4 State of the art of soil-gas sampling installation

Soil-gas sampling allows characterizing the soil-gas located sub-slab as well as in the vadose zone thanks to soil-gas wells. Temporary and permanent soil-gas sampling installations are usually distinguished. Soil-gas sampling is used for source or plume characterization (qualitative results) and assessment or monitoring (quantitative results). Multi-level sampling installations can also value gas transfer deep down. This information is particularly relevant for risk assessment, settling source parameters in models or simply estimating risk. Soil-gas measurements can also perform soil-gas characterization and monitoring, especially in the context of contaminated site management or remediation.

Here are presented the different sorts of soil-gas installations which are used in Europe. For each of them, recommendations of applications and constructions are made from American (ASTM D 5314-92; 011), German (VDI 3865-2; 014), International standard (NF ISO 10381-7; 013) as well as INERIS feedback.

4.1 Soil-gas sampling location and depth

Soil-gas well installation cannot be carried out without the identification of the most appropriate locations and depths. Of course, information must be obtained thanks to an historical study of the site: geology and hydrogeology characteristics, potential gas sources location, buildings and foundations structures, locations of underground networks...

If no information is available concerning lithology, at least, one continuous cored boring should be achieved from the surface to the greatest sampling depth considered. In case of risk assessment for public health, lithology should be well-known and well-understood (as precisely as the study needs). This information is especially important for modelling. Moreover if no information is available concerning potential sources location, screening investigations should be considered (soil sampling, sub-slab sampling, soil-gas sampling using temporary installations...).

Furthermore, it is primordial to get information about buried networks just like line voltage, sewerpipe or gas and water main, before drilling. In case of important lack of information concerning underground networks, visual observation during drilling is the minimal caution but it is not the safest method and seems to be insufficient in a lot of cases. Then, it is strongly recommended to use remote sensing, metal detector even ground penetrating radar. This investigation avoids a large number of inconveniences which can have hard consequences for the field crew and the project.

Lithologic profile (logs), geotechnical sampling and soil matrix sampling are strongly recommended and should be included in cored boring in order to use the appropriate parameters and reference values.
Sample locations, number and depths depend on each site. Choice should depend on the historical study and data provided by models. Moreover, choice should be steer depending on the contaminants and lithology. Of course, sample locations, sample number and sample depths strongly depends on the main objectives of the study (characterization, monitoring...) too.
Soil-gas samples should be taken at locations where permanent soil-gases are supposed to be generated by the source of pollution (at the source location or along migration pathways). Some others should also be located close to potential receptors. Finally, others have to be taken at potential non-contaminated zones in order to provide background concentration data.

Soil-gas samples should also be representative of the potential of contaminants attenuation and transfer, especially in permeable soils. Then, depth is an important parameter for soil-gas sampling.
Multi-depth data could be achieved thanks to soil-gas installations located at a single location (multi-detph sampling well) or at several close locations (close conventional sampling wells). Multi-depth soil-gas sampling provides numerous information:

- vertical distribution of contaminants in the vadose zone (characterization),
- transfer mechanisms geared to depth,
- remediation monitoring, valuing clean-up processes in progress.

Just like for single depth soil-gas sampling, multi-depth soil-gas sampling depends on the historical study, data provided by models as well as the objectives of the study. All data provided by previous investigations (cuttings, soil matrix sampling...) should be taken into account. Moreover, choice should be steer depending on the contaminants and lithology. Nevertheless, it is strongly recommended to not install screened interval at the capillary fringe depth. Usually maximal depths reached are around 5 meters deep.

4.2 Soil-gas sampling installation

In order to sample soil-gas located in the vadose zone, it is necessary to make a well, thanks to sounding. Sounding also provides some additional information about soil characteristics (permeability, geotechnics…). Then some tests are carried out in order to well start-up the installations (airproof test...) and finally soil-gas sampling.
Nowadays, various soil-gas well designs exist. The main documents dedicated to soil-gas sampling (ASTM D 5314-92; 011, VDI 3865-2; 014, ISO 10381-7; 013) do not precisely define how they should be implemented. This report tends to make recommendations to provide some guidance to people, according to the feedback gain in the frame of CityChlor project, in particular

with CityChlor project: Ile de France (01). Then, it reviews different soil-gas sampling installations, which are commonly used in Europe and more broadly speaking in the world. Advantages and limits of their applications (characterization, delineation, multi-depth sampling) and some recommendations for construction are also provided.
This report review the main drilling techniques used for soil-gas well construction as well as the different soil-gas well designs used in United-States and Europe. Usually, two different sorts of installations are distinguished: **temporary soil-gas installations** and **permanent soil-gas installations**.

4.2.1 Drilling methods for soil-gas installations

Sub-slab and temporary soil-gas installations are usually implemented using three different drilling methods:

- hand auger method
- hollow stem auger method
- percussion hammer method

Each drilling method is described in the next paragraphs. Drilling method selection should be based on soil properties and subsurface materials.

Hand Auger Method:

Hand auger is the cheapest method making a borehole. In order to advance the auger into the ground, one or two men need to press down on the cross-bar as they rotate it. When the borehole is deep enough, the auger is brought back to the surface. Many hand augers exist (see Figure 3). The usual preferred designs are those providing a core sample.

This drilling method is portable and useful especially in areas with limited access. It can be used for shallow soil gas installation construction or for initiating drilling (temporary rods methods). Hand auger method is particularly relevant for sandy soils, without any obstructions. If soil is not so permeable (clay, silt), the hand auger progression is very slow and the maximal depth is around 1 meter deep. But greater depth can be reached if soil contains gravel, cobbles or boulders. Nevertheless, hand auger is avoided in the presence of slab.

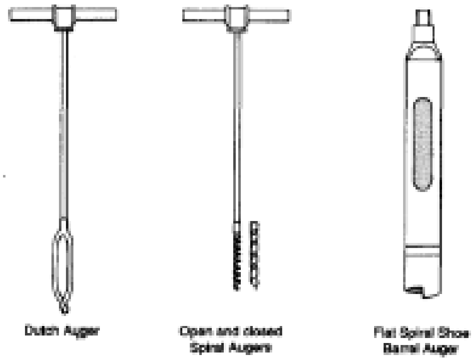


Figure 3: hand auger exemples *(source:*

- **Hollow Stem Auger Method:**

This method uses a continuous flight hollow stem auger. Prior to drilling, casing, filter pack and seal are installed inside the auger. A cutter-heads fixed at the bottom of the auger make easier drilling and maintaining an open borehole. Thanks to the hollow stem auger, drill cuttings are driven to the surface. Then, soil samples can be collected, using a sampler ahead of the auger. Nevertheless, this drilling method cannot provide accurate results for soil sampling. Drill cuttings are exposed to ambient air and volatile compounds may volatilize, especially VOCs.

The amount of unconsolidated soils penetrating the blank tube (casing) is minimized thanks to the auger design.

When the whole materials are at the correct depth, the auger is removed carefully. Filter pack and bentonite grout are added as and when the auger is taken off the borehole.

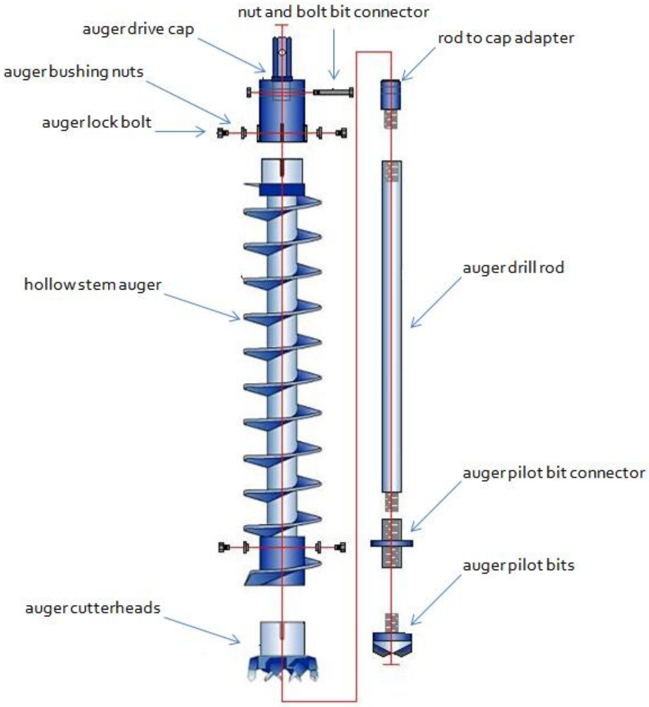


Figure 4: hollow stem auger method *(source: Mills Machine Company Inc.)*

- **Percussion Hammer Method:**

Percussion hammer is made of a tripod derrick with a winch. The system is usually mounted on pick-up trucks or tracks but it can also be hand-portable.

It uses a combined force generated by the vehicle static weight as well as percussion hammer. Then, the borehole is made by gravity percussion and a percussion gouge (cylindrical steel tube) is driven into the ground. This drilling method minimizes the disturbances to ground.

Vehicles are usually compact enough to enter into buildings and hand-portable percussion hammer can be used in case of very limited access area. It is noisy and should be avoided in specific locations.

This drilling method can be used for shallow drilling as well as for deep drilling up to 10 meters. Nevertheless, it cannot penetrate obstructions (brick, salb...) except if the drilling system combines percussion and rotary capability.

Figure 5: percussion hammer *(source: Geoprobe®)*

Different percussion gouges are available: window percussion gouges and windowless percussion gouges. Different diameters (40, 50, 60, 75, 100 mm) and length (5, 100, 200 cm) of each sort of gouge are available. Choice should be managed by the objectives of the investigation (core sampling, soil-gas well design...). Both can be used to take undisturbed samples, currently to drilling.

Figure 6: window percussion hammer gouge *(source: PDK)*

In addition to ordinary percussion gouges, it is possible to use specific core sampler in order to recover the drill cuttings for a potential laboratory analysis. This core sampler consists in a synthetic and inert sampling tubing.

In particular, percussion hammer is a drilling method used by the direct push technologies.

4.2.2 Temporary sub-slab installations

Sub-slab soil-gas measurement indicates which substances potentially transfer from soil to ambient air (indoor air) and thus, represent a potential exposition for people. Sub-slab method consists in sampling soil gas located under buildings, in sub-slab fill. Installations bottom are above the vadose zone (native soil). Installations depths are mostly comprised between 0.07 and 0.1 meter deep in the frame of sub-slab measurement in habitation until 0.30 meter deep in industrial buildings.

Temporary sub-slab installation is considered in case of punctual sampling events. Recommendations for sub-slab their construction have been detailed in American guidelines (022, 020, 027, 020). The main instructions are mentioned in the paragraph bellow.

The field crew should foresee only deionized water is used during all the steps of installation. Materials (bentonite, sand, tube...) should be free of pollutants and cleaned (of manufactured oils for example for metal tube).

Sub-slab construction should begin with floor covering removing (tiles, carpet...). Then, concrete slab is bared. All the buried networks have to be clearly indicated on the slab surface prior to consider drilling. A small-diameter hole (about 25 and 31 mm) is drilled thanks to electric hand drill and advanced in the concrete slab at the correct sampling depth, and reach the sub-slab fill. Finally, drilling material is removed from the borehole in order to build the sampling well. The borehole should be cleaned thanks to damp towel. It generally induces better sealing.

Sub-slab sampling well should also respect different criteria for better data acquisition. Usually, sub-slab soil-gas well intern diameter is around 3 to 6 mm. The bottom of this tube is permeable thanks to slits, making a screened interval. Metal, nylaflow, PEEK or Teflon® are the most recommended materials for tubing. Of course choice should be lead by the pollutants expected. The screened interval is installed in a sand pack in order to minimize the airflow disruption. Sand pack and screened interval should be overcome by a Teflon® sealing disk. Located between the screened interval (sand pack) and the blank tube (wet bentonite), it avoids wet bentonite and sand mixing, which may disturb sampling proceedings. In order to better seal the installation, hydrated bentonite should be placed above dry bentonite, up to the surface in case of temporary installation.

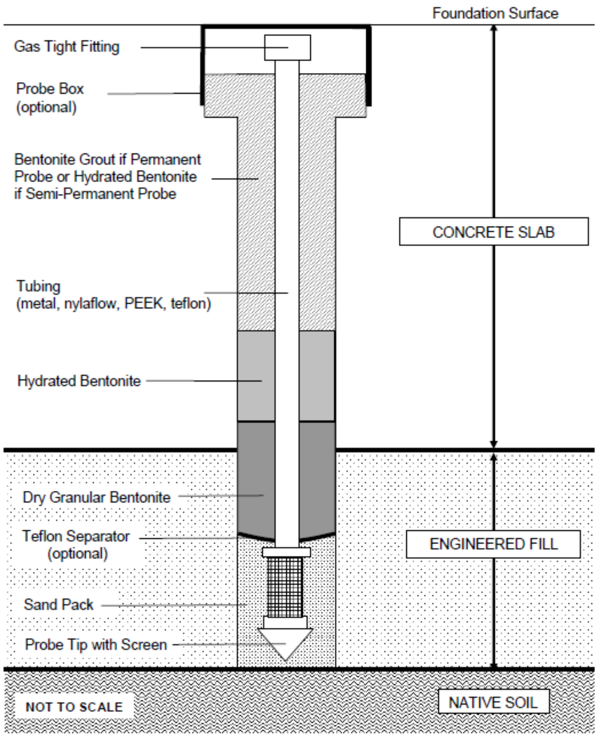


Figure 7: sub-slab sampling well
(source: Vapor Intrusion Guidance Document, DTSC, 2011, 020)

The sub-slab installation cannot be used since a short period of time (about 2 to 4 hours), necessary to reach again the soil-gas equilibrium. Purge volume testing, leak testing and shut testing are strongly recommended by the US EPA (020). Purge and sampling should not exceed 200 mL/min. As these installations have limited volume, the Department of Toxic Substances Control (DTSC) from the California Environmental Protection Agency recommends not sampling more than one litre of soil-gas (adapted containers).
The temporary sub-slab installations are removed from the ground at the end of the sampling event. All materials (casing, screened interval, bentonite...) should be getting back by over-drilling. The borehole has to be filled with grout and patch material. The floor slab should also be restored.

In France, simplest sub-slab temporary installation is usually used. A borehole is first drilled using a drill and spine bit, following the precautions mentioned previously. The borehole should be cleaned thanks to damp towel. Then inert tubing is directly inserted in the borehole and connected to the appropriate sampling device (sorbent tube, canister...). When sampling ends, floor slab is restored using cement.

4.2.3 Temporary soil-gas wells

Temporary soil-gas wells perform only one-shot sampling at one precise location and at one precise date and time. Then, these installations are advantageous if only one sampling round is required. They cannot be applied for real time tracking or long time monitoring. They are usually recommended for screening as well as soil-gas transfer characterization.
Using a suitable protocol of measurement (volume, temperature and exposition time), they provide qualitative or semi-quantitative results depending on which sampling technique is used (see part 5).

Temporary soil-gas wells are rapid to set up. Less material is placed in the ground that is why they minimize in-situ soil vapour disruptions and then latent time before sampling is not required (soil system is at its natural equilibrium).
Among the different temporary soil-gas well designs, two main methods are used: rod and direct push systems.

- **Temporary Rod system**

Rod systems, like Draëger® gas probe, are easy and rapid to set up. They are usually used when one-shot sampling needs to be carried out at low depth (from 0.5 to 2 meter deep). Rod is usually driven into the soil by the hand auger drilling method only if soil is permeable. They could also be driven in soil by mechanic tools like rotary, sonic or percussion drill rings, especially when soil is resistant to penetration. Then, a specific sampling casing (with screened interval on its bottom) is advanced in the borehole. This sampling casing is linked to a sampling system (see part 5).
The implementation is particularly rapid which minimize the disturbance and soil-gas sampling can be carried out without waiting for "stabilization". Most of the time, they are used for screening.

Figure 8: soil-gas sampling by rod method at CityChlor Pilot project Ile de France*(source: INERIS)*

Temporary Direct Push Technologies installations

Direct Push Technology (DPT) also provides temporary soil-gas wells. They are implemented using direct push drilling method mentioned previously and detailed in the CityChlor DPT Guideline (05). Since the current report is dedicated to soil-gas sampling, only soil-gas probes and sensors are detailed. If DPT matches soil-gas sampling and/or soil-gas contaminants detection objectives, the operator must refer to the specific DTP guideline to have more information about recommendations and cautions to take in application.

Soil-gas sampling by DPT is used to collect samples from the vadose zone, which are analyzed at the surface or to permit real-time chemical tracking (contaminant detection). Then, it provides soil-gas characterization profiles.

Most of the time, DPT soil-gas sampling is applied for screening or soil-gas transfer characterization while pre-site evaluation and decision. Two main sorts of DPT soil-gas sampler are distinguished: **continuous and discrete samplers**. Continuous samplers are not described in this report as they are not considered as soil-gas installation. But details are provided in the CityChlor dedicated guideline (05).

Discrete sampling devices consist in steel tip that screws into the end of the tool string and holds a disposable drive point. The whole system is sunk at the desired depth. Then, the sampling tool and the drive point are broken away. The rod is retracted slightly in order to expose the opening of the device to the soil gas. Just like for continuous sampling devices, soil-gas is collected by pumping or by inertia.

For some sampling systems, the drive point is left in the ground (see both expendable tip samplers). When sampling ends, the whole system is pulled out from the ground and decontaminated. Finally, a new drive point is mounted on the sampling tool before taking another sample at greater depth or at another location.

For other sampling systems, sampling tool and drive point could be gathered again (see retractable probes). Then, the whole system does not need to be pulled out but could be advanced deeper for another sample.

