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Estimation of Contaminant Subslab Concentration in Vapor Intrusion Including Lateral Source–Building Separation

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Abstract

Most current vapor-intrusion screening models employ the assumption of a subsurface homogenous source distribution, and groundwater data obtained from nearby monitoring wells are usually taken to reflect the source concentration for several nearby buildings. This practice makes it necessary to consider the possible influence of lateral source–building separation. In this study, a new way to estimate subslab (nonbiodegradable) contaminant concentration is introduced that includes the influence of source offset with the help of a conformal transform technique. Results from this method are compared with those from a three-dimensional numerical model. Based on this newly developed method, a possible explanation is provided here for the great variation in the attenuation factors of the soil vapor concentrations of groundwater-to-subslab contaminants found in the EPA vapor-intrusion database.

Vapor intrusion is the process in which volatile chemicals released by a subsurface contaminant source (e.g., polluted groundwater) are transported in soil gas, enter a building of concern, and negatively influence indoor air quality. The attenuation of the contaminant concentration from the source to the receptor usually occurs in two processes: groundwater-to-subslab transport and movement from the subslab to indoor air. The focus of this study is the former.

Mathematical modeling has been a useful tool in site investigations of vapor intrusion, and there have been many vapor intrusion models published in this field, including both multidimensional numerical models and analytical screening tools (Abreu, 2005; Abreu and Johnson, 2005; Anderssen et al., 1997; Bozkurt, 2009; Bozkurt et al., 2009; Brand et al., 2007; DeVaul, 2007; Johnson and Ettinger, 1991; Johnson et al., 1999; Jury et al., 1983; Lowell and Eklund, 2004; Parker, 2003; Shen et al., 2012; Turczynowicz and Robinson, 2001; Yao et al., 2011a, 2011b, 2012b, 2013a, 2013b, 2013c; Waitz et al., 1996). Although the numerical tools are useful for their capacity to capture comprehensively characteristics of a vapor intrusion scenario, they require significant computational effort and measured parameter data from a site. For this reason, convenient one-dimensional screening tools are much more popular in practice; however, compared with multidimensional numerical models, the weaknesses of one-dimensional models are quite obvious. Most one-

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dimensional screening tools focus on vertical soil vapor transport (Johnson and Ettinger, 1991; Brand et al., 2007; Waitz et al., 1996; Jury et al., 1983; Anderssen et al., 1997; Turczynowicz and Robinson, 2001; Johnson et al., 1999; Parker, 2003; DeVaul, 2007; Johnson and Ettinger, 1991; Brand et al., 2007; Waitz et al., 1996; Jury et al., 1983; Anderssen et al., 1997; Turczynowicz and Robinson, 2001; Johnson et al., 1999; Parker, 2003; DeVaul, 2007), which assumes a homogenous distribution of the groundwater contaminant source underlying the structures of interest. In these one-dimensional models, only the vertical contaminant transport is simulated, and simultaneous lateral transport cannot be considered. Thus mass continuity necessarily determines that the upward contaminant mass-flow rate from a subsurface source would finally be completely absorbed at a uniform upper boundary. Since the focus of these analyses is building entry, this upper boundary condition can only be the building foundation or crawl space. So whatever leaves a source beneath the building must end up in the building, unless biodegradation is assumed to intervene or mass conservation is violated. When models allowing for both vertical and lateral transport are examined, it is found that this assumption of homogenous distribution, which is fundamental in one-dimensional analyses, is unrealistic in many cases (Yao et al., 2011a).

The above problem results from the conflict between the mathematical requirement for homogeneity of the upper boundary condition and the physical reality of most sites. The upper surface-boundary condition needed in one-dimensional analyses must be the same for the building and building surroundings. To “avoid” lateral transport at that upper boundary interface, the contaminant concentration profile beneath the building cannot be different from that beneath the building’s surroundings. This in turn requires the building foundation to support a similar contaminant mass flux as the ground surface of its surroundings. This condition is generally not met.

Open ground surface communicating with the atmosphere is often assumed to exist around the building in many real cases. Open ground may be similar to a crawl space with no slab, but for slab-on-grade or basement scenarios, the building foundation serves as a significant diffusion block (no-flux-boundary) compared with the open ground surface. Even for the crawl space cases with open floors, there might be a nonzero concentration boundary that is different from the assumed zero-concentration atmospheric sink. In OCHCA (Daugherty, 1991), an empirical attenuation factor for the contaminant mass-flow rate is used to capture the difference in the ability of the slab foundation and surrounding atmosphere to act as a contaminant sink. The attenuation factor, however, also implies that lateral gradients must exist, an assumption inconsistent with purely vertical transport and that makes the calculation of the contaminant mass-flow rate itself inaccurate.

