Effects of Sampler Location and Sampling Procedure on Subsurface Vapour Intrusion

Paper 2011-A-213-AWMA

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ABSTRACT

Currently, soil vapour intrusion (VI) assessments are carried out predominantly by collecting soil gas samples outside but surrounding a target building to avoid potential interference to indoor air samples. These "exposure pathway" samples collected are then analyzed for vapour concentrations and the "point-of-exposure" vapour concentrations indoors are estimated using mathematical transport models.

The effectiveness of a soil gas sampler or probe depends on factors including the size of the sampler, the equilibration time after installation, barometric effects and sample collection rate. This paper presents a study of these factors using mathematical models.

INTRODUCTION

Currently, to avoid potential interference to indoor air samples, soil vapour intrusion (VI) assessments are carried out predominantly by collecting soil gas samples outside a target building[1,2]. These "exposure pathway" samples collected are then analyzed for vapour concentrations and "point-of-exposure" vapour concentrations indoors are estimated using mathematical transport models.

In order to collect representative soil gas samples for VI assessments, several aspects of the sampler and the sampling procedure need to be considered. The samplers used can range from small-diameter probes to sampling chambers (0.25 to 4.0 in) [1,3]. If a sampler is located too close to the ground surface or a building basement, short-circuiting may occur (*i.e.*, the soil gas sample collected is affected by atmospheric air or building air). After the sampler is installed, vapour concentrations in the soil gas surrounding the sampler will equilibrate with those in surrounding soils through diffusion. In order to collect a representative soil gas sample, sufficient equilibration time should be allowed. The size of the sampler will also affect the equilibration time. Similar to groundwater sampling, there is a debate between purging and no-purging prior to sampling. Soil gas samples are usually collected using a vacuum device such as vacuum canister or a sampling vacuum pump. The influence zone surrounding a sampler during sample collection would indicate the origin of the soil gas collected and is controlled by the sampling rate and the duration of sample. The volumetric soil gas sampling rate commonly used ranges from 20 to 1000 mL/min[1].

This paper presents the results of a mathematical modelling study that evaluates equilibration time and the effect of sampler location on VI assessments. Equilibration times are calculated using an analytical model. Effects of sampler location on soil gas sample quality are studied by evaluating potential barometric effects and the zone of influence during sample collection using vacuum pumps or vacuum canisters.

MATHEMATICAL MODELLING STUDY

Soil Parameters and Contaminant Characteristics

For the mathematical modelling study, three distinct soil types are used: coarse-grained (CG), fine-grained (FG) and very fine-grained (VF). The soil properties for these three types are presented in Table 1. The CG and FG properties are obtained from Alberta Environment classifications [4]. The VF parameters are assumed to be similar to those of FG except for hydraulic conductivity and intrinsic permeability. For diffusion simulations, the diffusion coefficient in air, D_{air} for petroleum hydrocarbon (PHC) fraction F1 and F2 is used and is listed[4] as 0.05 cm^2/s.

Table 1. Typical Soil Parameters Used in Model Study

	Coarse-Grained (CG)[4]	**Fine-Grained (FG)[4]**	**Very Find-Grained (VF)**
Total Porosity, ϕ_T	0.4	0.3	0.3
Air-Filled Porosity, ϕ_a	0.281	0.132	0.132
Hydraulic Conductivity, K (cm/s)	$1.0x10^{-3}$	$1.0x10^{-6}$	$1.0x10^{-7}$
Intrinsic Permeability, k (cm^2)	$6.0x10^{-8}$	$6.0x10^{-11}$	$1.0x10^{-12}$

VF properties are assumed to be the same as FG properties except for hydraulic conductivities.

Equilibration Time Model

The equilibration time is the time required for the vapour concentration inside a sampler to attain the same concentration as that in the surrounding soil gas subsequent to its first installation. The equilibrating process is achieved primarily through diffusion. Crank[5] provides two analytical solutions that can be used to estimate the equilibration time for volatile organic compounds (VOCs) inside cylindrical soil gas samplers installed in a homogeneous isotropic medium. One solution is for constant concentration in the soils surrounding the sampler while the other accounts for possible source reduction (due to soil gas extraction). The two solutions provide similar answers although the first solution is more conservative. Further details of the application of the two solutions can be found in Wong and Agar[3]. In this paper, only the constant soil concentration case is presented.