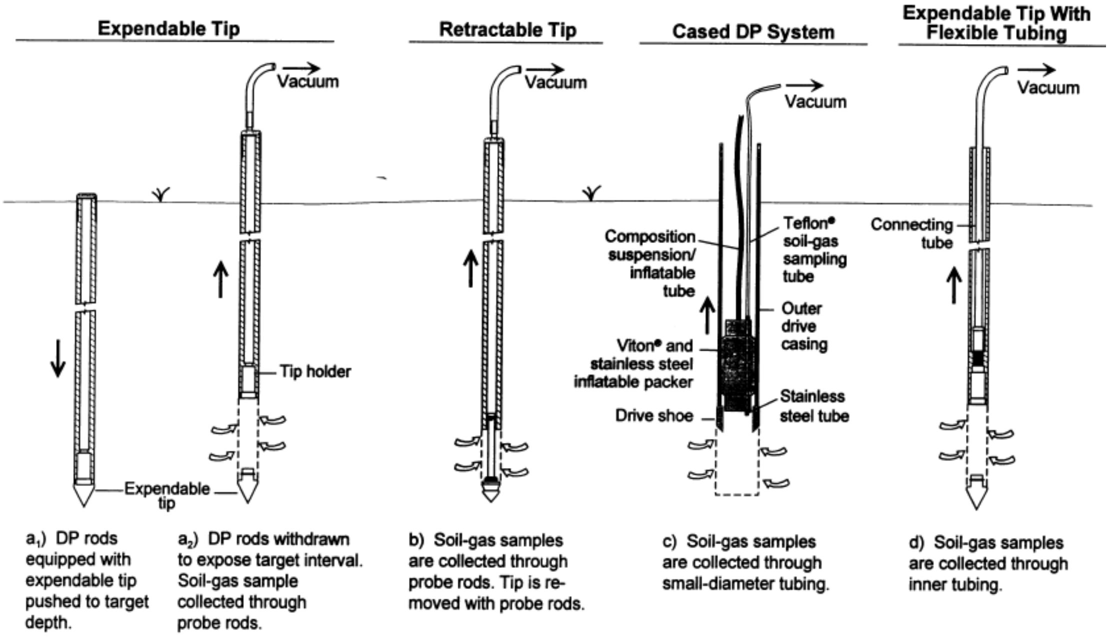


Figure 9: direct push measurement with discrete sampling devices *(source: CityChlor Technical Report: Direct Push Technologies, 2013, 05)*

Samples are taken in situ or by pumping from the surface. Usually, sorbent tubes, summa canister or Tedlar bags are the most used sampling techniques.

4.2.4 Permanent soil-gas well installations

Soil-gas permanent wells consist of permanent wells fitted with drilling tubes. These installations are dedicated to the investigation of soil-gas for low to medium depth (unsaturated zone). They are implemented in case of soil-gas regular monitoring, source characterization or over time soil-gas monitoring. Different designs already exist and are considered depending on the objectives of the study.

First, this review presents a typical permanent drilling hole and then focus on the various designs which enable a multi-depth measurement.

➥ Soil-gas well with one screened interval (conventional soil-gas well)

Usually, permanent soil-gas wells are drilling wells fitted with one screened interval. These installations are dedicated to sample soil-gas in the vadose zone, above the level of groundwater. The hole weatherproof (water and ambient air) is obtained by sufficient thickness of low permeability materials.

If soil-gas well has the same look and the same applications all around the world, some differences have been noted concerning its construction in the United States and in Europe. A permanent well is made of several components. Its diameter is generally from 20 to 80 mm and its depth from 80 cm to several meters (depending on the water table, source and plume locations as well as the objectives of the study). This hole is provided with a closed tube (casing) and a screened interval threadedly assembled. Different methods of installation can be used (see part 4.2.1). Choice should be lead by soil characteristics and slab properties.
Even through the recommended drilling methods are common to United States and Europe, some elements about soil-gas well design differ.

In Europe countries, according to the VDI 3865-2 standard (015), soil-gas wells are made of a solid tube and a screened interval threadedly assembled. The screened interval is located in sand pack. This filter bed is placed all along the screened interval with two barriers against atmospheric air intrusion (sealing rings). The primary sealing ring is located at the bottom of the screened tube and is often named “bottom cap”. The second is located above the screened interval. It consists of a layer of clay (at least 50 cm of thickness) and above it, a hydrated bentonite layer (at least 50 cm of thickness). Then, from the bentonite layer to the surface, the empty annular is filled with sand. Nevertheless, when soil-gas well screened interval is above 1 meter deep, these recommendations cannot be followed. Then, the empty annular is filled with bentonite from the sand pack to the surface.
It is strongly recommended to choose the materials for tubing (casing), fittings and valves depending on the nature of the targeted compounds: for HVOCs, or HDPE or nylon is usually recommended and PVC is avoided.

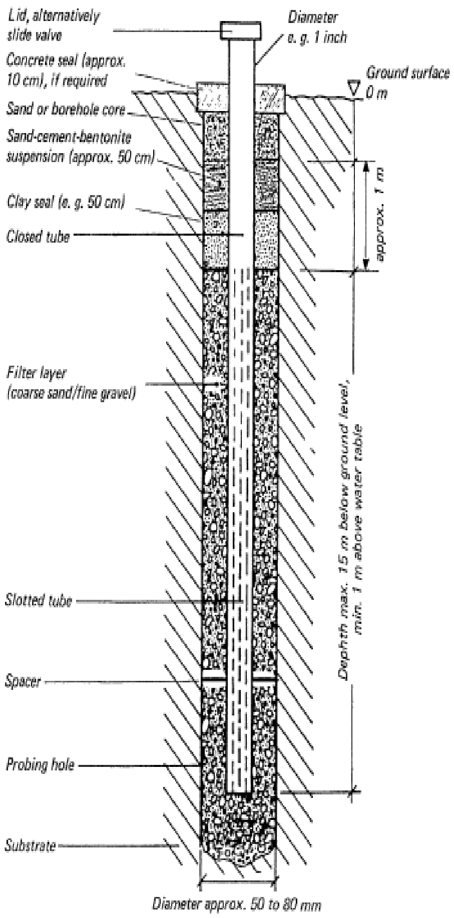


Figure 10: recommended soil-gas well design according to the VDI 3865-2 standard (015)

The screened interval should be located more than 50 cm above the water table in order to secure the soil-gas well from the potential water table variations. It should be located at least 50 cm below the ground surface in order to minimize the outdoor or indoor air intrusion into the well, during sampling.

In the United States, according to the Active Soil Gas Investigations Guidelines (018, 018, 020, 020), soil-gas wells are also made of a solid tube and a screened interval threadedly assembled. The screened interval is located in sand pack too, just like in European countries. It is strongly recommended that the sand pack thickness is more than 15 cm and the screened interval is placed in the middle of in this sand pack. Dry granular bentonite should be placed above the sand pack, sealing the screened interval from the surface (ambient air intrusion) but also prevent hydrated bentonite and sand pack mixing. This dry bentonite layer should also be, at least, 15 cm thick. Then, the borehole is filled from the top of the dry bentonite to the surface with hydrated

bentonite. It is recommended to hydrate bentonite at the surface before pouring it into the borehole. It is also possible to place a cement/bentonite layer between dry and hydrated bentonite if borehole annulus sealing is a specific criteria for the study.
In case of soil-gas well deeper than 4 meters, material should be installed with a hopper in order to avoid bringing or segregation during placement of the sand pack and bentonite seal.

Both regulations recommend the installation of a weatherproof and fixed lid to support the well casing in the borehole as well as to insure the screened interval is placed at the desired depth. This lid should prevent cross contamination, as well as atmospheric air and water intrusion.

➥ Soil-gas drilling well with two screened interval for multi-depth sampling

The ASTM D 5314-92 (011) recommends combining multiple depths sampling with soil-gas grid sampling method in case of "complex geologic settings and sites with multiple contaminant sources".
ISO 10381-7:2005 (014) recommends multi-depth sampling using several soils gas wells implemented at different depths (short slotted interval) and not sampling soil-gas at different depths in the same well (with long slotted interval).
Multi-level sampling has two main goals: monitoring changes in soil-gas composition (contaminants concentrations) versus depth and closely following a single sampling horizon for an entire soil-gas profile. Multi-level sampling is generally recommended if pollution source is located more than 1 m deep.

Multi-level sampling could be very helpful in case of volatile contaminants like chlorinated solvents because of the exchanges and transfers occurring in the vadose zone.
This review presents different sorts of multi-level soil-gas sampling drilling holes that are implemented on various sites. Some are made of different but similar boreholes, others are made of a single borehole, others a made of several screened intervals… It is important to value their radius of influence before their installation and at each sampling investigation (if sampling parameters change). Their radius must not other met another soil-gas well otherwise it must false the sampling results. However, their various designs are very similar to the simple soil-gas drilling hole but differ to provide multi-level samples.

◆ Feedback from CityChlor partners

A questionnaire was sent to all the CityChlor partners in order to have overall view of what sort of installation is used for single and/or multi-level sampling. Two companies sent back this questionnaire filled in. These are named company 1 and company 2 respectively in the following paragraphs.
Company 1 generally uses stationary boreholes for long term measurements as well as temporary boreholes and open boreholes for short term measurements. These installations are only used for

single stage of sampling and samples are usually taken 2 m above the water table. Soil-gas holes are purged using a pump flow at 2 L/min during a time period of 5 to 10 min (depending on volume of sampling well). Various surveys are used with these installations like activated charcoal tubes, Summa canister®, sample bag…

Company 2 also sends back the questionnaire. From their feedback, soil-gas sampling is usually carried out in permanent boreholes for long term measurements or in temporary boreholes for shorter measurements. Samples are only taken as single stage of sampling. Just like Company 1, various analytical tools are used in both type of hole like activated charcoal tubes, Summa canister®, syringe or sample bag.

This questionnaire reveals no boreholes for multi-level sampling seems to be already used by CityChlor partners. The next paragraphs concern this theme, in order to show that multi-level sampling installations can be implemented on investigated site and could provide a more precise characterization of the sources and their plumes as well as a better remediation monitoring.

- Soil-gas well multi-depth sampling, using packers

Conventional soil-gas wells are sometimes used for multi-depth sampling. Their design is based on the regulations mentioned previously (see part 4.2.4). Long screened interval is essential. Indeed, when sampling is carried out, each screened interval is separate and airproof from the other screened intervals thanks to packers. It is get into the well at the correct depth depending on the sampling needs. Each sampling areas are sealed (by packers swelling) before the purge begins. Various sorts of packer can be used and it is strongly recommended to test sealing performance before sampling. After these two steps, sampling can be carried out, according to the conventional sampling techniques (see part 5).

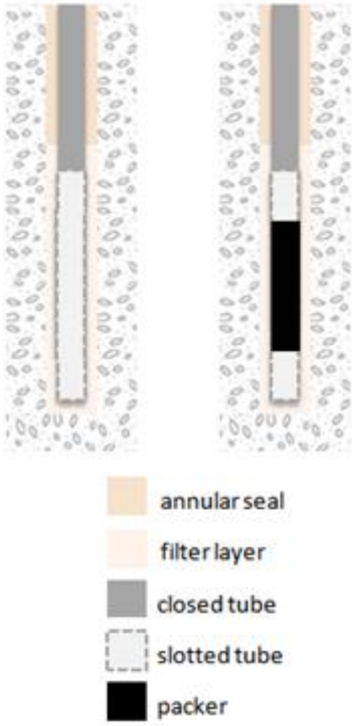


Figure 11: Multi-depth sampling with conventional soil-gas well and packers

An important limit of this system is related to the absence of sealing bed between the different sampling intervals. Then, soil-gas transfer from a specific depth to another is probable (depending in the lithology) and may disturb the sampling accuracy. As this design does not seem to reach the best criteria for multi-depth soil-gas sampling, it was not set up at CityChlor Pilot project Ile de France.

- Multi-level sampling in soil-gas wells with several screened intervals

A second multi-depth well design is mentioned in the literature: the soil-gas well with several screened intervals. Multi-depth sampling can be achieved thanks to a soil-gas well holding several successive and closed screened intervals.

Their design follows the European recommendations mentioned previously (see part 4.2.4). These multi-depth sampling soil-gas wells are made of a solid tube and several screened intervals threadedly assembled. The each screened interval is located in an individual sand pack. Several sealing rings are installed in order to avoid atmospheric air intrusion as well as soil gas transfer from the other sampling depth. The primary sealing ring is located at the bottom of the deeper screened tubing interval and is often named “bottom cap”. The others are located above each screened interval. It consists of a layer of clay and above it, a hydrated bentonite layer, following the recommendations mentioned previously (50 cm of thickness each is usually recommended).

Then, from the bentonite layer to the next screened interval and then to the surface, the empty annular is filled with sand. In case of shallow soil-gas well (< 1 meter deep), the empty annular is filled with hydrated bentonite from the sand pack to the surface.
It is also strongly recommended to choose the materials for tubing (casing), fittings and valves depending on the nature of the targeted compounds: for HVOCs, HDPE or nylon are usually recommended and PVC is avoided.
The shallower screened interval should be at least 50 cm bellow the ground surface. The deepest screened interval should be located more than 50 cm above the water table in order to secure the soil-gas well from the potential water table variations.

When sampling is carried out, each screened interval is separated and airproof from the other screened interval(s) thanks to a packer. It is get into the well at the correct depth depending on the sampling needs. Each sampling areas are sealed before the purge begins. Packer performance should be tested and verified thanks to sealing test sealing before sampling. After these two steps, sampling can be carried out, according to the conventional sampling techniques (see part 5).

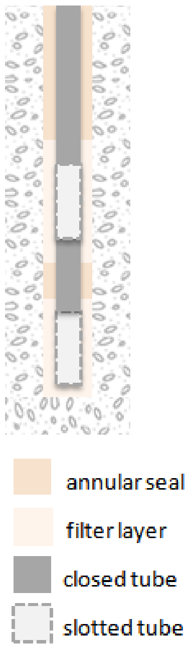


Figure 12: soil-gas well with several screened interval

This multi-level soil-gas sampling design has been set up at CityChlor Pilot project Ile de France. Then, results and recommendations are presented in the dedicated parts (see parts 6.3 and 7 respectively).

- Multi-level sampling in multi-depth nested soil-gas wells

From the literature, multi-depth sampling can be carried out in permanent multi-depth nested wells. These wells are implemented in the same borehole. The different depths of measurement (casing and filter layer) are separated thanks to a bentonite or bentonite/cement seal.

Building method is similar to the American method described previously for simple-depth soil-gas wells (see part 4.2.4). According to the Active Soil Gas Investigations Guidelines (018, 018, 020, 020), soil-gas wells are also made of a solid tube and a several screened interval threadedly assembled. Each screened interval is located in sand packs. It is strongly recommended that the sand pack thickness is more than 15 cm and the screened interval is placed midway in this sand pack. 50 cm of dry granular bentonite should be placed on the top of each sand pack. Above it, hydrated bentonite is poured into the borehole until the next sand pack and until the surface (if the deepness screened interval). It is also possible to place a cement/bentonite layer between dry and hydrated bentonite if borehole annulus sealing is a specific criteria for the study.

In case of soil-gas well deeper than 4 meters, materials should be installed with a hopper in order to avoid bringing or segregation during placement of the sand pack and bentonite seal.

Lid is also recommended for nested wells (one lid for each well) in order to support the different well casings in the borehole as well as to insure the screened intervals are placed at the desired depth. These lids should prevent cross contamination, as well as atmospheric air and water intrusion.

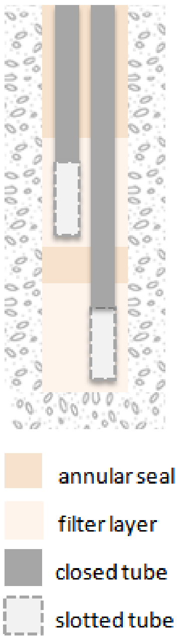


Figure 13: permanent nested soil-gas wells

This multi-level soil-gas sampling design has been set up at CityChlor Pilot project Ile de France. Then, results and recommendations are presented in the dedicated parts (see parts 6.3 and 7 respectively).

- Multi-level sampling in multi-depth non-nested soil-gas wells

Other publications mention the use of multi-depth non nested wells. It is the usual multi-depth soil-gas well used in France. Their design are very similar to multi-depth nested wells except the wells are set up in different but similar boreholes. The installation method is very similar to the methods available and recommended for the emplacement of single-depth soil-gas wells (see European and American methods decribes previously, part 4.2.4). Nevertheless, an important recommendation should be taken into account before installing them. Depending on purge and sampling flows, the different wells should be outside the influence radius of the others.

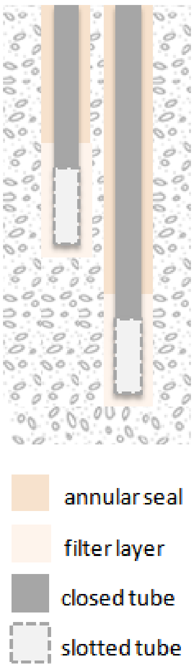


Figure 14: Multi-depth non nested soil-gas wells (different but similar boreholes)

This multi-level soil-gas sampling design has been set up at CityChlor Pilot project Ile de France. Then, results and recommendations are presented in the dedicated parts (see parts 6.3 and 7 respectively)

- Direct Push multi-level soil-gas wells

Direct Push Technologies offer a large number of solutions for multi-depth soil-gas sampling. These wells can be permanent systems mostly provided with multi-channels. These wells are implemented with exposed or protected screen and can be used with small-size pumps or build-in lost pumps.

Wells with exposed screened intervals are usually recommended for sandy soils and shallow depth sampling. Silt or clay may plug the screened intervals when the whole system is advanced into the ground. Wells are driven into the ground with little or no annular space, using a single string of rods. Then, soil collapse around the screened intervals.

Wells with protected screened intervals are usually recommended for cohesive soils (silt, clay). They can be installed according to two methods which avoid the soil to collapse the screened intervals. Either, they are placed into a protective out drive rod and the whole system is advanced into the ground. Either they are lowered into a protective outer drive rod which has been driven into the ground previously. In both cases, the protective drive rod is removed when casing and screened intervals are at the correct depth. Then, it creates an annular space around the casing and the screened interval. Filter pack and annular seal should be poured into this annular space (according Geoprobe recommendations, 026).