To avoid having to account for lateral transport within an assumed one-dimensional model domain, the upper boundary condition should be homogenous. However, in many one-dimensional models, a perimeter crack is used to represent the entry into the building foundation. It is obviously unreasonable to use the crack area as the corresponding cross-sectional area of the model domain, because most of the domain is topped by an impermeable slab. So again, the homogenous boundary condition requirement is violated. The solution to this dilemma employed in the Johnson–Ettinger model (Johnson and

Ettinger, 1991) involves assigning an effective source area, which is defined by the area of foundation in contact with soil (slab plus walls). Thus the cross-sectional area for contaminant transport is neither the crack area nor the projected area of building footprint, but rather an empirical area related somehow to the actual building footprint. According to a recent study (Yao et al., 2011a), this effective source area is not constant and changes according to the boundary conditions assigned for the cracks.

The last problem with one-dimensional approaches is related to role of the atmosphere. In the setting of many one-dimensional models, there must exist an open surface surrounding the building, otherwise the soil gas flow induced by pressure difference is difficult to explain, because the origin of any pressure gradient would be unclear. Earlier studies (Lowell and Eklund, 2004; Yao et al., 2011a, 2012) show that the atmosphere plays a more significant role as a sink for contaminants than the foundation cracks do, which is also common sense. In other words, the atmosphere above an open surface around a building serves as a much more important sink than cracks in the foundation slab, due to the open surface's much larger area. The atmosphere also defines any advection in the process by setting the background pressure in the domain. This shows the danger in assuming that all of the contaminant released below must necessarily enter the structure as required in one-dimensional models. Some site investigations indeed showed (Provoost et al., 2009, 2010) that one-dimensional screening tools tend to overestimate soil air concentrations.

To avoid the above problems inherently existing in the one-dimensional models, an alternative is to construct a two-dimensional scenario to take the roles of the atmosphere and lateral transport into consideration. Moreover, it means that the upper boundary of the model does not have to be uniform. In a study by Tillman and Weaver (2007), a two-dimensional, variably saturated water-flow model, HYDRUS-2D, was used to simulate the soil moisture content across 2 yr. The simulated results were then used to calculate the effective diffusivities of three soil layers with the Millington–Quirk equation (Millington and Quirk, 1961). However, the indoor air concentration was still obtained on the basis of a one-dimensional model, the Johnson–Ettinger model.

In our previous research (Yao et al., 2012), the analytical approximation method (AAM) was developed for a two-dimensional scenario where an infinite source is assumed to be uniformly distributed at bottom and effective diffusivity is uniform or vertically layered. However, in reality, contaminant-source distribution is generally not uniform except perhaps in some certain localized areas. Hence the question will often arise as to how a contaminant-source distribution might affect any particular structures that might be subject to vapor intrusion from that source. In this paper, a lateral source–building separation was taken into consideration on the basis of the previously published AAM.

The USEPA, in its draft guidance of 2002 (USEPA, 2002), has suggested that buildings within 100 ft of a plume be evaluated for vapor intrusion, a conclusion echoed by the Interstate Technology and Regulatory Council (2007), which noted, however, that the distance could be influenced by both the potential for biodegradation of the contaminant, by preferential pathways, and by the possibility of transient effects.

The issue of lateral source–building separation has been addressed by a few studies. Little et al. (1992) considered convection due to a pressure difference between a landfill and receptor to be the main driving force for transport of the contaminant. But in most instances of vapor intrusion, advection plays only a minor role in influencing subsurface concentration profiles (Abreu and Johnson, 2005; Bozkurt et al., 2009; Yao et al., 2011b, 2012). Lowell and Eklund (2004) employed a simple mathematical analysis to study the process of lateral diffusion in vapor intrusion, but in that study, the role of a building was not considered, which prevents the use of the analysis in practice.

Another study (Abreu and Johnson, 2005), which was based on a three-dimensional fluid dynamics model, explored several aspects of this problem in the context of typical scenarios and has in many ways reaffirmed many of the earlier conclusions, indicating the significant role of lateral diffusion in soil gas concentration attenuation processes, though it also made clear that there can be no single “answer” to the question of a safe distance. The quantitative influences of model parameters, however, were not discussed.