Crank[5] presents a non-steady state solution for the vapour concentration inside a cylinder with the concentration, C_o, at the cylinder wall kept constant (or a constant source boundary). If the concentration inside the cylinder is initially zero, the concentration, C, at time t is given by:

$$\frac{C}{C_0} = 1 - \frac{2}{a}\sum_{n=1}^{\infty}\frac{exp(-D_a\alpha_n^2 t)J_0(r\alpha_n)}{\alpha_n J_1(a\alpha_n)} \qquad \textbf{(Eq. 1)}$$

where a is the radius of the cylinder, r is the radial distance from the centre, J_o and J_1 are Bessel functions of orders 0 and 1, respectively, and α_n is the roots of:

$$J_0(a\alpha_n) = 0 \qquad \textbf{(Eq. 2)}$$

Equations 1 and 2 were solved using a spreadsheet for a range of sampler diameters installed in soils impacted by PHC Fraction F1 and F2. The equilibration time for each sampler was obtained as the time when the vapour concentration inside the sample reached the same concentration as that in the surrounding soils.

Soil Gas Flow Model

The movement of soil gas in the subsurface during sample collection is controlled by advection, which is the movement induced by a pressure gradient. The basic airflow equation used in this paper follows the derivation by Baehr and Hult[6] for steady temperature distribution and can be written as

$$\frac{\partial}{\partial t}(P\phi_a) + P(\nabla \bullet \overline{q}) + T\nabla\left(\frac{P}{T}\right) \bullet \overline{q} = 0 \qquad \textbf{(Eq. 3)}$$

where P is the absolute air-phase pressure, ϕ_a is the air-filled porosity, $\overline{q}$ is the air-flow velocity vector and T is the absolute temperature. In addition, $\overline{q}$ can be expressed as[5]:

$$\overline{q} = -\frac{\rho g}{\mu}k\nabla\left[z + \frac{RT}{\omega g}ln\frac{P}{P_{atm}}\right] \qquad \textbf{(Eq. 4)}$$

where ρ is the density of air, μ is the dynamic viscosity of air, k is intrinsic permeability of the medium, z is the elevation, ω is the molecular weight of air and P_{atm} is the absolute atmospheric pressure.

In this study, Equation 3 is solved numerically using the finite element code SVAirFlow[7]. The performance of SVAirFlow was verified using an analytical solution for steady state air flow and validated using the field vapour extraction results presented in Baehr and Hult[6,8]. SVAirFlow was then used to simulate the propagation of a pulsed barometric pressure increase and investigate the zone of influence during soil gas sample collection using a vacuum canister.

RESULTS

Equilibration Time Simulations

Equilibration times were calculated using the constant concentration at sampler wall boundary condition (Equations 1 and 2) for various sampler diameters. Results are tabulated in Table 2 and plotted in Figure 1.

Table 2. Estimated Minimum Equilibration Time for Various Sampler Diameters

Sampler Diameter	Coarse-Grained (CG) Soil		Fine-Grained (FG) and Very Fine-Grained (VF) Soil	
1 in. (25 mm)	500 s	0.1 hr	4000 s	1.1 hr
2 in. (50 mm)	2000 s	0.6 hr	17600 s	4.9 hr
4 in. (100 mm)	7000 s	1.9 hr	48000 s	13.3 hr
6 in. (150 mm)	21600 s	6.0 hr	115200 s	32.0 hr

Figure 1. Estimated Equilibration Time for Soil Gas Samplers of Various Diameters for Coarse-Grained and Fine-Grained Soils.