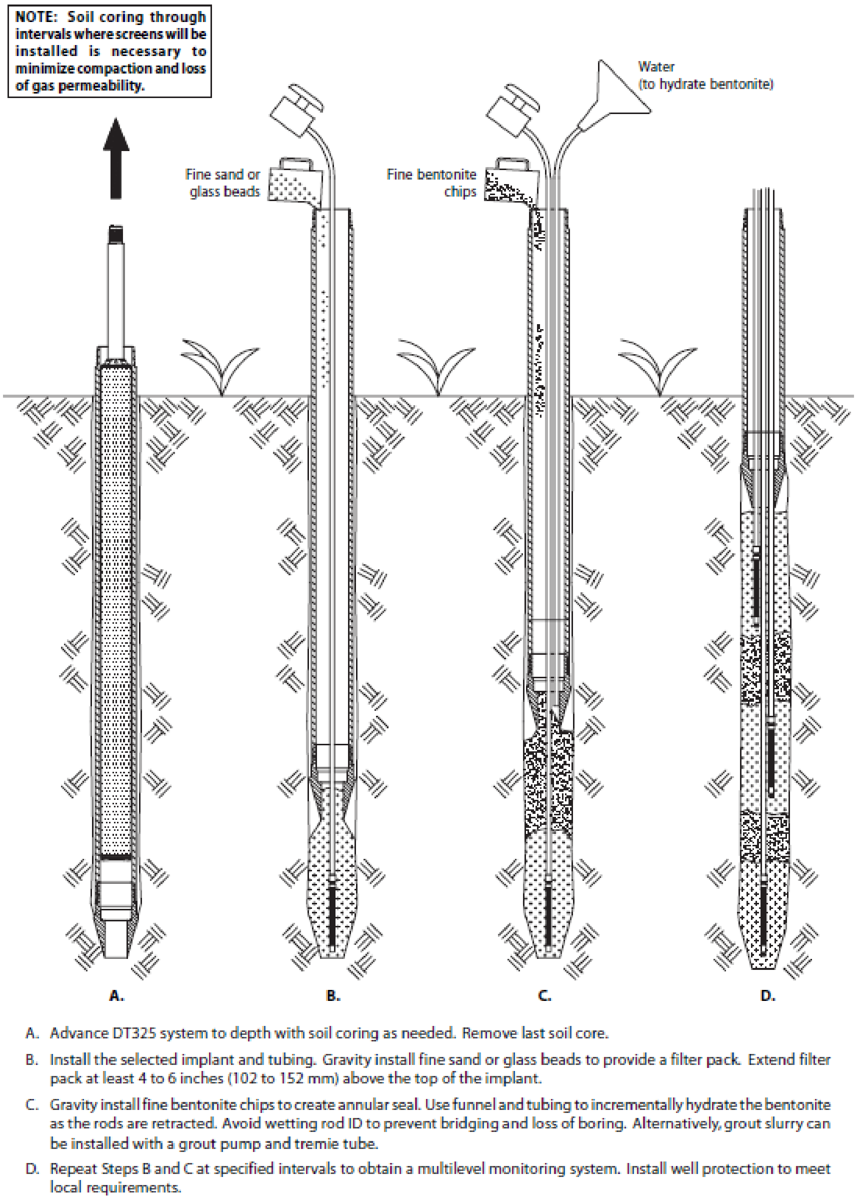


Figure 15: Direct Push Technologies for multi-depth soil-gas sampling (DT325 system), (source: Direct Push Installation of devices for Active Soil Gas Sampling and Monitoring, Geoprobe® Systems[2]

- Other multi-depth drilling wells

The different designs presented in the previous paragraphs are not an exhaustive list. For exemple, "multi-port soil-gas well" has already been tested in the frame of a American study "Monitoring of VOCS in the deep vadose zone using multi-port soil gas wells and multi-port soil gas/groundwater wells". Other sorts of multi-depth drilling holes have been designed for

[2] INERIS recommends to mix bentonite chips and water before their introduction into the annular space.

groundwater sampling and may be used for soil-gas sampling, just like “conventional well and double pump system”, “multi-packer system” or “schauchpacker”. At the moment, feedback and utilization is too limited to put forwards recommendations.

4.2.5 Precaution before soil-gas well utilization

Prior sampling, soil-gas well should go through different tests in order to value its construction and attest of its weatherproof.

First a sufficient period of time should be allowed for soil-gas system re-equilibration depending on soil characteristics (about 3 to 5 hours for sub-slab installations, 24 to 48 hours for permanent soil-gas wells).

As ambient air entertainment may have an impact upon the validity of the soil-gas sampled, it is particularly important to carry out a leakage test on soil-gas wells prior sampling.

For example, leakage may occur at the surface if soil-gas well and ground are not well sealed. Then indoor air gets into the well and induces a dilution of the targeted contaminants during sampling. As a result, soil-gas well leakage test is strongly recommended in order to confirm that indoor or ambient air does not get into the well during a sampling event (especially for shallow installations, < 0.5 meter deep). This test consists in placing a shroud over the installation and introducing a tracer gas (helium, propane, alcohol...) to allow above ground air entertainment to be detected during sampling. Then conventional sampling is carried out. Gas tracer should represent less than 10% of the whole sampled volume of gas.

Leakage might also occur above ground, due to bad sealing along the sampling train. Then, another test should be carried out. The same tracer gas is in a sample bag (known concentration). This tracer gas goes thought the whole sampling train, until the sampler. If the concentration measured using the sampler is lower than the initial concentration tracer gas leakage is occurring.

Gas emissions into the head space of a well can also be evaluated by recirculation tests.

5 State of the art of soil-gas sampling techniques

Soil-gas sampling measures the gas contained in soil interstitial spaces. A lot of techniques can be used for soil-gas sampling. Most of them do not require an excessive volume of gas. In general, the simplest devices are most often used because they can realized successive analysis quickly, which is particularly necessary in case of source and plume characterization (screening) as well as in case of sampling strategy requiring an important number of samples.
The following list brings the main techniques used on site:

- reactive tubes, more or less specific
- device using photo-ionization (photo ionization detector - PID) which is a nonspecific techniques,
- measuring device detecting infrared (IR), used in particular for the measurement of total hydrocarbons
- device using flame ionisation (flame ionization detector - FID) which is more specific than PID, and may be associated with a short separation column
- device combining these sensors in a "multigas" unit,
- photoacoustic device, which is still little used for soil-gas, but is able to discriminate the desired compounds
- device using gas chromatography which provides a precise concentration value for VOC / COHV. Among the basic detectors used, FID is usually used for BTEX and ECD for COHV,

In the frame of Citychlor Pilot project Ile de France and this specific research work dedicated to soil-gas sampling and soil-gas permanent well design for multi-depth sampling, only a few of these sampling techniques have been used. PhotoIonized Detector (PID) and sorbent tubes are the two main techniques used. Sample bags and summa-canisters® have also been implemented less often. Then, this report focuses its recommendations and explanations on these sampling techniques.
Recommendations concerning hose, pump flow and calibration, sample transport and storage are also provided for each technique.

Active sampling techniques are usually arranged in two different categories: mechanical suction techniques (using a pump) and natural suction techniques.

5.1 Mechanical suction sampling techniques

Mechanical suction techniques are all the active sampling techniques which use a calibrated mechanical pump in order to suck the gaseous compounds. The report deals with sample bags and sorbent tubes as mechanical suction techniques for soil-gas sampling.

5.1.1 Soil-gas sampling using sample bags

Sample bag is not the most used sampling technique but should be mentioned as a sampling option for soil-gas sampling. They are usually used for permanent soil-gas sampling (CO_2, NO_x...) or ambient air sampling. Nevertheless, nowadays, different sort of sample bags are available. For example, some of them are designed for VOCs:

- for low[3] VOCs: SamplePro FlexFilm Air Sample Bags, FlexFoil Plus Gas Sample Bag and FluoroFilm FEP Air Sample bags…
- for low to moderate[4] VOCs: Tedlar bags, Milar bags...
- for moderate to high[5] VOCs: Standard Flex Foil Gas Sample bags...

Several compounds (chlorinated compounds and BTEX for example) could be analyzed thanks to only one sample bag. This could be very relevant in case of complex contamination (different compound families targeted). Thus, the appropriate sampling bag should be selected depending on their properties. This sampling technique is usually not recommended in case of very low concentrations, except if important volume of gas can be sampled (more than 5 litres). It can be used with both types of soil-gas installation (rods methods or permanent wells) as well as surface flux chamber.

Sampler bag requires a pump to pull the vapours from the soil through the sampling installation (see pump recommendations 5.3) as well as an inert hose (see recommendations for tubing 5.3) to linked the sampler from its valve or septum (PEHD, stainless steel or polypropylene) to the pump which is connected to the soil gas well. The use of lung sampler could also be considered for better quality measurement, especially in the frame of contaminated sites. The sample bag should not be filled more than 2/3 full. The sample bag size can be adjusted depending on the volume of gas necessary for the analysis. Volumes from some millilitres to several dozen litres are available. Then, depending on soil characteristics, soil-gas installation designs and the targeted quantification limits, sampling duration and pumping flow are determined.
After sampling, the sample bags should be stored out of sunlight, at room temperature.
The analysis should be done within 28 hours (for sulphur and active chemically compounds...) to 48 hours (for chlorinated solvents, aromatic compounds...) after sampling. The sample is usually

[3] in term of molecular weight
[4] in term of molecular weight

made by GC-MS with direct injection. Gas is collected by pumping the sample bag to an adsorbent tube, which is then analyzed by thermal desorption or gas chromatography or flame ionization detector (for BTEX).

The limits of quantification are included, depending on the compound and the volume of the bag, between 0.3 and 2 µg/m3. An appropriate standard scale is needed, depending on the level of contamination.

Various analytical methods have been established by different institutions. EPA TO-14A, TO-15, ASTM D5466, OSHA PV2120, NIOSH protocol are the most known methods.

Figure 16: Tedlar® sample bags *(source: INERIS)*

5.1.2 Soil-gas sampling using sorbent tubes

Sorbent tube is the most used sampling technique for soil-gas sampling, whatever the soil-gas installation. The implementation of these tubes is usually carried out for ambient air sampling. That is why the CityChlor report dedicated to ambient air sampling also presents this sampling technique. It can be used for a large number of compounds (C3 to C30) as the sorbent is adapted depending on the targeted molecules. The main materials used for COHV include (INERIS, 2010):

- Carboxen (carbon support),
- Tenax TA (resin-based polymers),
- mixtures of adsorbent: Carbopack C and B, Carbosieve SIII (Air Toxic, CT300 ...),
- the Carbosieve SIII, Carboxen 1000, Carbosphere (media type carbon molecular sieve ...),
- the Carbopack B, Carbopack X, B Carbotrap, Carbograph 4 or 5 (media type graphite carbon),
- activated charcoal.

[5] in term of molecular weight

Using a pump, gaseous compounds are drawn through the tube, containing one or several absorbent beds. The adsorbent depends on the targeted compounds. The sorbent tube is linked to the pump which is linked to the soil gas well, with an inert hose. Recommendations for pump calibration and hose are detailed in the dedicated part (see part 5.3). This active sampling method provides an integrative concentration over the whole sampling period. It is strongly recommended to use tubes containing a trap guard. Its analysis will confirm that all compounds were trapped and tube is not saturated.

Soil-gas volume, pump flow and sampling duration must be adapted depending on the level of contamination, the adsorption capacity of the sorbent as well as the targeted limit of quantification (about 1 $mg.m^{-3}$). Sampling duration, pump flow, pressure, temperature should be well-mastered during the sampling event for better calculation and interpretation. Indeed, temperature and pressure may influence the volume of gas sampled. Then, if these two parameters are monitored, recalculation could be considered to provide results under normal conditions. The volume of soil-gas sampled varies from 0.1 litre to 10 or so litres, depending on the contamination level of the site and the quantification limits targeted for analysis. Usually, sampling duration varies from 15 min to 8 hours for soil-gas sampling. Also, sampling flow varies from 1 $mL.min^{-1}$ to 250 $mL.min^{-1}$. Maximal sampling flow for sorbent tubes is around 150 $mL.min^{-1}$ if their diameter is 3 mm and 250 $mL.min^{-1}$ if their diameter is 4 mm.

The presence of a large range of contaminants could disturb the adsorption of the targeted compounds, due to competition phenomenon. It is also important to notice that humidity may reduce the adsorption rate of contaminants. The utilization of specific trap upstream the adsorbent bed is strongly recommended in these cases.

Figure 17: soil-gas sampling with sorbent tubes, CityChlor Pilot project Ile de France (source: INERIS)

Once the sampling period ends, tubes should be storage in cold (< 4°C) and dark environment until their analysis.

The analysis is carried out in a specific laboratory. First, trapped compounds are extracted by thermal desorption or chemical desorption and then quantified by GC-MS. Various analytical methods have been established for sorbent tubes analysis: EPA TO-17, ASTM D6196, ISO 16017, ISO 16000-6 or NIOSH 2549. They are internationally admitted and validated. Depending on the mass of the compound extracted from the sorbent tubes, the sampling flow and the sampling duration, concentration can be calculated.

This sampling technique is easy to implement but sampling duration and sorbent choice might sometimes be complex. Tubes are easily transported and stored. A large number of compounds can be targeted with this method as the adsorbent is chosen depending on the pollution type.
Nevertheless, humidity met in soil-gas wells may be an important inconvenient if the sorbent is hygroscopic.

5.2 Natural suction sampling techniques

Natural suction sampling technique deals with a natural suction process that is to say, without mechanical pump. The main sampling technique known and used is Summa-Canister®, which is presented in the following part.

5.2.1 Soil-gas sampling using Summa-Canister®

Summa-Canister® is a stainless steel container which the internal surfaces have been treated (summa process) to avoid adsorption of compounds. This process combines an electropolishing step with a chemical deactivation step to produce a surface that is nearly chemically inert. Summa-Canister® volume is usually around 1 to 6 litres. But smaller canisters have also been developed for specific applications, just like soil-gas sampling or in case of high concentrations. The volume of these smaller devices is about 0.4 to 1 litre.

The use of summa-canister® is particularly helpful when extreme concentrations are met (both high and low concentrations). Indeed, this technique is able to eliminate analytical limits related to very high or very low concentrations, encountered with the previous analytical tools.
Nevertheless, concerning soil-gas sampling, the use of summa-canister® is relevant even if soils are enough permeable to not cause a too high depressure phenomenon. In case of too less permeable soil, another sampling technique should be considered just like sorbent tubes or sampling bags.

Before each sampling measurement, speaker reusable is cleansed (dilution, heat and high vacuum combination) and white level is checked. Then, the canister is evacuated just before it is sent to the field. The valve is opened at the beginning of the sampling event and the gas enter into the canister spontaneously (because of the difference of pressure between the container and room atmosphere). This valve can be equipped with a flow controller (veriflow ®) for filling in a targeted flow rate. Filling the canisters is controlled by the pressure gauge fitted them. Usually, sampling duration is around 1 to 24 hours, depending on the sampling flow and the device volume. The US EPA recommends a maximal suction flow around 200 $mL.min^{-1}$. Programmable solenoid valves have also been developed to sample soil gas at specific periods and for a period of time well-mastered. When sampling ends, the valve is closed and the whole system is sent to the analytical laboratory. Storage and transport should be carried out at room temperature. Canisters are bulky and heavy devices which may create problems or difficulties of conveyance. Field blank is highly recommended, especially in case of low concentrations.

Returned to the laboratory, the sample should be analysed as soon as possible, usually by GC-MS with direct injection. Gas is collected by pumping the canister to an adsorbent tube, which is then analyzed by thermal desorption or gas chromatography or flame ionization detector (for BTEX).

This method allows several analysis on the same sample of air: vinyl chloride, BTEX: benzene, toluene, ethylbenzene, xylenes, and trichlorethylene and tetrachlorethylene. The limits of quantification are included, depending on the compound, between 0.3 and 2 μg/m3. An appropriate standard scale is needed, depending on the level of contamination.

Various analytical methods have been established by different institutions. EPA TO-14A, TO-15, ASTM D5466, OSHA PV2120, NIOSH protocol are the most known methods.

Figure 18: Summa-Canister (6 L, suction rod and veriflow system) ***(source: INERIS)***

This technique is easy to implement and not breakable. Nevertheless it may be sometimes difficult to transport and store canisters because of their size and weight. Compared to sorbent tubes, longer period of exposure are reached and this technique do not need pump (more “autonomous”). But summa-canister® seems to be more sensitive to humidity which could create some problems with soil-gas sampling as wells are very often characterized by high humidity level.

5.3 General sampling recommendations

Prior to sampling, the soil-gas installation should be purged. Two purging strategies can be considered. The first one is based on the volume of gas pumped. Indeed, the volume of soil-gas extracted by pumping from the soil-gas well has to match 3 to 5 times. The second strategy is based on the stabilization of monitored parameters. An on-line tracking method is used in order to measure different parameters like temperature, humidity and mainly contaminants concentration (PID monitoring). The purge should continue until the soil-gas well conditions are stable. Purging a soil gas well using a PID whose pump has been calibrated seems to be an appropriate system which combines both purging strategies.

Depending on the objectives of the investigations and site specific constraints, several sampling techniques can be considered. Choice should be managed according to the targeted substances, the different levels of contamination depending on the compounds and the appropriate limit of quantification required for each of them. Once collected, samples have to be labelled. Date and time for the beginning and the end of the sampling period should be noticed as well as sampling duration and sampling location. A PID measurement is also recommended when the sampling ends in order to compare de values measured at the end of the purge and at the end of the sampling period.

In case of active sampling, pumping system, even mechanical or natural suction, has to be calibrated and checked, shortly before (no more than some days before), during and after each investigation.

If the sampling technique requires the utilization of hose, it should be an inert material towards the contaminants. Usually, the use of hose made of Teflon® is recommended. This hose has to be transport and stored in safe environment (without contamination) and has to be considered for single-use only.

Samplers have to be stored and transport in appropriate conditions: in most cases, in dark and cold (< 4°C) environment. Analysis should also be carried out according to the recommendations provided by the supplier and the laboratory.

In order to provide a better results and data interpretations, trip blank and field blank are strongly recommended. Finally, for each site, several investigations should be carried out in order to value the variations due to the weather (seasonal investigations).

5.4 Additional measurements recommended for better data interpretation

Meteorological conditions have an important impact on contaminants transfer from the saturated zone to the ambient air. Then, it is strongly recommended to monitor pressure (soil-gas, indoor as well as barometric pressure), temperature (indoor and outdoor buildings), wind speed and rainfall during the whole sampling campaign, even some few days before and after. The use of weather station seems to be an appropriate way to reach this information which would be beneficial for data interpretations.

The water-table depth variations depending on the season and the rainfalls may also have an impact on soil-gas transfer. Then, it is recommended to measure the water table depth in the groundwater well implemented at close areas for each soil-gas well location.
Finally, it is strongly recommended to avoid soil-gas sampling campaigns in case of rain events, frost and snow when soil-gas installations are outdoor.

Humidity and temperature inside the soil-gas well installations are also relevant parameters. Their measurements are recommended at least at the beginning and at the end of each investigation. Monitoring well pressure is also strongly recommended (atmospheric pressure and static borehole pressure).

Moreover, in case of soil-gas well screened interval closed to the water-table and which may be impacted by the water table variations, the operator should verify the absence of water downhole.

6 CityChlor Pilot project Ile de France: multi-depth soil-gas sampling

6.1 CityChlor Pilot project Ile de France

This pilot project was an in-service facility located near Paris, France in an urban area. The site area was 6 700 m2. Industrial activities started around 1926 and today the main activity is the production of door locks, metal fittings and their surface coatings. An aerial view of the site is presented in Figure 19. On site, soils were composed of 50 cm to 1 m of embankments, then about 3 m of clay/sandy-clay and finally fine sand to 10 m deep. The alluvial aquifer was studied during the project: on site, the mean depth of the water table was 1.5 to 2 m below the ground surface and the groundwater was about 10 m deep. The groundwater flow direction was monitored during the project and two main flow directions were identified: from north to south (during high water periods, direction n°1, see Figure 19) and from east to west (during low water periods, direction n°2, see Figure 19).