In this paper, a vapor-intrusion model based on a two-dimensional analytical approximation is developed to provide an estimate of contaminant subsurface concentration. This new method not only includes the influence of lateral source–building separation but also clearly identifies the role of important parameters in the vapor-intrusion scenario.

METHOD DEVELOPMENT

The Equation Governing Soil-Vapor Transport

In vapor intrusion, the general governing equation for soil-vapor transport in the vadose zone can be described as follows (Abreu and Johnson, 2005):

$$\varphi_{g,w,s} \frac{\partial c_{ig}}{\partial t} = -\nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right) + \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad [1]$$

where

$$\varphi_{g,w,s} = \varphi_g + \frac{\varphi_w}{H_i} + \frac{k_{oc,i} f_{oc} \rho_b}{H_i} \quad [2]$$

In Eq. [1] $\varphi_{g,w,s} \frac{\partial c_{ig}}{\partial t}$ refers to the time dependence of the contaminant mass contained in the soil gas, the soil moisture, and the soil organic carbon as shown in Eq. [2];

$-\nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right)$ is the convection term reflecting contaminant movement with soil gas and, if relevant, groundwater flow;

$\nabla \cdot (D_i \nabla c_{ig})$ describes the diffusion of contaminant in the soil gas phase (contaminant diffusion through the water phase is neglected because of its much lower diffusivity in a condensed phase compared with that in a vapor phase); q_g is the soil gas flow per unit area [$L_{gas}^3 L_{soil}^{-2} T^{-1}$]; q_w is the groundwater flow per unit area [$L_{water}^3 L_{soil}^{-2} T^{-1}$]; Φ_g is the

air-filled porosity [$L_{\text{gas}}^3 L_{\text{soil}}^{-3}$]; Φ_w is the moisture-filled porosity [$L_{\text{water}}^3 L_{\text{soil}}^{-3}$]; H_i is the Henry's Law constant for the contaminant [$(M_i L_{\text{gas}}^{-3})/(M_i L_{\text{water}}^{-3})$], linearly relating the vapor-phase contaminant concentration to the water-phase concentration; $k_{oc,i}$ is the sorption coefficient of contaminant i to organic carbon in the soil [$(M_i M_{oc}^{-1})/(M_i L_{\text{water}}^{-3})$]; f_{oc} is the mass fraction of organic carbon in the soil [$M_{oc} M_{\text{soil}}^{-1}$]; ρ_b is the soil bulk density [$M_{\text{soil}} L_{\text{soil}}^{-3}$]; c_{ig} is the concentration of contaminant i in the gas phase [$M_i L_{\text{gas}}^{-3}$]; D_i is the overall effective diffusion coefficient for transport of contaminant i in porous media [$L^2 T^{-1}$]; R_i is the rate of loss of contaminant i by biodegradation [$M_i L_{\text{soil}}^{-3} T^{-1}$]; and $\Phi_{g,w,s}$ is the effective transport porosity [$L_{\text{air}}^3 L_{\text{soil}}^{-3}$], defined in Eq. [2].

In summary, there are four general factors that play a key role in soil vapor transport: advection, diffusion, transient processes, and biodegradation.

1. In this study, the focus is on contaminants that are considered to be nonbiodegradable under normal conditions, for example, perchloroethylene and trichloroethylene (USEPA, 2011), so biodegradation is not taken into consideration here.
2. The advection can involve water or soil gas. In a distant-landfill scenario (Little et al., 1992), advection due to a large pressure difference between a landfill site and ambient was the principal driving force for lateral transport. On the other hand, water flow in the vadose zone, for example that induced by rain water, can also have a significant effect on soil vapor transport. In most vapor intrusion sites, these effects are not considered. In models of most vapor intrusion scenarios, soil gas advection was induced by depressurization of an indoor air space.
3. It was reported that a highly permeable soil layer accompanied by high indoor depressurization (Nazaroff et al., 1987) and unbalanced depressurization induced by a wind effect (Luo et al., 2009) can produce a significant advection, which could play a role in the subslab contaminant concentration profile. Similar phenomena were also found by a series of studies conducted with three-dimensional numerical models by Abreu (2005) and Bozkurt et al. (2009). However, in other studies (Abreu, 2005; Abreu and Johnson, 2005; Yao et al., 2012), the advection induced by a pressure difference between the indoor air and the atmospheric is usually too weak to affect the general soil gas concentration profile. This was true in cases with soil permeability from 10^{14} to 10^{10} m^2 for indoor-atmosphere pressure differences ranging from +5 to $\pm 20 \text{ Pa}$, as shown by three-dimensional simulations. Site investigations have also shown that the subslab contaminant concentrations were independent of the indoor air-pressure change in most cases (McHugh et al., 2012). In this study, it is assumed that the advection induced by underpressurization of indoor air is not a parameter with a significant effect on subsurface soil gas profiles and is therefore ignored.
4. In one document (USEPA, 2012a), the EPA discussed the effects of moisture contents and sorption on transient transport. In another paper (Yao et al., 2010), the effect of source depletion was simulated. Both studies showed that these transient processes need months or years to play a role in soil-gas concentration profiles. The