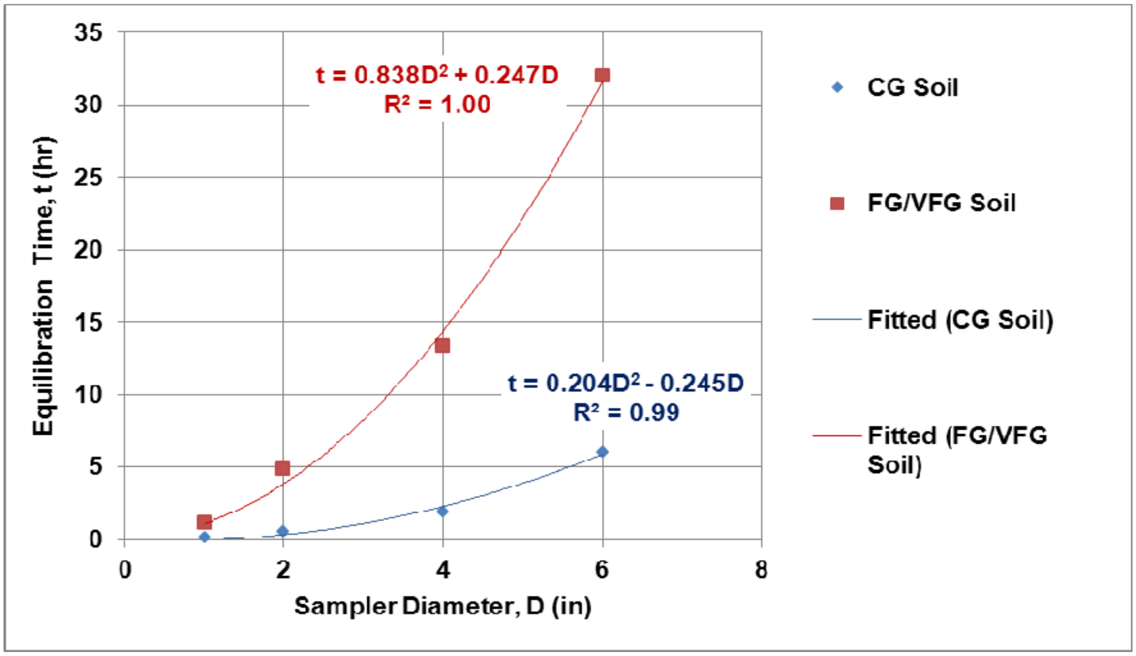
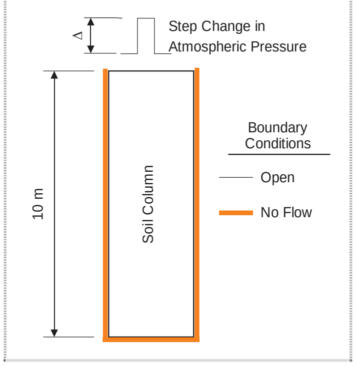


Figure 2. Schematic Showing 1D Model



Response Due to a Step Increase in Atmospheric Pressure

A one-dimensional (1D) model is used to simulate how a step increase in atmospheric pressure will be transmitted vertically down a homogenous isotropic soil column 10 m deep. A schematic of the model is shown in Figure 2 together with the boundary conditions applied. The applied pulse atmospheric pressure changes last 30 s in duration and the pressure pulses, Δs, are 0.01, 0.05 and 0.1 kPa, respectively. The total simulation time is 1800 s. The soil properties used are listed in Table 1.

Typical pressure change profiles are shown in Figure 3 for Δ = 0.05 kPa in FG soils. It can be seen that the effect of a pressure pulse are only transmitted to a depth of about 3 m at the end of the 1800 s simulation time. Figure 4 shows that the maximum normalized pressure change profiles for VFG soils for Δ = 0.01 kPa, 0.05 kPa and 0.10 kPa overlap each other. Normalized pressure changes are obtained by dividing the soil air pressure by the corresponding Δ-value. This suggests that the penetration of barometric effects into the subsurface is not affected by the magnitude of the pressure change but is dependent on the soil type as shown in Figure 5.

Figure 3 Soil Air Pressure Profiles in a Fine-Grained Soil for Δ = 0.05 kPa

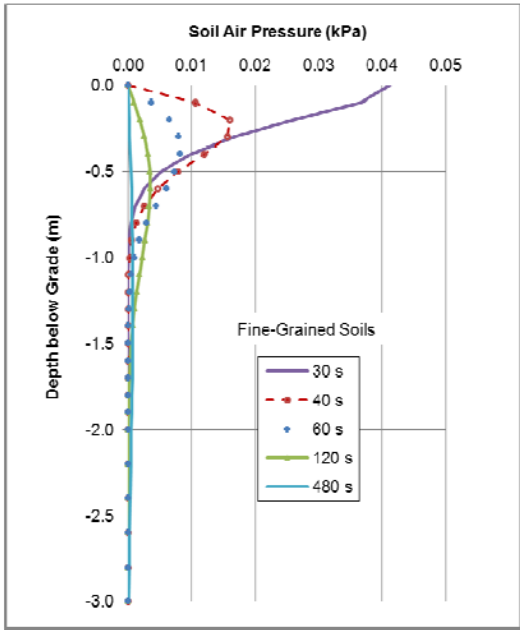


Figure 4 Maximum Normalized Pressure Change Profiles in a Very Fine-Grained Soil for Δ = 0.01, 0.05 and 0.10 kPa