Figure 19: CityChlor Pilot Project Ile de France *(source: INERIS)*

Different painting, electroplating, polishing and assembly shops succeed each other at various locations during its business activity. perchloroethylene (PCE) and trichloroethylene (TCE) were used and are still used, that is why soils and groundwater are polluted with chlorinated solvents (perchloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE) and VC, source zones identified with red dots in Figure 19).

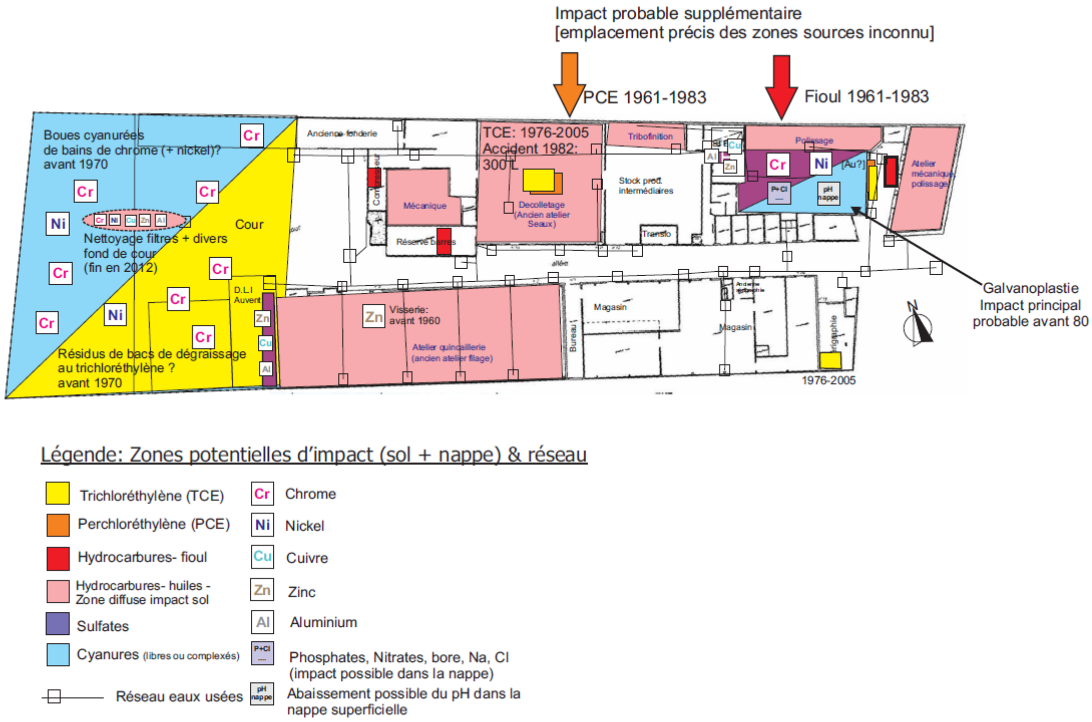


Figure 20: shop historical locations of CityChlor Pilot project Ile de France

In 2006, because the electroplating shop came to an end, a diagnosis of soil and groundwater quality assessment was carried out (2007). These investigations have demonstrated that the activities have an impact on soil and groundwater quality. Then, a management plant had been created in 2010. Finely, it suggested natural attenuation as a measure of pollution management. However, because of the current French regulation about natural attenuation, the authorities required biannual monitoring of groundwater on site and off site, since 2011.

CityChlor Pilot project Ile de France presentation and the whole tests and measurements carried out at this pilot site are detailed in the Pilot project Ile de France report.

6.2 Soil-gas well designs set up at CityChlor Pilot project Ile de France

Three different designs of soil-gas wells have been implemented at CityChlor Pilot project Ile de France:

- **design 1**: one soil-gas well with two screened intervals (at 0.4-0.7 and 1-1.3 meters deep); the two screened interval are separated thanks to a packer (airproof),
- **design 2**: two soil-gas wells installed in the same borehole (screened intervals at 0.4-0.7 and 1-1.3 meters deep respectively),

- **design 3**: two soil-gas wells installed in two different but similar boreholes (screened intervals at 0.4-0.7 and 1-1.3 meters deep respectively).

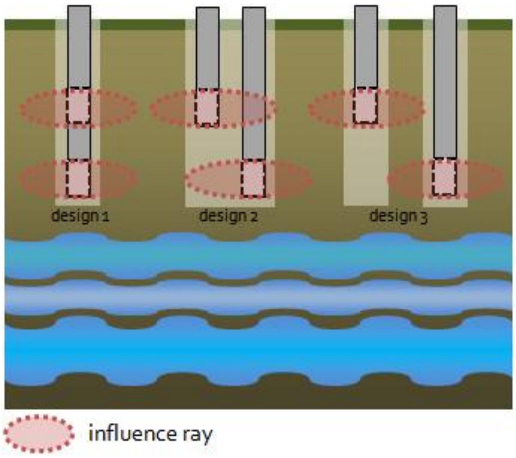


Figure 21: multi-depth soil-gas well designs implemented at CityChlor Pilot project Ile de France *(source: INERIS)*

All of them have been set up regarding the recommendations mentioned previously (see part 4.2.4). They were set up closely in order to achieve the various sampling and tests in the same conditions. They are also far enough to be out of their influence radius. For each soil gas well, its influence ray was calculated thanks to the formula bellow.

$$r_{influence} = \sqrt{\frac{V_{sampled} - V_{soil-gas\,well} + \pi\, r_{soil-gas\,well}^{\;2}\, h}{\epsilon\, \pi\, h}}$$

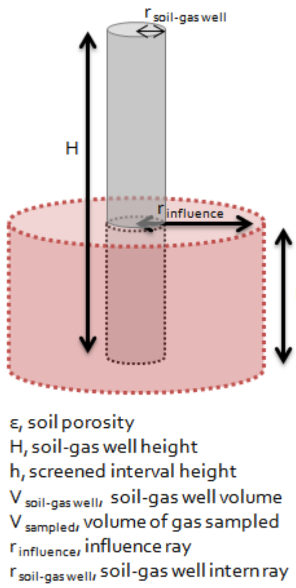


Figure 22: influence radius of soil-gas wells during purge and sampling *(source: INERIS)*

For better understanding in the next paragraphs, the three designs are named design 1, design 2 and design 3 respectively.

The main objectives of this study are carrying multi-depth sampling using different soil-gas wells designs and then gain knowledge and feedback about their performances and limits.

Designs 1, 2 and 3 have been set up closely at different locations at the pilot site. These locations have been chosen in order to encounter different ranges of concentration of chlorinated solvents and different lithology profiles (see Figure 23).

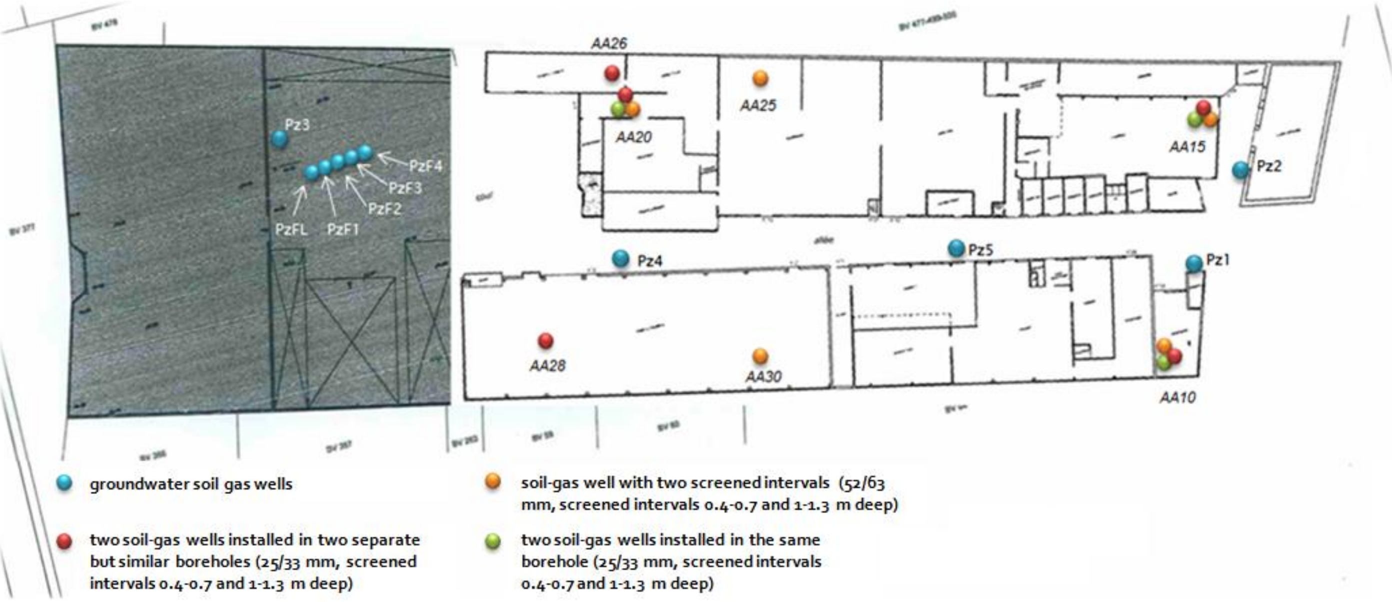


Figure 23: soil-gas well locations at CityChlor Pilot project Ile de France *(source: INERIS)*

6.3 Tests carried out and results

From the beginning of CityChlor project, seven sampling campaign have been carried out. Different analytical techniques have been used for soil-gas sampling: adsorbent tubes (active charcoal), summa-canister®, Tedlar® bags ... Thanks to the results obtained, it is possible to show some limits of these methods and thus provide recommendations.

Some other tests have been carried out on each design of soil-gas well (1, 2 and 3) in order to value their performances and differences in term of measurement.

6.3.1 Soil-gas sampling techniques

These seven sampling campaigns provided a large number of data as well as a better feedback from the sampling tools that have been tested.

Finally, soil gas sampling using sorbent tubes (with active charcoal) is the sampling method that has been mostly used (5 campaigns in all). The following table presents the concentration ranges in Cis-dichloroethylene (cis-DCE), Trans-dichloroethylene (trans-DCE), perchloroethylene (PCE) and trichloroethylene (TCE) measured in each soil gas well, using sorbent tubes during the three last campaigns (March, April and June 2012).

		soil-gas well design	screened interval depth (m)	Cis-DCE maximal concentration (mg.m^{-3})	Cis-DCE minimal concentration (mg.m^{-3})	Trans-DCE maximal concentration (mg.m^{-3})	Trans-DCE minimal concentration (mg.m^{-3})	PCE maximal concentration (mg.m^{-3})	PCE minimal concentration (mg.m^{-3})	TCE maximal concentration (mg.m^{-3})	TCE minimal concentration (mg.m^{-3})
AA10	pza10-H	soil-gas well with two screened intervals	0.40 - 0.70	5.23	LQ (0.06)	LQ (0.58)	LQ (0.58)	1.52	0.52	113.26	2.62
	pza10-B	(design A)	1.00 - 1.30	-	-	-	-	-	-	-	-
	pza11	two soil-gas wells installed in the same	1.00 - 1.30	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.75	0.38	0.35	0.11
	pza12	borehole (design B)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.98	0.26	0..68	0.67
	pza13	two soil gas wells installed in two different	1.00 - 1.30	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.53	0.53	0.47	0.47
	pza14	but similar boreholes (design C)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.5	0.5	1.6	1.6
AA15	pza15-H	soil-gas well with two screened intervals	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	30.1	27.61	2.97	2.86
	pza15-B	(design A)	1.00 - 1.30	0.24	LQ (0.06)	LQ (0.63)	LQ (0.63)	41.14	24.82	5.45	1.49
	pza16	two soil-gas wells installed in the same	1.00 - 1.30	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	17.86	6.64	1.3	0.24
	pza17	borehole (design B)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	8.09	7.89	2.37	1
	pza18	two soil gas wells installed in two different	1.00 - 1.30	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	62.61	20.78	1.81	0.55
	pza19	but similar boreholes (design C)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	29.4	1.57	5.69	0.89
AA20	pza20-H	soil-gas well with two screened intervals	0.40 - 0.70	353.6	244.82	LQ (0.63)	LQ (0.63)	1.137	1.04	1439.8	836.5
	pza20-B	(design A)	1.00 - 1.30	944.5	LQ (0.06)	LQ (0.63)	LQ (0.63)	16.03	1.05	2155.92	LQ (0.025)
	pza21	two soil-gas wells installed in the same	1.00 - 1.30	262.37	403.22	0.64	LQ (0.63)	1.92	0.96	1764.09	1215.84
	pza22	borehole (design B)	0.40 - 0.70	32.91	24.81	LQ (0.63)	LQ (0.63)	1.03	0.51	253.18	251.35
	pza23	two soil gas wells installed in two different	1.00 - 1.30	8153.15	445.53	2.28	LQ (0.63)	3.91	0.29	37504.48	1822.16
	pza24	but similar boreholes (design C)	0.40 - 0.70	44.44	28.59	LQ (0.63)	LQ (0.63)	1.245	0.4	296.32	218.27
AA25	pza25-H	soil-gas well with two screened intervals	0.40 - 0.70	1.06	0.24	LQ (0.63)	LQ (0.63)	94.64	79.15	39.58	11.44
	pza25-B	(design A)	1.00 - 1.30	-	-	-	-	-	-	-	-
AA26	pza26	two soil gas wells installed in two different	1.00 - 1.30	15.04	8.82	LQ (0.63)	LQ (0.63)	1.408	0.42	13.118	3.88
	pza27	but similar boreholes (design C)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	1.211	0.48	1.72	0.48
AA28	pza28	two soil gas wells installed in two different	1.00 - 1.30	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.71	LQ (0.03)	LQ (0.03)	LQ (0.03)
	pza29	but similar boreholes (design C)	0.40 - 0.70	LQ (0.06)	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.62	0.25	LQ (0.03)	LQ (0.03)
AA30	pza30-H	soil-gas well with two screened intervals	0.40 - 0.70	0.55	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.81	0.49	20.94	0.19
	pza30-B	(design A)	1.00 - 1.30	4.9	LQ (0.06)	LQ (0.63)	LQ (0.63)	0.95	0.67	33.66	0.13

Figure 24: concentration ranges measured in each soil-gas well, using sorbent tubes (active charcoal)

Thanks to these results, maps were drawn for the main contaminants (perchloroethylene (PCE), trichloroethylene (TCE), Cis-dichloroethylene (cis-DCE)) for each campaign. These maps give a better view of the substances layout depending on depth measurement (screened intervals at 0.4 – 0.7 and 1.0-1.3 meters deep), sampling location and season.

Concentrations measured during the other campaigns (using sorbent tubes with active charcoal as well) are always of the same order of magnitude, whatever the contamination level (see Figure 25).

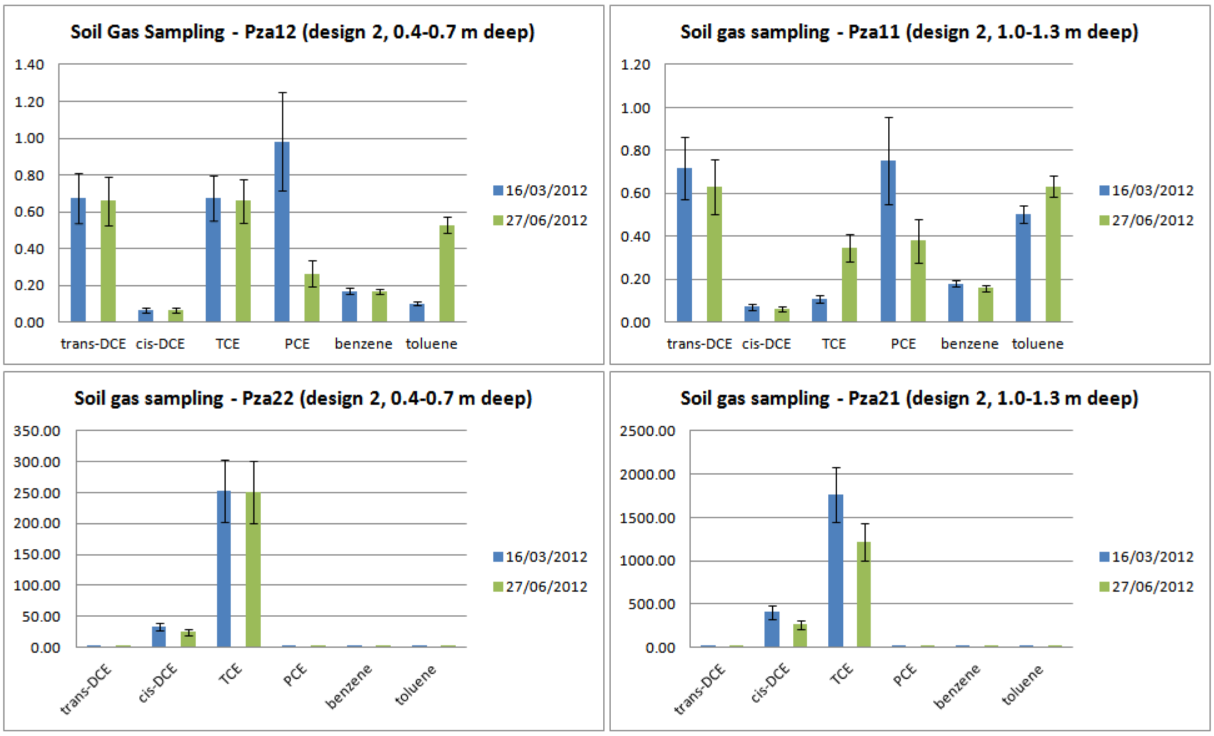


Figure 25: soil-gas concentrations measured at two different periods (mg/m^3), using sorbent tubes (active charcoal)

Then, maps have the same look and the most contaminated area (AA20, see Figure 21) is the same whatever the period of sampling even meteorological parameters (temperature, atmospheric pressure) were quite different (winter and summer conditions respectively). The following maps show trichloroethylene (TCE) and perchloroethylene (PCE) results obtained thanks to design 3 soil-gas wells, in June 2012, for the intervals 0.4-0.7 meters deep and 1.0-1.3 meters deep.