method developed in this study provides an estimate of source-to-subslab soil-gas concentration attenuation factor in a steady state, which makes transient effects negligible. But the possible influence of transient effects should always be kept in mind.

Therefore, in this study, a semi-analytical model was developed based on the assumption of a steady-state soil gas diffusion with uniform effective diffusivity. Advection and dispersion are not considered in this model, as explained above. A lateral displacement of contaminant vapor source from the edge of the building foundation is also assumed. The general governing vapor-transport equation in steady state can be simplified to the Laplace equation, and this makes the solution to the concentration profile independent of the diffusion coefficient.

Scenario Construction

The entry of subsurface gas-phase contaminants by advection through foundation cracks or breaches is believed to be the primary pathway for soil gas to enter a building of concern located above or near contaminated sites (Robinson and Sextro, 1997). Although in some vapor-intrusion screening tools advective flow through foundation cracks is assumed to also influence the transport soil vapor of deeper soil (Brand et al., 2007; Jury et al., 1983; Waitz et al., 1996), already-discussed recent studies, including three-dimensional simulations and site experiments (Abreu and Johnson, 2005; McHugh et al., 2012; Yao et al., 2012;), suggest that the role of building operation conditions on the subslab contaminant concentration profile is limited.

In a previous study (Yao et al., 2012), a simple two-dimensional approximation to the full three-dimensional situation was first developed on the basis of the scenario shown in Fig. 1. The line EF approximates the groundwater source at the bottom of the domain shown in Fig. 2b. At this boundary, the contaminant vapor concentration (c) is taken to be at its source value, $c = c_s$. The line segment AB represents the open ground surface at which $c = 0$, indicating the contaminant vapor concentration in the atmosphere. The line segments BC and CD represent the outside boundaries of a building foundation, which is assumed to be impermeable for soil gas flux. The perimeter foundation slab crack shown in Fig. 2c is not explicitly considered in the simplified two-dimensional scenario, since the focus here is on the concentration profile around the foundation.

The Laplace Equation

A simple semi-analytical approach to describing steady-state subsurface contaminant vapor profiles that was used in a previous study (Yao et al., 2012) will serve as the basis for the current work. In that method, the Laplace equation was applied to describe subsurface contaminant gas profiles:

$$\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} = 0 \quad [3]$$

where c represents the contaminant concentration in soil gas, and x and y represent the lateral and horizontal coordinates in a domain of interest. As shown in Fig. 2, a vapor source

is assumed at the bottom of the soil domain of interest, which provides contaminant vapor at concentration c_s , and an open ground surface is assumed outside of the building of interest, where the contaminant soil gas concentration is assumed to be zero. The mathematics for handling this problem are presented by Yao et al. (2012). In short, a conformal transformation of the upper half-plane onto the interior of a simple polygon, called a Schwarz–Christoffel mapping (Carslaw and Jaeger, 1959), was used to obtain the normalized contaminant concentration at point C in a two-dimensional scenario, as shown in Fig. 2d, and the results can be shown as:

$$\frac{c(\text{at point C})}{c(\text{at line EF})} \approx \sqrt{\frac{d_f}{d_s}}, \text{ or } \left(\frac{d_f}{d_s}\right)^{0.7} \text{ for 3-D} \quad \text{(Yao et al., 2012)} \quad [4]$$

where d_f is the depth of the building foundation and d_s is the depth of the vapor source, as shown in Fig. 2d. In the same reference, the equation was also extended to include cases with multilayer soil. However, these equations only work for cases with an infinite uniform source, as assumed in the Johnson–Ettinger model (Johnson and Ettinger, 1991).