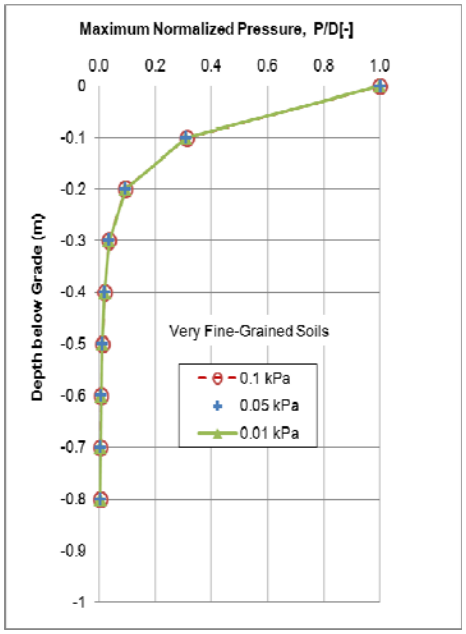


Figure 5. Maximum Normalized Pressure Profile for Various Soil Types

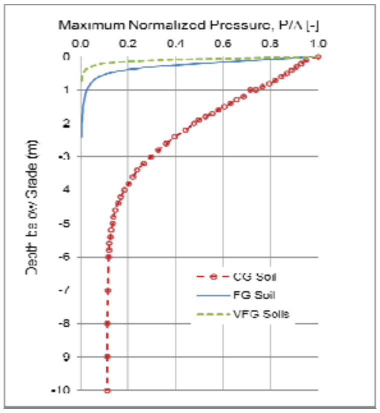


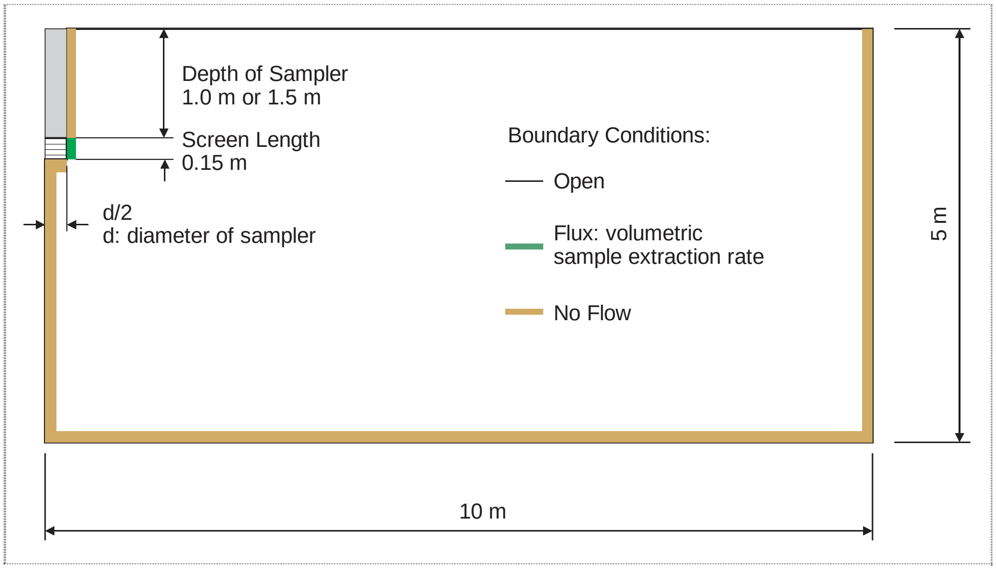
Figure 5 shows the penetration depth into the subsurface due to a step pressure change that lasts 30 s. After 1800 s, the maximum penetrations are about 0.8 m and 2.0 m for VFG and FG soils, respectively. For a CG soil, the pressure effect travels through the soil column at a fast rate; a pressure change at about 10% of the applied pulse is registered at 10 m below grade after about 120 s of simulation time.

These simulations indicate that soil samplers when installed in FG and CG soils to depths less than 2 m will likely be affected by barometric pressure changes.

Influence Zone Surrounding a Soil Gas Sampler during Sample Extraction

A two-dimensional axisymmetric (2D) model is used to study the size of the influence zone that will be generated during soil gas sample extraction. A schematic of the modelled region and boundary conditions is shown in Figure 6.

Figure 6. Schematic Diagram Showing the 2D-Axisymmetric Model



The 2D model is used to study the zone of influence induced during sample collection for sampler diameters and sample extraction rates summarized in Table 3. The maximum sampling time was 30 min.