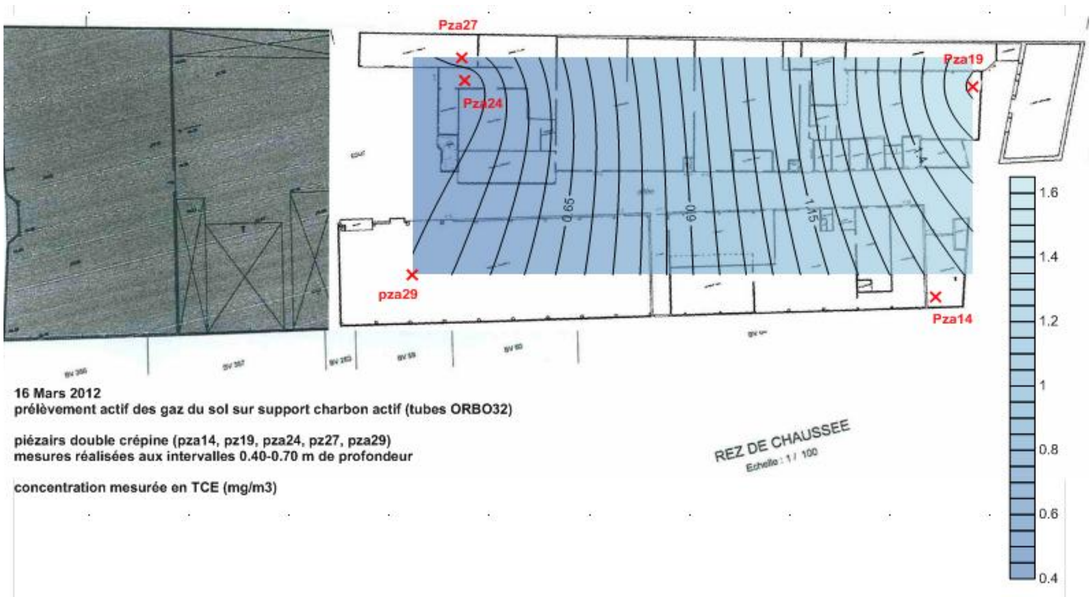


Figure 26: trichloroethylene (TCE) contamination 16th March 2012, soil-gas wells in two different but similar boreholes (design 3), 0.4-0.7 meters deep

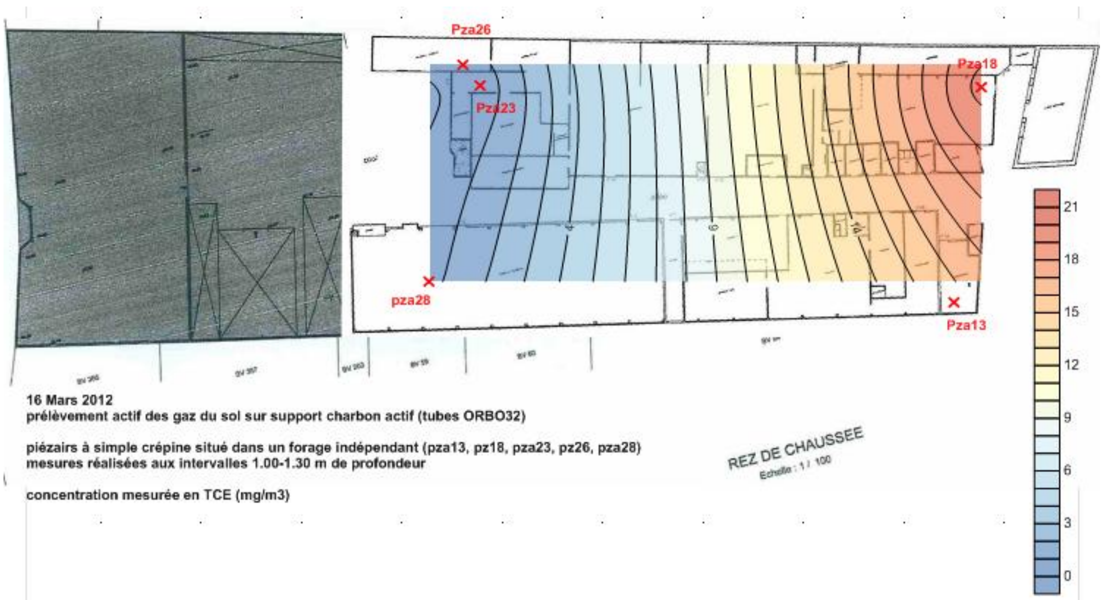


Figure 27: trichloroethylene (TCE) contamination 16th March 2012, soil-gas wells in two different but similar boreholes (design 3), 1.0-1.3 meters deep

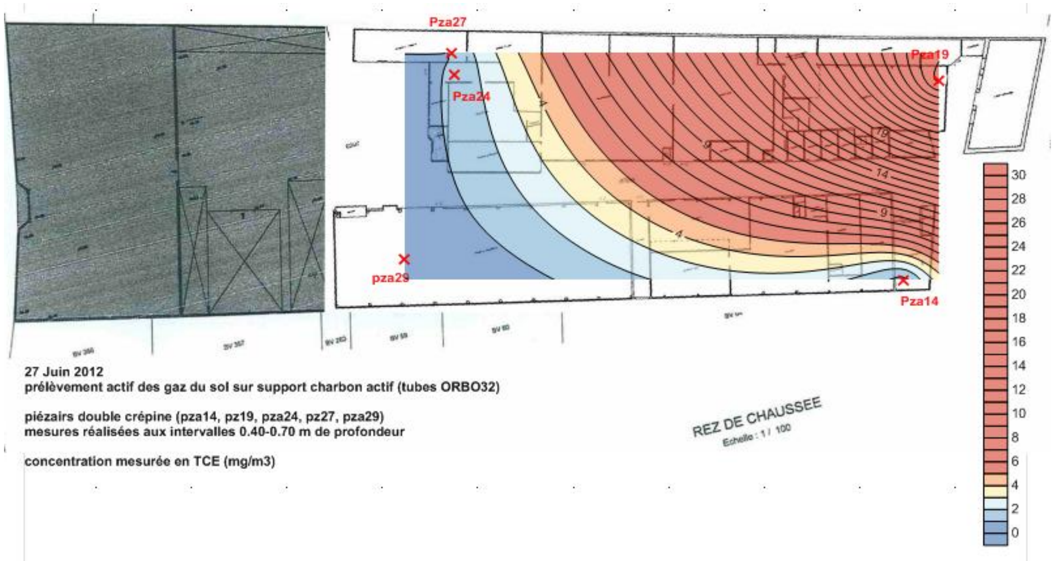


Figure 28: trichloroethylene (TCE) contamination <u>27th June 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 0.4-0.7 meters deep

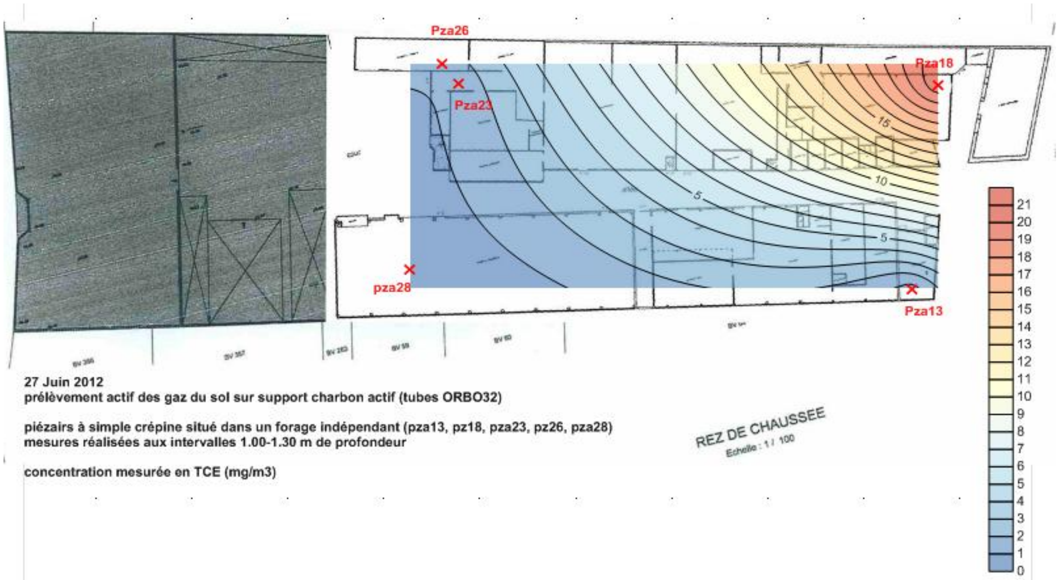


Figure 29: trichloroethylene (TCE) contamination <u>27th June 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 1.0-1.3 meters deep

Concerning trichloroethylene (TCE), concentrations are of the same order of magnitude for the screened interval at 1.00-1.30 meters deep. The highest concentration measured at this depth is around 20 $mg.m^{-3}$ (AA15, see Figure 21). At 0.4-0.7 meter deep interval, concentrations are also very similar except at the trichloroethylene (TCE) highest contaminated zone (Pza 19, AA15, see Figure 21). This variation may be due to the trichloroethylene (TCE) storage vat located close to the soil-gas wells. This container is non-buried into the ground. These results reveal potential leakages from this container to the soil (historical or current leakages).

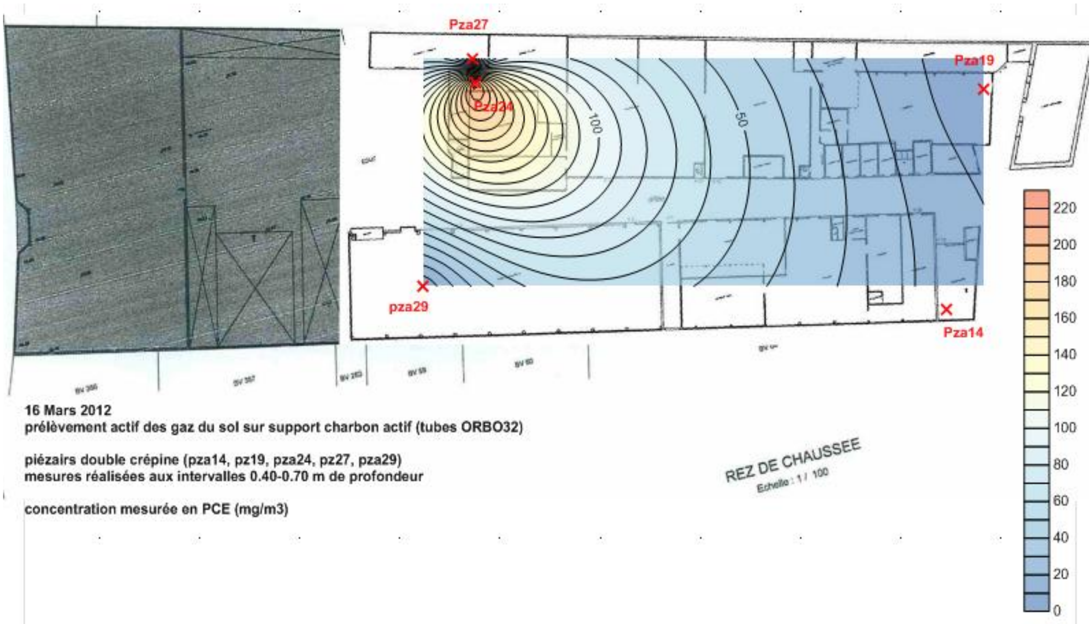


Figure 30: perchloroethylene (PCE) contamination <u>16th March 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 0.4-0.7 meters deep

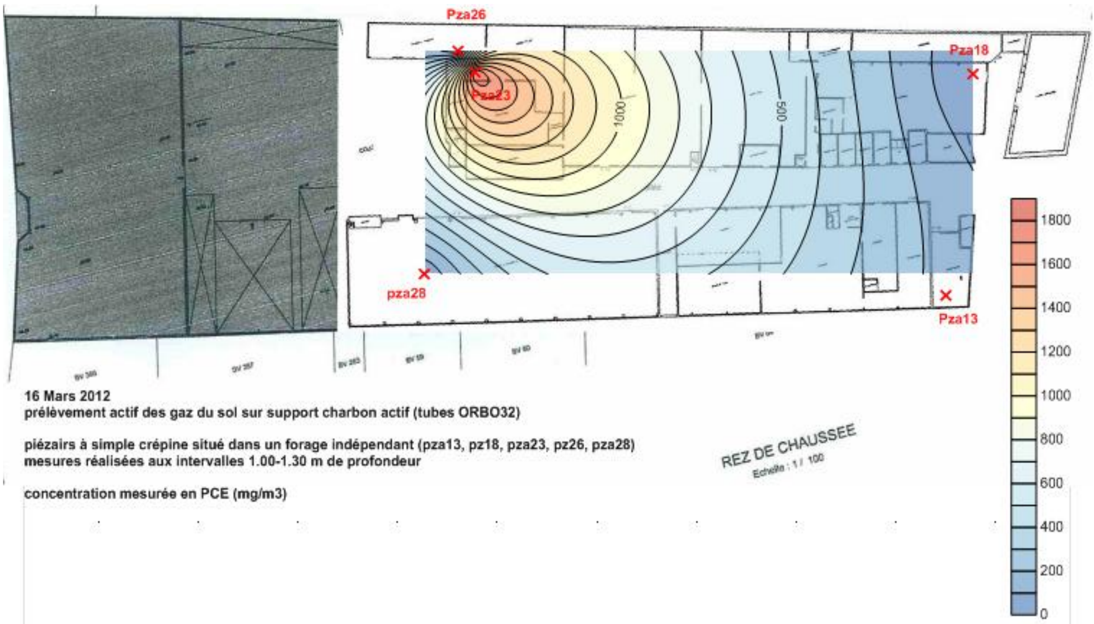


Figure 31: perchloroethylene (PCE) contamination <u>16th March 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 1.0-1.3 meters deep

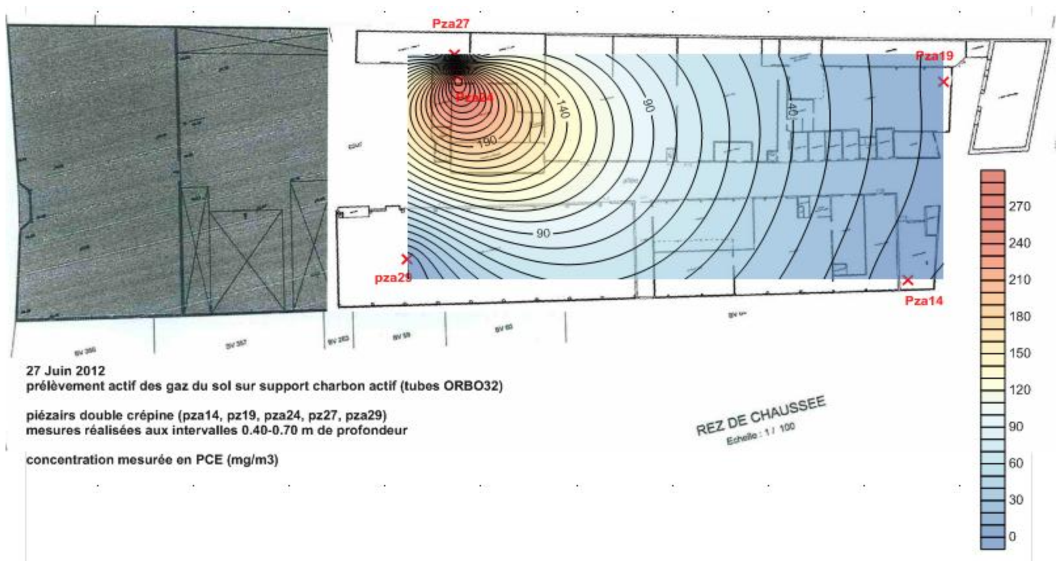


Figure 32: perchloroethylene (PCE) contamination <u>27th June 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 0.4-0.7 meters deep

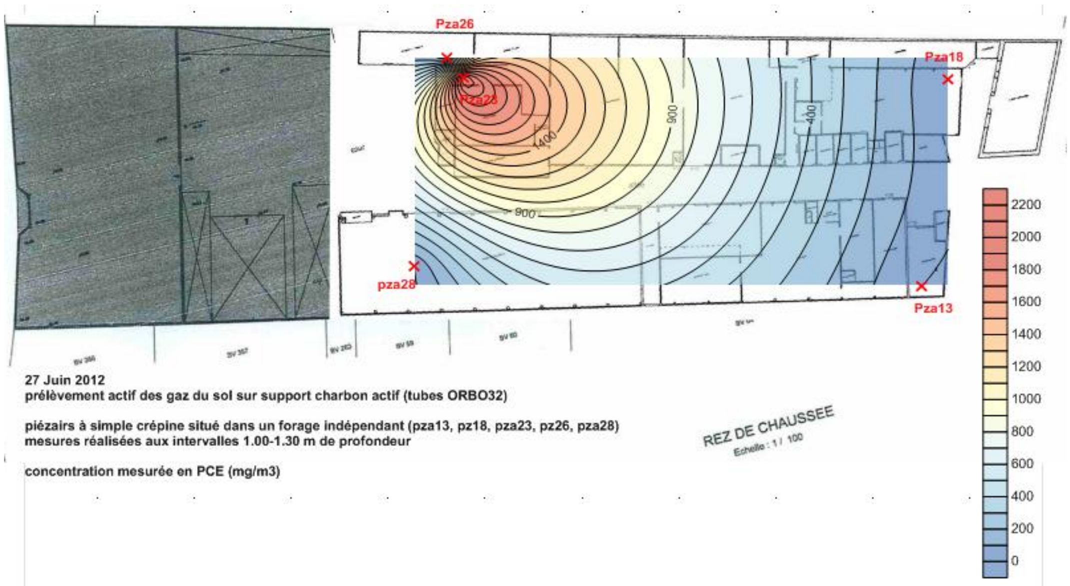


Figure 33: perchloroethylene (PCE) contamination <u>27th June 2012</u>, soil-gas wells in two different but similar boreholes (design 3), 1.0-1.3 meters deep

Concerning perchloroethylene (PCE), whatever the period of sampling the highest contaminated zone is the same (AA20, see Figure 21). At 1.0 meter deep, perchloroethylene (PCE) concentration is around 2000 $mg.m^{-3}$. At 0.4-0.7 meter deep, perchloroethylene (PCE) concentrations are around 250 $mg.m^{-3}$.

These results confirm the existence of two pollution sources of perchloroethylene (PCE) and trichloroethylene (TCE) respectively. Perchloroethylene (PCE) source is located close to the AA20 area (see Figure 21). Perchloroethylene (PCE) concentration is around 2000 $mg.m^{-3}$ at 1 meter deep. Perchloroethylene (PCE) transfers from deeper zone to ambient air since perchloroethylene (PCE) concentration is around 250 $mg.m^{-3}$ at 0.4-0.7 meter deep. Trichloroethylene (TCE) is located close to the AA15 area (see Figure 21).