Analytical Approximation Method: Considering Lateral Source–Building Separation

Here, we further develop the earlier analytical approximation to include an offset between the vapor source and receptor structure. The relevant scenario is shown in Fig. 3. The line GF approximates the groundwater source at the bottom of the domain ($c = c_s$), but note that it does not extend below the structure of interest, which is defined by the line segments BC and CD. The segment EG is assumed to be an impermeable groundwater surface, but at this boundary, the groundwater is assumed to be clean and does not serve as a source of contaminant vapor.

The same Schwarz–Christoffel mapping that was noted above can be used to obtain a solution to this problem (Carslaw and Jaeger, 1959; Yao et al., 2012). Figure 4 shows a graphical representation of the mapping.

The conformal transform in scenario of Fig. 4 can be written

$$\frac{dz}{ds} = \frac{C_1(s+1)^{0.5}}{s(s+a)^{0.5}} \quad [5]$$

where a is the x -coordinate of $B'(-a, 0)$ in the s plane, and C_1 is a constant.

The general solution of Eq. [5] is

$$z = C_1 \ln \left[\frac{1 + \sqrt{(s+1)/(s+a)}}{1 - \sqrt{(s+1)/(s+a)}} \right] + \frac{C_1}{\sqrt{a}} \ln \left[\frac{\sqrt{a(s+1)/(s+a)} - 1}{\sqrt{a(s+1)/(s+a)} + 1} \right] + C_2 \quad [6]$$

where C_2 is another constant.

Substituting the transforms of $D(-\infty, 0)$ to $D'(0,0)$, $C(0, d_s - d_f)$ into $C'(-1, 0)$ and $B(0, d_s)$ to $B'(-a, 0)$, Eq. [6] becomes:

$$z = \frac{d_s}{\pi} \ln \left\{ \frac{1 + \sqrt{\frac{s+1}{s+[d_s/(d_s-d_f)]^2}}}{1 - \sqrt{\frac{s+1}{s+[d_s/(d_s-d_f)]^2}}} \right\} + \frac{d_s - d_f}{d_s} \ln \left\{ \frac{\frac{d_s}{d_s - d_f} \sqrt{\frac{s+1}{s+[d_s/(d_s-d_f)]^2}} - 1}{\frac{d_s}{d_s - d_f} \sqrt{\frac{s+1}{s+[d_s/(d_s-d_f)]^2}} + 1} \right\} \quad [7]$$

And the domain in Fig. 4a can be approximately transformed into a half plane shown in Fig. 4b.

What is of main interest is the concentration at the point C, which is a surrogate for the subslab concentration (in a perimeter crack type of model, it is the most relevant subslab concentration, as it is that which exists at the building entry point). In the transformed space, it is only the position of C' relative to the source at G' and sink B' that determines the concentration c at the point C' (C).

According to Yao et al. (2012), the concentration at segment $B'G'$ in the s plane can be described as

$$c \left[-\left(\frac{d_s}{d_s - d_f}\right)^2 < X < \frac{d_s}{d_s - d_f} e^{(d_h/d_s)\pi}, 0 \right] \\ \approx \arccos \left[-2 \frac{X - \frac{d_s}{d_s - d_f} e^{(d_h/d_s)\pi}}{\frac{d_s}{d_s - d_f} e^{(d_h/d_s)\pi} + \left(\frac{d_s}{d_s - d_f}\right)^2} - 1 \right] \quad [8]$$

For $C'(1, 0)$, there is

$$c(-1, 0) \approx \arccos \left[-2 \frac{1 - \frac{d_s}{d_s - d_f} e^{(d_h/d_s)\pi}}{\frac{d_s}{d_s - d_f} e^{(d_h/d_s)\pi} + \left(\frac{d_s}{d_s - d_f}\right)^2} - 1 \right] \quad [9] \\ \approx \sqrt{\frac{d_f}{d_s}} e^{-(d_h/2d_s)\pi}$$

This result permits examining how the subslab concentration should vary as a function of source depth, foundation depth, and source displacement distance.