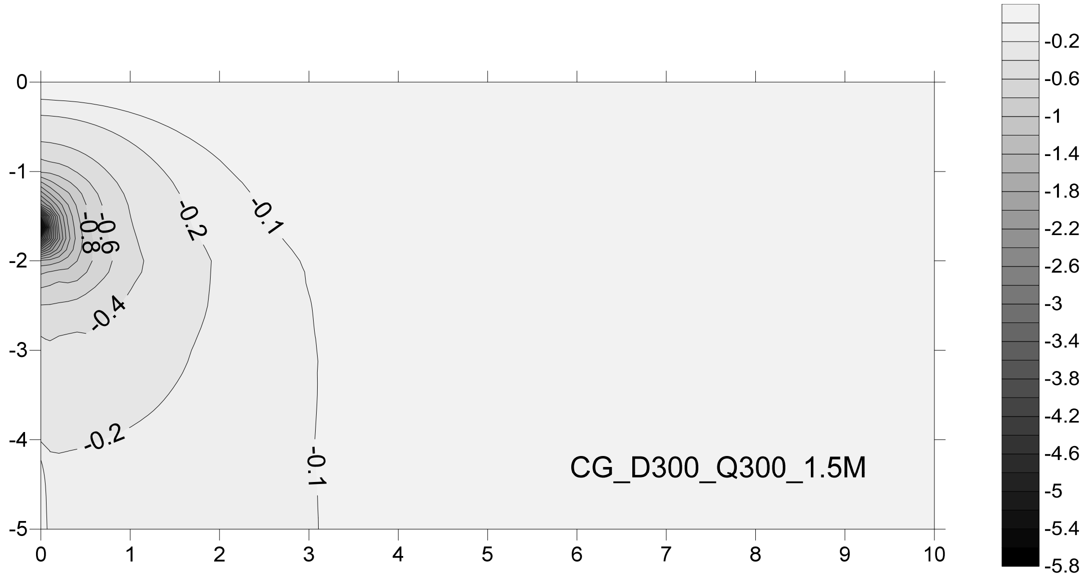
Table 3. Depth to Sampler, Sampler Diameters and Sampling Rates Used in 2D Simulations

Model Parameter	**Values**
Depth to Sampler, D (m)	1.0; 1.5
Sampler Diameter, d (mm)	10; 50; 100; 300
Sampling Rate, Q (mL/min)	50; 100; 200; 300

It should be noted that, in the following discussion, soil air pressures are reported as gauge pressures and the reference atmospheric pressure is 90 kPa absolute (the mean pressure for the City of Calgary).

To-date only a limited number of simulations has been carried out. As a result, we are unable to evaluate fully the response of a sampler to different sampling rates. However, results of the limited number of simulations indicate that the pressure build-up within the sampler is significantly different among the three soil types. The pressure inside a sampler ranges between -5.3 and -8.1 kPa in the CG soil and is about -90 kPa in the FG and VF soils; and it only changes by less than 5% throughout the sampling time. Figure 7 is a contour plot of the pressure distribution in the subsurface for a sampler 300 mm in diameter installed at 1.5 m below grade under a sample extraction rate of 300 mL/min. If one chooses the -0.1 kPa (i.e. about 1% of the mean atmospheric pressure) contour as the boundary of the zone of influence, one can then compare the performance of the various sampler sizes. As can be seen in Figure 7, the pressure effect travels to about 3 m radially from the sampler. This distance is much smaller in finer-grained soils.

Figure 7. Pressure Distribution during Sampling at an Extracting Rate of 300 mL/min for a 300 mm Diameter Probe Installed at 1.5 m below Grade



CONCLUSIONS

Using analytical solutions, look-up charts are developed to estimate the equilibration time for cylindrical soil gas samplers in both coarse-grained and fine-grained soils.

The computer software SVAirFlow has been demonstrated to be capable of simulating soil gas movement in response to barometric variations and during soil gas sample collection using vacuum canisters or vacuum sampling pumps. Based on these simulations, it appears that barometric effect can reach most soil gas samplers installed within 2 m of the ground surface except in very fine-grained soils of low permeability.

The parametric study of the effect of sampler size, sampling rate and depth of sampler are still incomplete. Preliminary results indicate that the pressure effect during sampler would propagate up to 3 m in coarse-grained soils. Particle-tracking is a numerical method that traces the paths of particles placed in a finite element mesh, and offers an alternative to assessing the zone of influence.

Most permanent or semi-permanent soil gas samplers are installed in bore-hole and are isolated from grade using hydrated bentonite seals. Numerical models can also be used to evaluate the effect of imperfect seals during sampling collection.

ACKNOWLEDGMENTS

The authors would like to thank the reviewer, Mr. Matt Traister, and their co-workers James Carss and Anne Vickers for reviewing this paper. Their comments are very much appreciated. In addition, thanks are due to Camille Dupety for initiating the work on soil gas flow modelling during her internship with O'Connor Associates.

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KEYWORDS

Vapour intrusion, soil gas sampling, barometric effect, equilibration time, sampling rate, zone of influence