The concentration ranges encountered are quite extensive: from the quantitative limit (0.03 $mg.m^{-3}$) to 2000 $mg.m^{-3}$ for perchloroethylene (PCE), from the quantitative limit (0.03 $mg.m^{-3}$) to 30 $mg.m^{-3}$ for trichloroethylene (TCE), from the limit of quantification (0.06 $mg.m^{-3}$) to 350 $mg.m^{-3}$ for cis-dichloroethylene (cis-DCE). Some traces of trans-dichloroethylene (trans-DCE) have also been detected.

The detection and quantification of cis and trans-dichlororethylene (cis-DCE, trans-DCE), which are not used as crude solvents in this factory, show the natural degradation of perchloroethylene (PCE) and trichloroethylene (TCE) respectively.

6.3.2 Multi-depth soil-gas sampling

Several sorts of soil-gas measurements have been carried out using the three soil-gas well designs described previously. Protocols are detailed in the Pilot project Ile de France report. In this section are presented the most important results and tendencies in order to better explain the recommendations as regards multi-level soil-gas sampling.

- **Soil-gas sampling with sorbent tubes**

Soil-gas sampling with sorbent tubes (active charcoal) have been carried out in all the soil-gas wells, whatever their design. From these results, maps have been drawn depending on sampling depth (intervals 0.4-0.7 meters deep and 1.0-1.3 meters deep are distinguished) and soil gas well design.

The three maps below present the results obtained for perchloroethylene (PCE) in June 2012, for each design presented previously (design 1, design 2, design, 3; see 6.2).

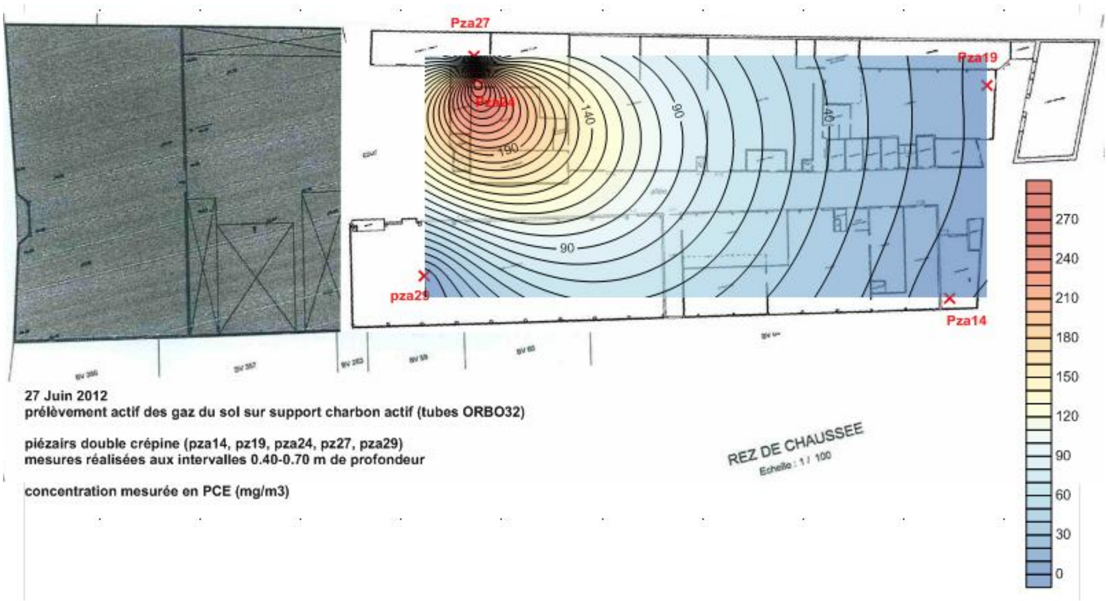


Figure 34: perchloroethylene (PCE) contamination 27th June 2012, soil-gas wells in two different but similar boreholes (design 3), 0.4-0.7 meters deep

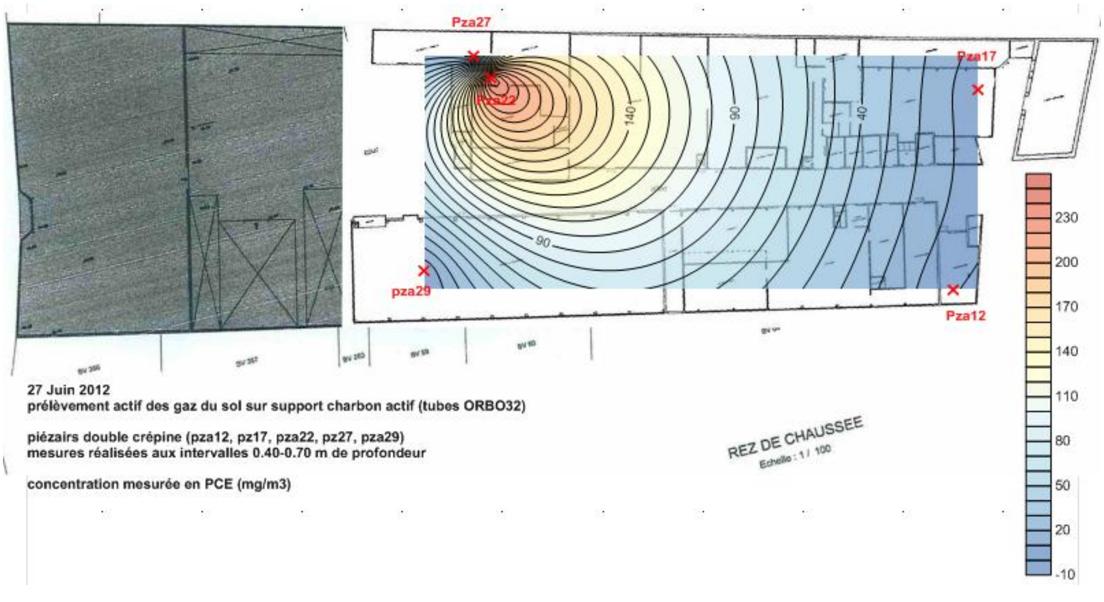


Figure 35: perchloroethylene (PCE) contamination 27th June 2012, soil-gas wells in the same borehole (design 2), 0.4-0.7 meters deep

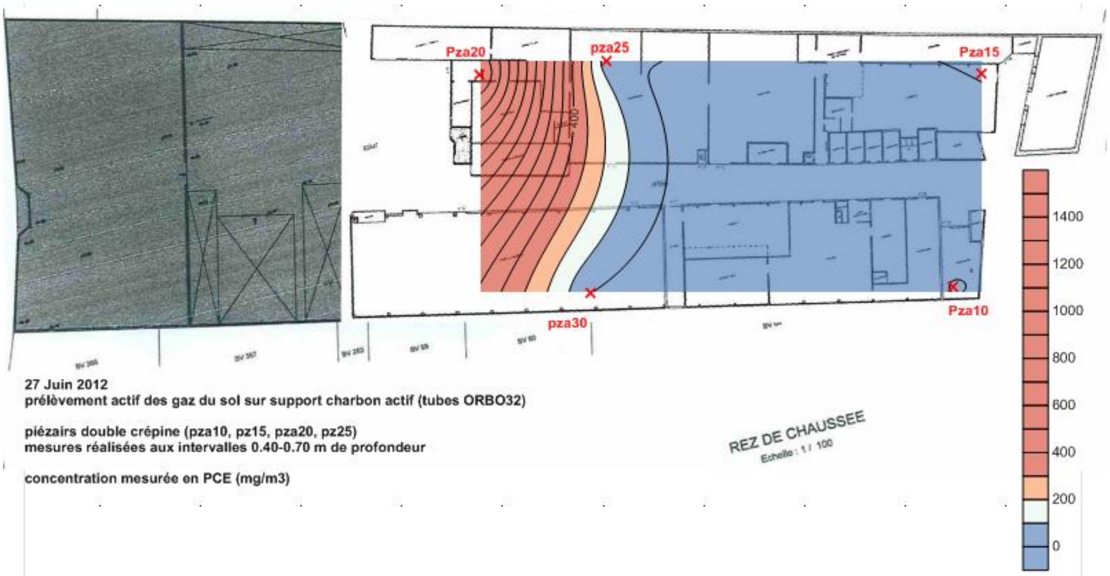


Figure 36: perchloroethylene (PCE) contamination27th June 2012, soil-gas wells with two screened intervals (design 1), 0.4-0.7 meters deep

Figure 34 and Figure 35 present perchloroethylene (PCE) results obtained in June 2012 (screened interval 0.40-0.70 m deep). Perchloroethylene (PCE) concentrations measured in soil-gas well are very similar in term of concentration range. Design 2 and design 3 soil-gas wells are all set up at the same location (AA10, AA15, AA20, AA26, AA28; see Figure 21). Then design 2 and design 3 maps are very similar. According to these maps, it seems design 2 and 3 give comparable results. This record is confirmed by the other campaigns, not only with perchloroethylene (PCE) but also with cis-dichloroethylene (cis-DCE), trans-dichloroethylene (trans-DCE) and trichloroethylene (TCE) results at the two different sampling depths (screened interval at 0.4-0.7 meters deep and 1.3-1.3 meters deep).

Figure 36 presents perchloroethylene (PCE) results obtained in June 2012 in soil-gas wells with design 1 (screened interval 0.40-0.70 m deep). This map is not as similar as Figure 34 and Figure 35. The record is due to design 1 soil-gas wells location. Design 1 soil-gas wells were set up at AA10, AA15, AA20, AA25, AA30. Then, only three sampling areas are common to design 1, design 2 and design 3. In term of concentrations, perchloroethylene (PCE) contamination measured in design1 soil-gas wells and in design 2 and design 3 soil-gas wells are of the same order of magnitude at AA15 and AA10 (see Figure 21) but much higher at AA20 (about 1500 $mg.m^{-3}$ measured in design1 and about 250 $mg.m^{-3}$ in design 2 and 3). Then, it seems design 1 is linked to an increase of perchloroethylene (PCE) concentration.

This record is confirmed by Figure 37, Figure 38 and Figure 39. Except for perchloroethylene (PCE) concentration at AA15 and trichloroethylene (TCE) concentration at AA20 in June 2012, the concentration measured in the design 1 soil-gas well (screened interval 0.40-0.70 m deep), is always the highest, whatever the compound (Cis-dichloroethylene (cis-DCE), trichloroethylene (TCE), perchloroethylene (PCE)...) and the concentration range.

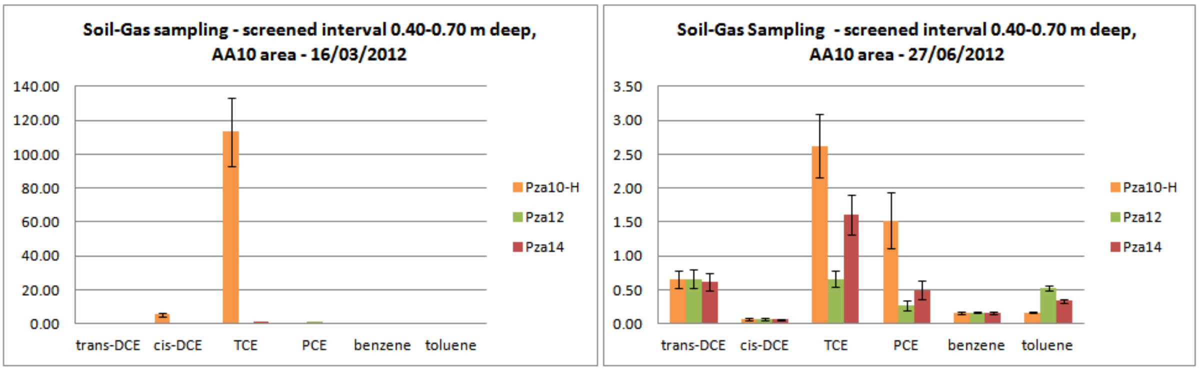


Figure 37: concentrations obtained in March and June 2012, AA20 area, screened interval 0.40-0.70 m deep

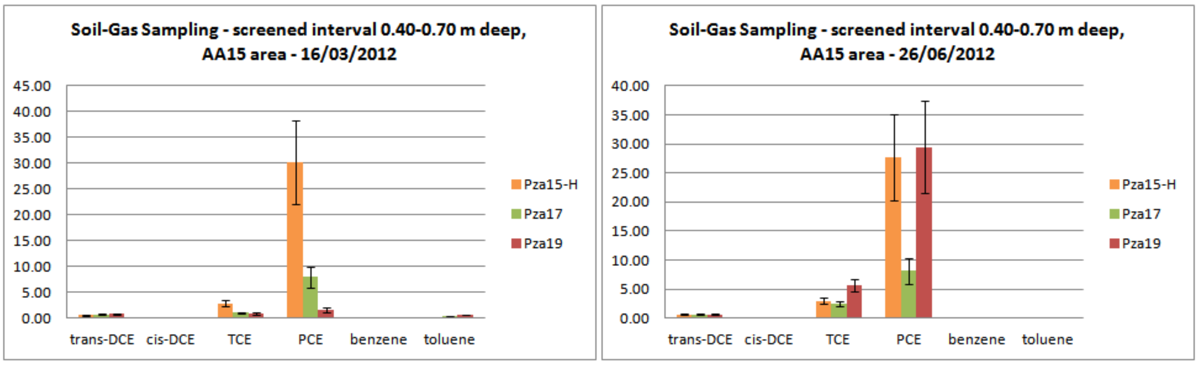


Figure 38: concentrations obtained in March and June 2012, AA15 area, screened interval 0.40-0.70 m deep

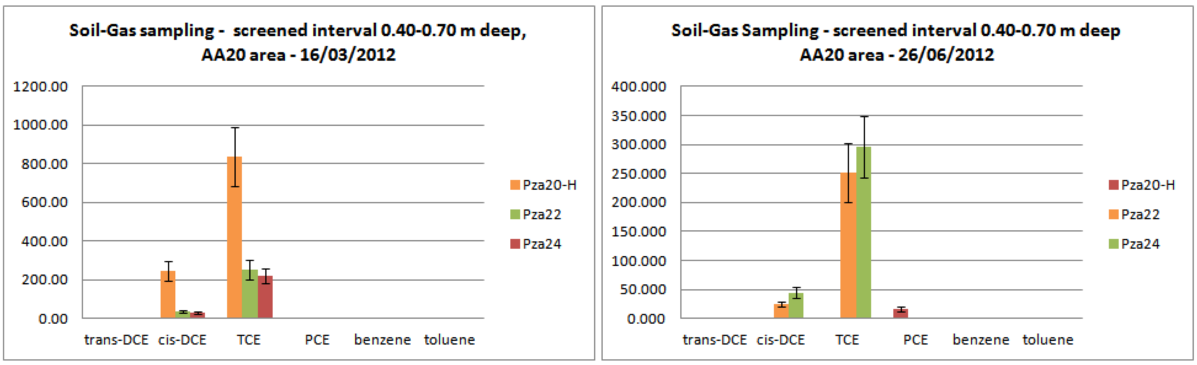


Figure 39: concentrations obtained in March and June 2012, AA20 area, screened interval 0.40-0.70 m deep

If design 1 seems to over value the concentration of substances when measurement is carried out in screened interval 0.40-0.7 m deep, this is not the case when measurement is carried out deeper, in screened interval 1.00-1.30 m deep. Figure 40 and Figure 41 present the concentrations of Cis-dichloroethylene (cis-DCE), Trans-dichloroethylene (trans-DCE), perchloroethylene (PCE), trichloroethylene (TCE), Benzene and Toluene measured in design 1; design 2 and design 3 soil-gas wells respectively. Except for perchloroethylene (PCE) at AA15 area in June 2012, all the concentrations are of the same order of magnitude and differences are contained in the uncertainty interval of measurement. According to these results design 1, design 2 and design 3 give consistent results (screened interval 1.00-1.30 m deep).

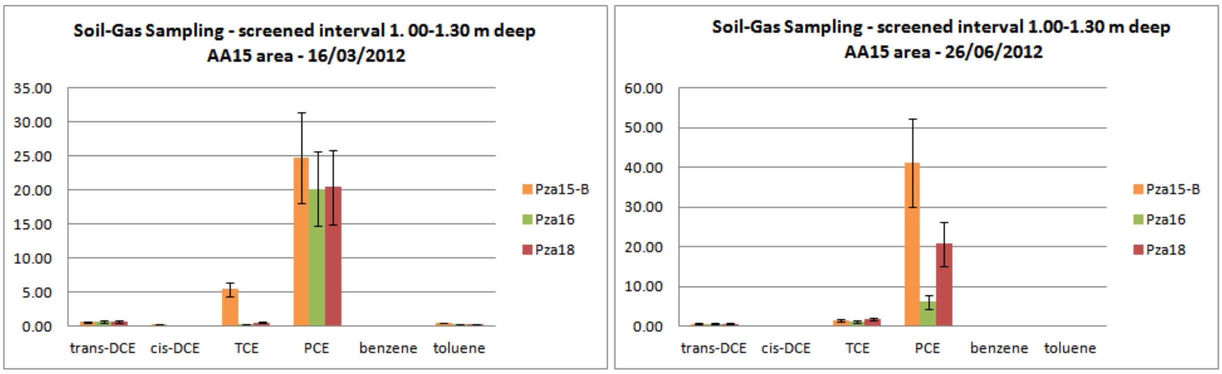


Figure 40: concentrations obtained in March and June 2012, AA15 area, screened interval 1.00-1.30 m deep

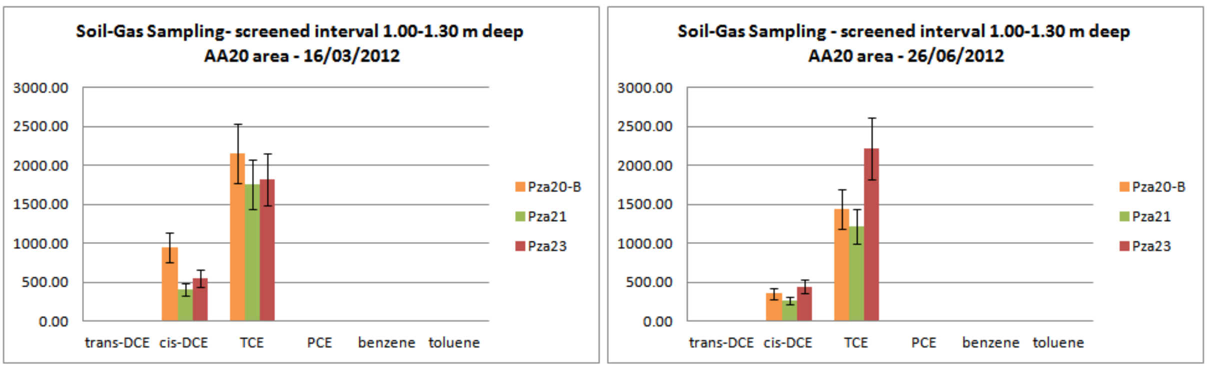


Figure 41: concentrations obtained in March and June 2012, AA20 area, screened interval 1.00-1.30 m deep

According to the previous comparison, design 2 and design 3 soil gas wells give consistent results whatever the chlorinated compound and whatever the screened interval considered. Concerning design 1, the record is more complex. Concentrations measured at the 0.40-0.70 meter-deep screened interval are higher than those measured in design 2 and design 3 soil-gas wells. Concentrations measured at the 1.00-1.30 meter-deep screened interval are same range of order than those measured in design 2 and design 3 soil-gas wells. The contaminants may transfer from the deepest screened interval to the shallowest one thanks to a potential leak of the packer.

According to these results and even if a packer is used to make “airproofness” between the two screened intervals, design 1 soil gas well is not the most appropriate soil gas well to get accurate sampling results.

- **Soil-gas well purge monitoring**

As described in the sampling protocol (see Pilot project Ile de France report), whatever the soil-gas well design (1, 2 or 3), it is purged before sampling. Purge is achieved thanks to the pump of the PhotoIonized Detector (PID), in order to fulfil a purge monitoring simultaneously. Photoionized Detector gives an approximate contamination concentration in equivalent of isobutylene, detecting the whole VOCs present in soil gas. It provides a qualitative monitoring of soil gas contamination from the beginning of the purge to its end.

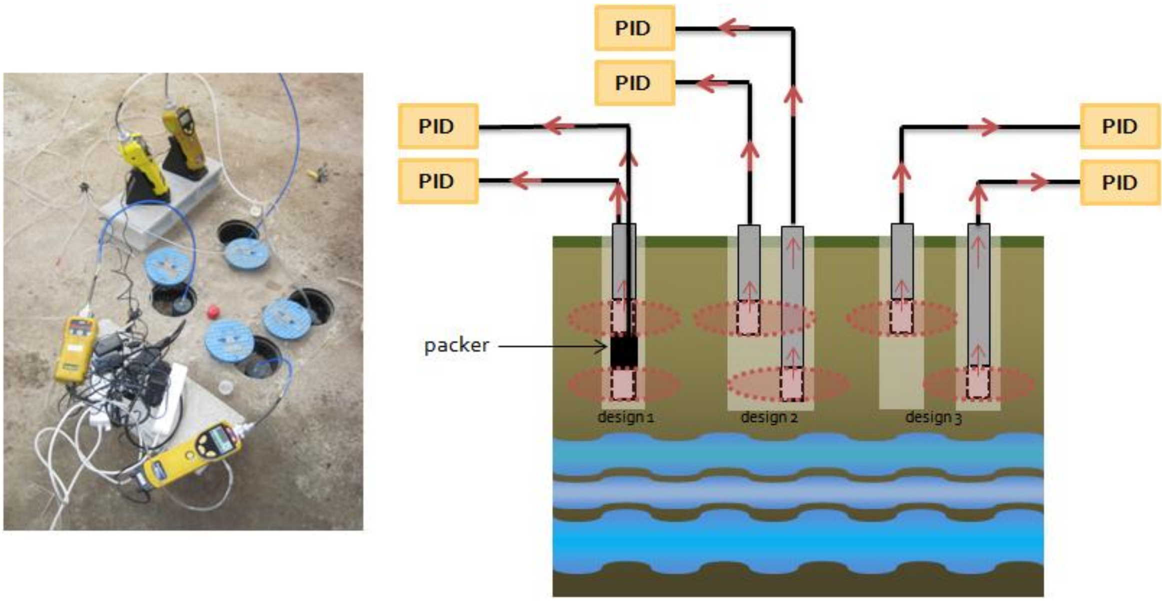


Figure 42: purge monitoring using PhotoIonized Detector (PID)

Purge flow is 500 $mL.min^{-1}$ (if screened interval is 1.00-1.30 meter deep) or 280 $mL.min^{-1}$ (if screened interval is 0.40-0.70 m deep) depending on the type of PID used. The equivalent of 3 volumes of each well is pumped each time.
Soil gas wells having the same design are purged at the same time (meaning, for example the soil gas well design 2 with screened interval at 0.4-0.70 meter deep and the soil gas well design 2 with screened interval at 1.00-1.30 meters deep are purges simultaneously).

Results of the two screened interval (0.40-0.70 and 1.00-1.30 meters deep) are presented below successively. The three designs are compared to each other.

Concerning the screened interval set up between 0.40 and 0.70 meter deep, Figure 43 presents the curves of purge monitoring achieved in June 2012.

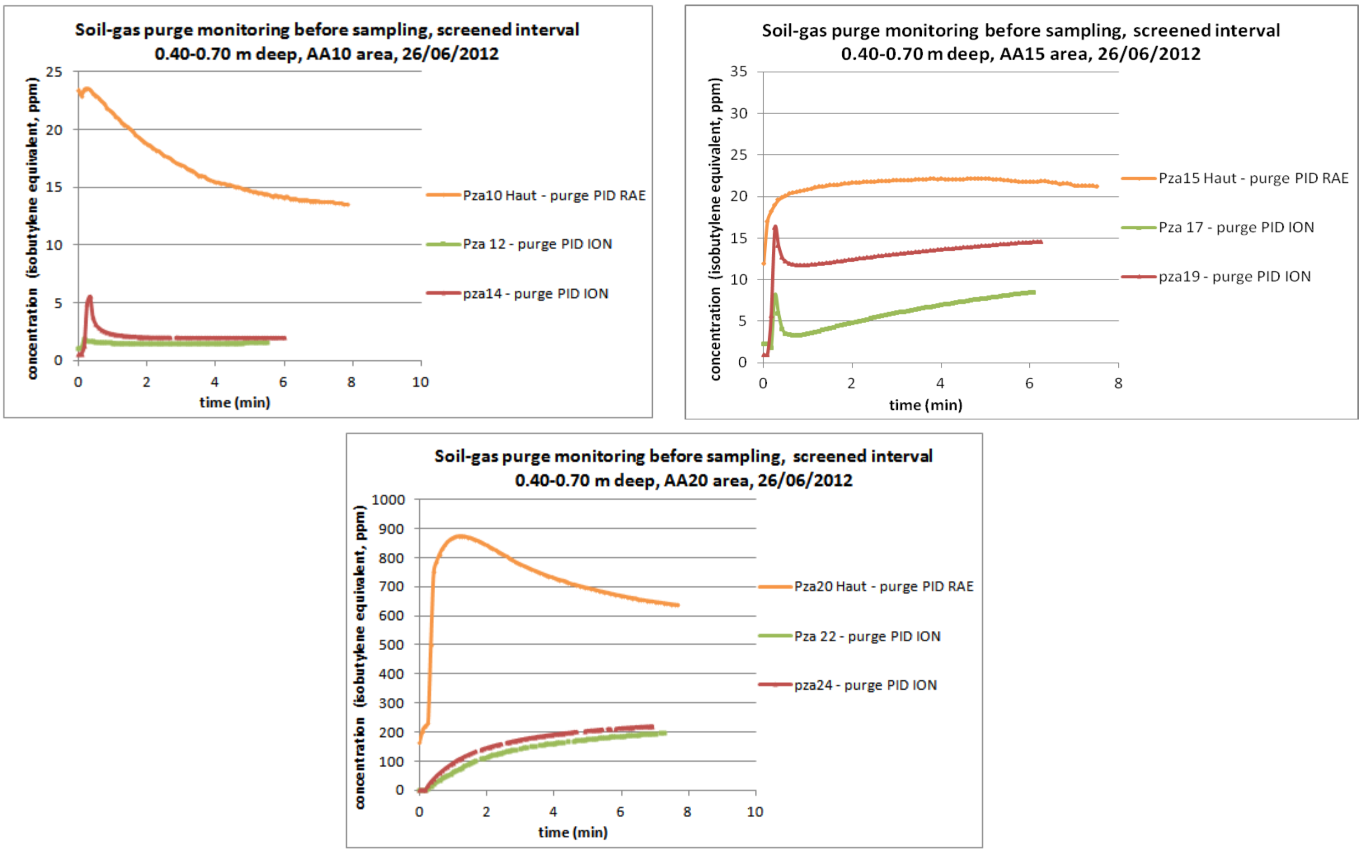
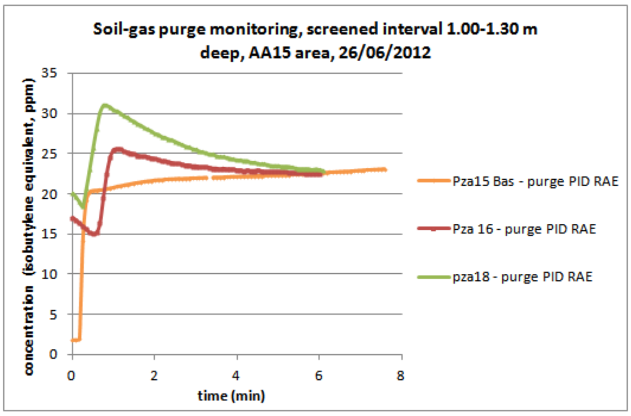


Figure 43: soil-gas purge monitoring, screened interval 0.40-0.70 meter deep, June 2012

During the purge, whatever the design considered, the isobutylene equivalent concentration tends to a stabilized value. The main observation is the design 2 and 3 concentrations tend to a very similar concentration whereas design 1 concentration is higher. This record is very same to the tendency noted with the sampling concentrations (see 6.3.2, soil-gas sampling with sorbent tubes).

Concerning the screened interval set up between 1.00 and 1.30 meters deep, Figure 44 presents the curves of purge monitoring achieved in June 2012.



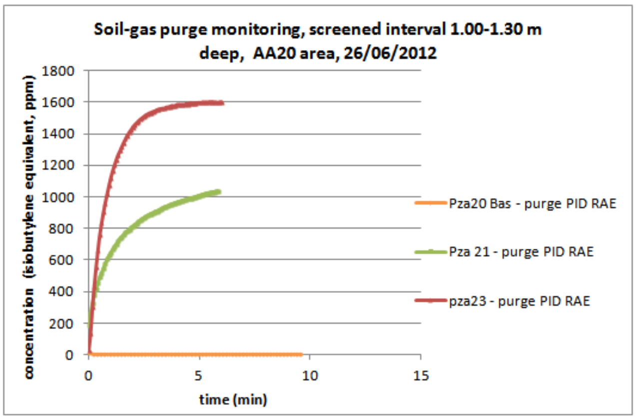


Figure 44: soil-gas purge monitoring, screened interval 1.00-1.30 meters deep, June 2012

No general tendency can be deduced. Nevertheless, PID measurements from nested-wells (design 2) and non-nested-wells (design 3) are generally closest than these from soil-gas wells with two screened intervals. According to these results it is not possible to conclude about the convergence or separation of the purge curves to a stable value.

Soil-gas purge and recirculation monitoring

Another test was achieved to compare the three different soil-gas well designs. It was inspired by the André Tartre test (028).

The main objective is to value the soil-gas well behaviour under depression (purging) and its behaviour during its equilibration (bounce just after purging). Thus, this test can be divided in two different steps. The first one consists in purging the well. The air pumped from the soil-gas well is released into the ambient air. The second step consists in pumping gas from the well and re-injecting it into the soil-gas well, creating a recirculation of soil gas. Pression (P), continuous PID and Ecoprobe measurements are carried out during the whole test.

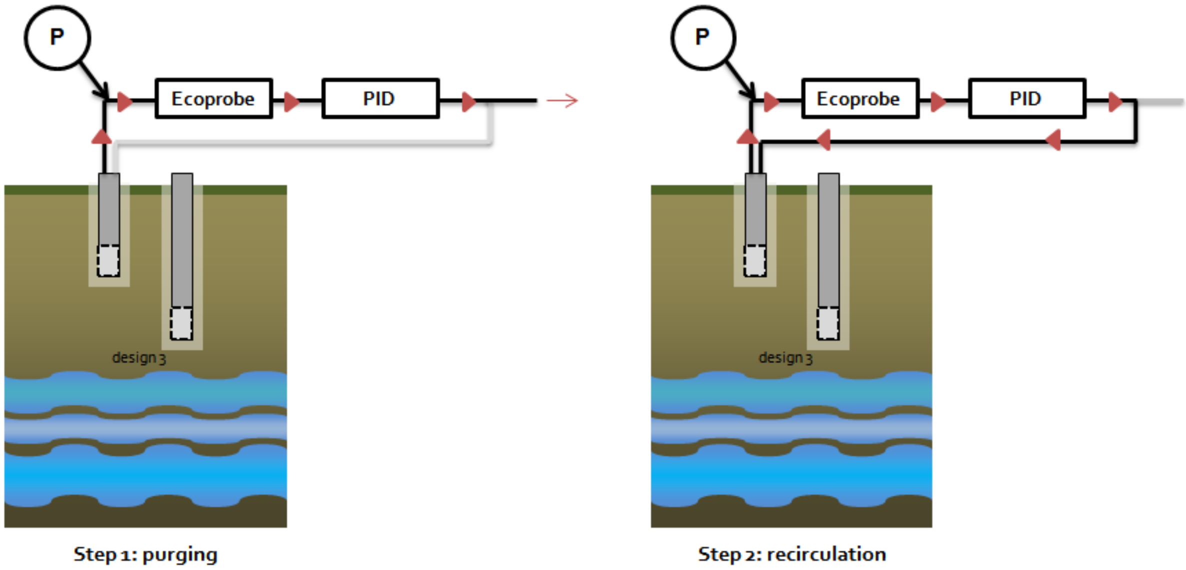


Figure 45: soil-gas purge and recirculation monitoring using PID and Ecoprobe *(source: INERIS)*

This test was carried out on soil-gas wells design 2 and design 3. Results are briefly detailed on the following paragraphs.

Figure 46 and Figure 47 present the Ecoprobe results. PID values are very similar and consequently, curves looks very similar too. Then, only Ecoprobe data are presented in this report.

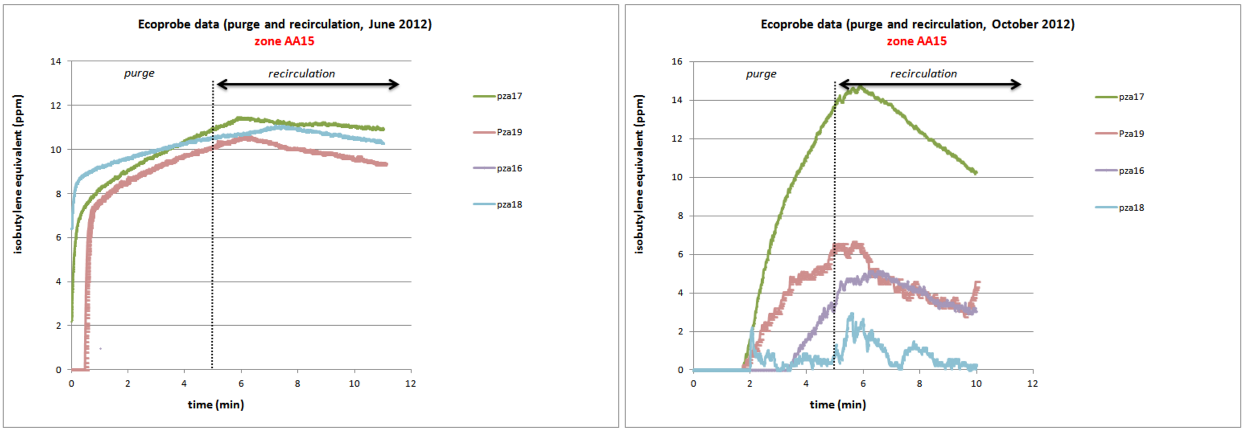


Figure 46: Ecoprobe data, Zone AA15 (pza16: design2/1.0-1.3 meters deep; pza17: design2/0.4-0.7 meters deep; pza18: design3/1.0-1.3 meters deep; pza19: design3/0.4-0.7 meters deep)

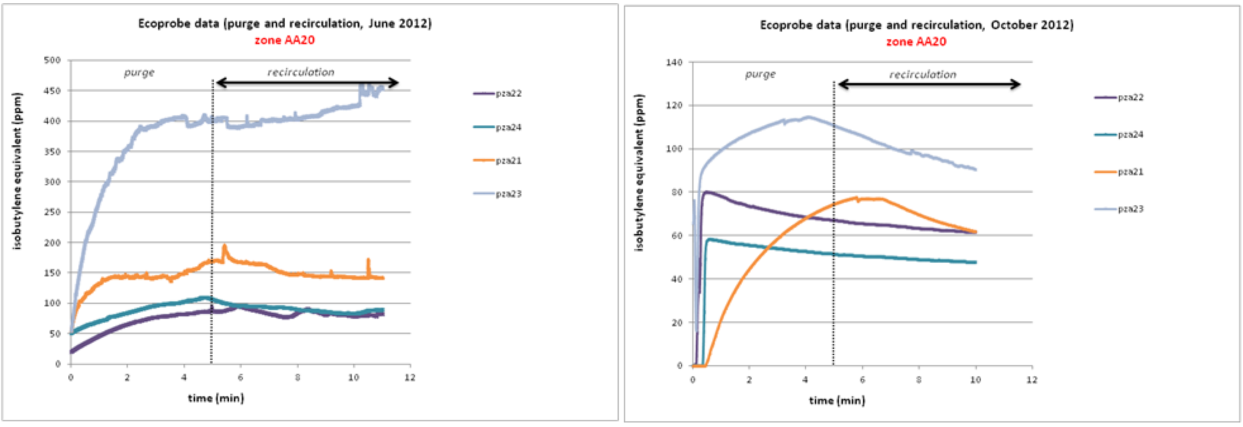


Figure 47: Ecoprobe data, Zone AA20 *(pza21: design2/1.0-1.3 meters deep; pza22: design2/0.4-0.7 meters deep; pza23: design3/1.0-1.3 meters deep; pza24: design3/0.4-0.7 meters deep)*

According to Figure 46 and Figure 47, generally the contamination level increases during the purge and decreases during recirculation. Purging data and recirculation data are increasing and decreasing proportionately: if purging data increases quite a lot then recirculation data decreases quite a lot whereas if purging data are quite stable, then recirculation data are quite stable too. Curves looks the same in case of shallow soil-gas wells (screened interval: 0.4-0.7 m) whatever the soil-gas well design (Pza 17 and Pza19; Pza 22 and pza24) and the season (June or October). Whereas there are more differences for deeper soil-gas wells (screened interval: 1.0-1.3 m) in term of contamination level even they look similar too. Concentrations are higher in June than in October (for exemple, for pza23, Ecoprobe measures about 400 ppm in June and 100 ppm in October). These differences may be due to the capillary fringe variation depending on the season. Nevertheless, concentrations measured in soils-gas wells design 3 are lightly higher than design 2.

Also, Ecoprobe provides CO_2 concentration. All the curves look very similar during the purge. But, a main difference between june and October results occurs for each soil-gas well, when recirculation begins. In June, a lightly variation is observed whereas in October, an abrupt decreasing occurs. Maybe this is due to a leak and/or to an artefact caused by the use of a sampling loop (see Figure 45).

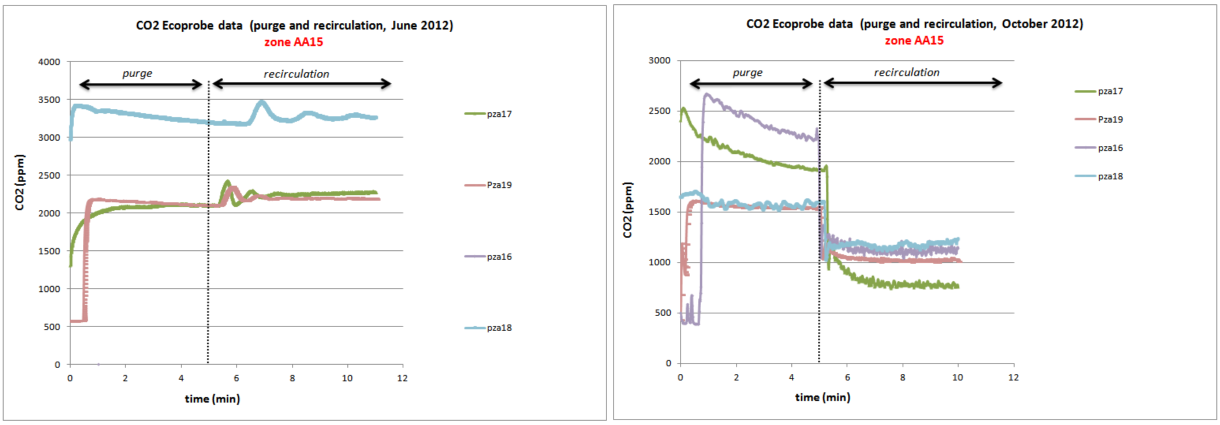


Figure 48: CO2 Ecoprobe data, Zone AA15 (pza16: design2/1.0-1.3 meters deep; pza17: design2/0.4-0.7 meters deep; pza18: design3/1.0-1.3 meters deep; pza19: design3/0.4-0.7 meters deep)

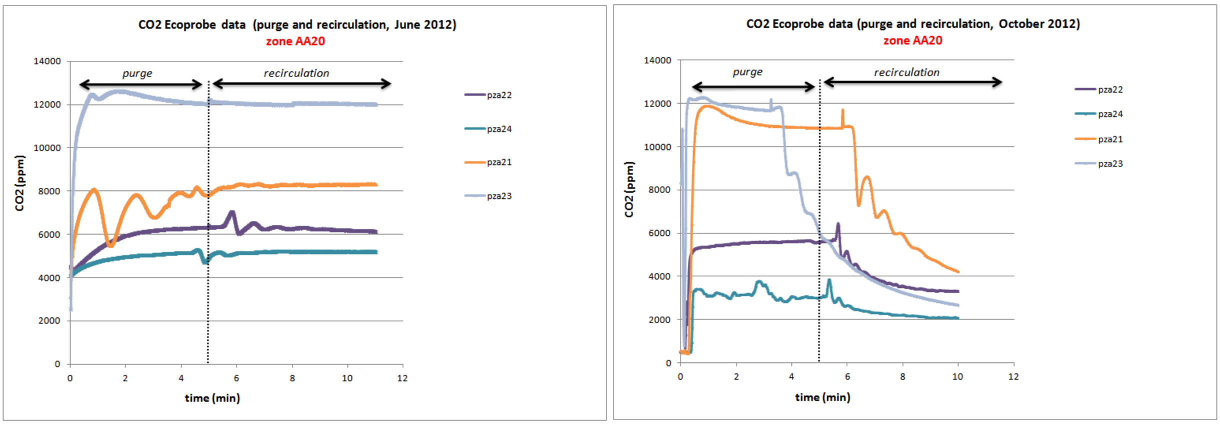


Figure 49: CO2 Ecoprobe data, Zone AA20 *(pza21: design2/1.0-1.3 meters deep; pza22: design2/0.4-0.7 meters deep; pza23: design3/1.0-1.3 meters deep; pza24: design3/0.4-0.7 meters deep)*

Just like for PID Ecoprobe results, shallow soil-gas well measurements are more similar, whatever the design, than deeper soil-gas well measurements which are more exploded in terms of CO_2 levels. PID curves and CO_2 curves layout is the same for each sampling campaign (June and October).

Pression data were also acquired during the whole test. But results cannot be clearly interpreted with only two campaigns for this test.

Finally, this test confirms the previous conclusion obtained with sorbent tube sampling: design 2 and design 3 soil-gas wells have similar behaviour, whatever the season and whatever the screened interval depth. As this test was not carried out in soil-gas wells design, it is not possible to confirm the difference observed previously.

7 General guidelines for a relevant selection of soil gas well design and sampling techniques for soil-gas measurement

7.1 Soil-gas well design recommendations for multi-depth soil-gas sampling

Some American, Canadian and European guidelines and standards mention some recommendations concerning soil-gas well design. As detailed previously (see 4.2), these recommendations differ a little for conventional soil-gas well design (material used to fill the borehole, above the sand pack) even they provide similar recommendations about the other aspects of soil-gas well designs.

Concerning the drilling method, INERIS recommends the use of percussion hammer with percussion gouges and in case of appropriate lithology conditions, a core sampler with a synthetic sampling tube (like Geoprobe®). This system enables core soil sampling which would provide some more information about soil characteristics (lithology) as well as being more representative of the soil-gas conditions deepdown, at the sampling location. It is also recommended to establish PID vertical profiles thanks to these soil cores in order to get information on the level of contamination as well as its depth. Then, PID vertical profiles may be used to modify the screened interval depth. According to these measurements, soil sampling could be considered based on the PID profiling results and the lithology.

Concerning soil-gas well design, it is made of a closed tube and screened interval assembled by screwing (without glue). The screened interval should be located in a sand pack. This filter bed is placed all along the screened interval with two barriers against atmospheric air intrusion (sealing rings). The primary sealing ring is located at the bottom of the screened tube and is often named "bottom cap". The second is located above the screened interval. It consists of a layer of clay (at least 50 cm of thickness) and above it, a bentonite/cement layer (at least 50 cm of thickness). Then, from the bentonite layer to the surface, the empty annular is filled with sand. Nevertheless, when soil-gas well screened interval is above 1 meter deep, these recommendations cannot be followed. Then, the empty annular is filled with bentonite from the sand pack to the surface. It should be in the form of liquid pastry for a better solidification.

It is strongly recommended to choose the materials for tubing (casing), fittings and valves depending on the nature of the targeted compounds: for HVOCs, HDPE or nylon is usually recommended and PVC is avoided.

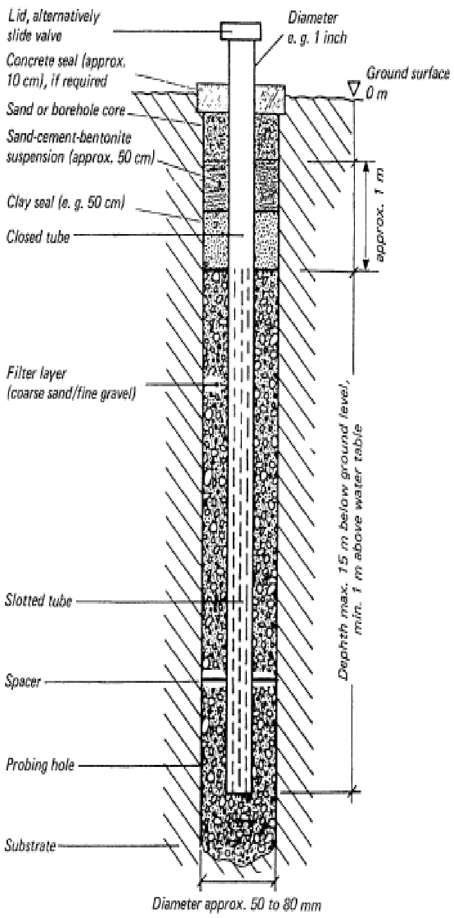


Figure 50: recommended soil-gas well design according to the VDI 3865-2 document

The screened interval should be located at least 50 cm below the ground surface and more than 50 cm above the water table in order to secure the soil-gas well from the potential water table variations. Long screened interval should be avoided (> 0.5 m). Shorter screened intervals implemented at different depths are more relevant (0.3 – 0.5 meter). Screened interval length depends on lithology, investigations objectives as well as the contaminants. It ois strongly recommended to not installed along two different sorts of lithology (especially if they do not have the same properties).

Concerning multi-depth sampling, European document does not mention any specific recommendation. Since, when multi-depth sampling is needed, several conventional soil-gas wells are installed closely but far enough, not being in each well radius of influence. Then, several soil-gas wells (casing and screened interval) are installed in different but similar borehole. This is equivalent to design 3, presented by Figure 51 (see part 6.2). American documents also mention another design: multi-depth nested wells, which is like design 2, presented by Figure 51. Two soil-gas wells (casing and screened interval) are installed in the same borehole. Finally, a third design has been installed. This soil gas well is very similar to conventional soil gas well except it has several screened intervals which are weatherproof using packer when purge and sampling occurred.

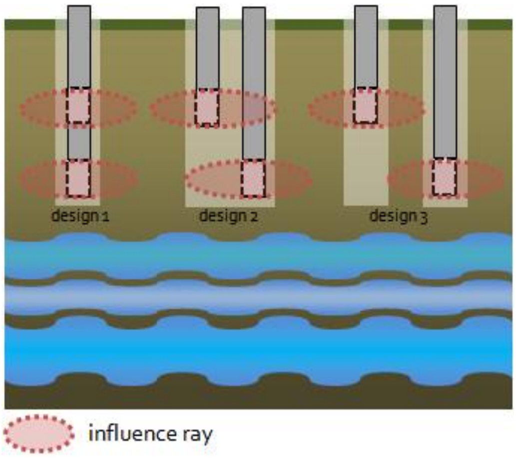


Figure 51: multi-depth soil-gas well designs implemented at CityChlor Pilot project Ile de France (source: INERIS)

According to the results obtained in the frame of CityChlor project (5 sampling campaigns), it seems design 3 and design 2 have very similar behaviour and results of concentration are very consistent, whatever the season (winter, summer…), whatever the screened interval depth (0.40-0.70 or 1.00-1.30 meters deep).

Design 1 data are less consistent, especially concerning the shallower screened interval (0.40-0.70 meter deep). Concentrations measured are most of the time higher than those measured with design 2 and design 3 soil-gas wells. This may be due to a gas transfer from the deeper screened interval to the shallower one. But this hypothesis has not been confirmed.

Then, two soil-gas well designs can be recommended for multi-depth sampling: multi-depth nested wells (design 2) and soil-gas wells installed in different but similar boreholes. These wells should be installed according to the recommendations detailed previously (see part 4.2.4). Ray of influence of each of them should be calculated (see Figure 22, part 6.2) and each of them should be far enough to avoid any influences and disturbances during purging and sampling.

Design 2 (multi-depth nested wells) should be more relevant than design 3, when lithology varies at low distances Nevertheless, design 3 installations required more common construction procedures (similar to conventional soil-gas well) whereas design 2 remains more delicate and complex to implement. Finally, design 1 should be considered only if packer weatherproof could be well-mastered.

When the soil-gas well is properly installed, some precaution should be taken before sampling. First a sufficient period of time should be allowed for soil-gas system re-equilibration depending on soil characteristics (3 to 5 hours for sub-slab installations, 24 to 48 hours for permanent soil-gas wells). Also, a soil-gas well leakage test is strongly recommended in order to confirm that indoor or ambient air does not get into the well during (especially for shallow installations, < 0.5 meter deep).

7.2 Soil-gas sampling techniques recommendations

Meteorological conditions have an important impact on contaminants transfer from the saturated zone to the ambient air. Then, it is strongly recommended to monitor barometric pressure, temperature (indoor and outdoor buildings), wind speed and rainfall during the whole sampling campaign, even some few days before and after. The use of a weather station seems to be an appropriate way to reach this information which would be beneficial for sampling data interpretations. The water-table depth is also required. Moreover, it is recommended to avoid soil-gas sampling campaigns in case of rain events, frost and snow when soil-gas installations are outdoor.

Humidity and temperature inside the soil-gas well installations are also relevant parameters. Their measurements are recommended at least at the beginning and at the end of each investigation.

Moreover, in case of soil-gas well screened interval closed to the water-table and which may be impacted by the water table variations, the operator should verify the absence of water downhole.

Prior to sampling, the soil-gas installation should be purged. Two purging strategies can be considered. The first one is based on the volume of gas pumped. Indeed The volume of soil-gas extracted by pumping from the soil-gas well has to match 3 to 5 times. The second strategy is based on the stabilization of monitored parameters. An on-line tracking method is used in order to measure different parameters like temperature, humidity and mainly contaminants concentration (PID monitoring). The purge should continue until the soil-gas well conditions are stable. Purging a soil gas well using a PID whose its pump has be calibrated seems to be an appropriate system which combine both purging strategies.

Depending on the objectives of the investigations and site specific constraints, several sampling techniques can be considered. Choice should be managed according to the targeted substances, the different levels of contamination depending on the compounds and the appropriate limit of quantification required for each of them. Once collected, samples have to be labelled. Date and time for the beginning and the end of the sampling period should be noticed as well as sampling duration and sampling location. A PID measurement is also recommended when the sampling ends in order to compare de values measured at the end of the purge and at the end of the sampling period.

In case of active sampling, pumping system, even mechanical or natural suction, has to be calibrated and checked, shortly before (no more than some days before), during and after each investigation.

If the sampling technique requires the utilization hose, it should be an inert material towards the contaminants. Usually, the use of hose made of Teflon® is recommended. This hose has to be transport and stored in safe environment (without contamination) and has to be considered for single-use only.

Samplers have to be stored and transport in appropriate conditions: in most cases, in dark and cold (< 4°C) environment. Analysis should also be carried out according to the recommendations provided by the supplier and the laboratory.

In order to provide better results and data interpretations, trip blank and field blank are strongly recommended. Finally, for each site, several investigations should be carried out in order to value the variations due to the weather (seasonal investigations).

8 Conclusion

According to American, Canadian and European guidelines or standard and thanks the feedback gained through CityChlor Pilot project: Ile de France, it is possible to enhance the current practices and then, give guidance to people on soil-gas well design and sampling measurement protocols. Soil-gas well construction should follow some specific recommendations concerning the drilling method used, its design as well as the implementation of some tests prior sampling.

Concerning the drilling method, INERIS recommends the use of percussion hammer with percussion gouges and in case of appropriate lithology conditions, a core sampler with a synthetic sampling tube (like percussion hammer method).

Concerning soil-gas well design, closed tube and screened interval should be threadedly assembled. The screened interval should be located in a sand pack. Two barriers against atmospheric air intrusion (sealing rings) have to be implemented at the bottom of the screened tube ("bottom cap") and above the screened interval respectively. The screened interval should be located at least 50 cm below the ground surface and more than 50 cm above the water table in order to secure the soil-gas well from the potential water table variations. Shallower soil-gas wells could be considered if weatherproof conditions are reached (especially towards ambient air).

Screened interval length depends on lithology, investigations objectives as well as the contaminants. It is strongly recommended against installing a screened interval along two different sorts of lithology.

Concerning multi-depth sampling, European document does not mention any specific recommendation. Since, when multi-depth sampling is needed, several conventional soil-gas wells are installed closely but far enough, not being in each well radius of influence.

According to the results obtained in the frame of CityChlor project (5 sampling campaigns), two soil-gas well designs can be recommended for multi-depth sampling: multi-depth nested wells and soil-gas wells installed in different but similar boreholes. Multi-depth nested wells should be more relevant than soil-gas wells installed in different but similar boreholes, when lithology varies at low distances Nevertheless, soil-gas wells installed in different but similar boreholes installations required more common construction procedures (similar to conventional soil-gas well) whereas multi-depth nested wells remains more delicate and complex to implement. Finally, soil-gas well with two screened interval should be considered only if packer airproof could be well-mastered.

When the soil-gas well is properly installed, some precaution should be taken before sampling: re-equilibration period, leakage as well as recharge and recirculation tests are recommended to implement.

For each type of sampling installations, several sampling techniques can be used. Some are active samplers with mechanic or natural pumping, others passive. All are complementary tools which enable an improved soil-gas characterization.

Prior to sampling, the soil-gas installation should be purged. Two purging strategies can be considered. The first one is based on the volume of gas pumped. Indeed The volume of soil-gas extracted by pumping from the soil-gas well has to match 3 to 5 times soil-gas well volume. The second strategy is based on the stabilization of monitored parameters. Purging a soil gas well using a PID whose its pump has be calibrated seems to be an appropriate system which combine both purging strategies.

As a result, depending on the objectives of the investigations and site specific constraints, several sampling techniques can be considered. Choice should be managed according to the targeted substances, the different levels of contamination depending on the compounds and the appropriate limit of quantification required for each of them. Sorbent tube is the most used but Summa-canister® could also be considered. All the materials used in the frame of sampling have to be calibrated and free of contaminant.

In order to provide better data interpretations, trip blank and field blank are strongly recommended.

Finally, for each site, several investigations should be carried out in order to value the variations due to the weather (seasonal investigations).

As meteorological conditions have an important impact on contaminants transfer, it is strongly recommended to monitor barometric pressure, temperature (indoor and outdoor buildings), wind speed and rainfall during the whole sampling campaign, even some few days before and after. Humidity and temperature inside the soil-gas well installations are also relevant parameters. Their measurements are recommended at least, at the beginning and at the end of each investigation. Also, the operator should verify the absence of water downhole. Moreover, it is recommended to avoid soil-gas sampling campaigns in case of rain events, frost and snow when soil-gas installations are outdoor.

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Document description

Title: Soil-gas monitoring: soil-gas well designs and soil-gas sampling techniques

INERIS reference: DRC-13-114341-03542A

Number of Pages: 81

Date of publication: April 11 2013

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Investing in Opportunities

This project has received European Regional Development Funding through INTERREG IV B.

INTERREG IVB