RESULTS AND DISCUSSION

The Averaged Subslab Crack Concentration

There is no single value for crack concentration in an actual three-dimensional representation, a result of the differences of the crack distance to the source. Although this method can provide a conservative estimate of the subslab crack concentration, an averaged subslab concentration is still preferred for obtaining the entry rate of the contaminant into the building. Here we use a full three-dimensional numerical model to examine the relationship between the maximum subslab concentrations where it is closest to the vapor source edge and the averaged subslab perimeter crack concentration. This model was developed with the help of the Comsol finite element package, and the model has been

introduced and used in previous studies (Bozkurt et al., 2009; Pennell et al., 2009; Shen et al., 2012; Yao et al., 2011a or 2011b, 2012). The cases considered can be again described as a single structure built atop an otherwise flat, open field underlain by a homogeneous soil that stretches from the ground surface to a water table (as in Fig. 3). There is a contaminant vapor source located at some distance from the building foundation edge. Relevant modeling parameters are shown in Table 1, and the simulated results are shown in Table 2.

Based on the numerical simulations, a value of half that in Table 2 is suggested for an averaged crack concentration, due to the variation of crack location relative to source:

$$\left(\frac{c_{ck}}{c_s}\right)_{\text{average}} \approx \frac{1}{2} \sqrt{\frac{d_f}{d_s}} e^{-(d_h/2d_s)\pi} \quad [10]$$

Comparison with Other Three-Dimensional Simulations

The three-dimensional modeling cases shown in Table 3 were published by Abreu and Johnson (2005), but the actual values used here were taken from Abreu's dissertation (2005). Although it is not directly shown in the dissertation or paper, the subslab crack contaminant concentration was calculated from the simulation results for the indoor air attenuation factor and other given model parameters. The data in Table 3 are the averaged subslab crack concentrations normalized to the source concentration (c_{ck}/c_s) (Eq. [10]). In general, the results all agree quite well, providing a partial validation for this new method.

Examination of EPA vapor intrusion database when considering lateral diffusion

Figure 5 was constructed using the above new AAM and data from the EPA vapor intrusion database (USEPA, 2012b) and by defining a new parameter, $r = d_h/d_s$, which is the ratio of the distance between the source edge and building (d_h) to the source depth. The predictions of the earlier basic model (Yao et al., 2012), which involved no separation, are shown as the solid line, but the various dash-dotted curves show different values of r . It is apparent that even a modest displacement ($r = 1$) relative to d_s can make a very large difference in the predicted subslab concentration. Again, this conclusion by itself is not necessarily new, but seeing it in the context of the variation of field results is revealing.

Analytical simulations with r values up to 6 capture most of the variability in the data published in the USEPA database. If the average source depth were 4 m, then the largest implied distance of separation (lateral diffusion distance) implied by $r = 6$ would be about 24 m. This is based on the assumption that lateral diffusion is the main cause of the measured groundwater-to-slab concentration attenuation factor.

Figure 5 is not to be taken as a validation or evaluation of the the AAM, since there is no such lateral source–building distance information recorded in the EPA database. Based on Table 3, the AAM would be a good estimate of subslab concentration if diffusion is the main mechanism of soil vapor transport, which is also a common assumption of most vapor intrusion models involving no biodegradation. Although the application of this method is limited to cases with homogenous soil, it is shown that lateral diffusion could potentially be playing an important role in actual cases.

The practical interpretation of Fig. 5 is that care must be exercised in assuming that the contaminant concentrations in “nearby” monitoring wells will be sufficient to characterize the source in a conceptual site model, since the models show that the influence of a subsurface source falls off very quickly as that source is moved away from beneath a building. It is the case that in many instances, monitoring wells characterizing a groundwater source may be located at some distance from where subslab vapor sampling takes place, and there is a need to guess at the extent and boundaries of a groundwater source plume.

Ignoring lateral diffusion could be a possible explanation for the overestimation of soil air concentration by screening-level models reported in earlier studies (Provoost et al., 2009, 2010), since these screening tools focus only on vertical transport. Take, for example, a water table at a depth of 8 m ($d_s = 8$ m). Then if the effective edge of the contaminated plume were 16 m laterally removed from a 2-m deep basement, $d_f/d_s = 0.25$ and $r = 2$. The “effective edge” is defined by where the contaminant groundwater concentration becomes that value reported from a monitoring well as characterizing the source. Under such circumstances, the normalized subslab contaminant concentration would be approximately 0.01. This is much lower than the expected vapor contaminant concentration if the source of that concentration were directly below the building ($0.1 < c_{ck}/c_s < 1$).

As another example of how Fig. 5 could be used, consider a case of slab-on-grade construction over a water table at a depth of 4 m (such that $0.01 < d_f/d_s < 1$). Then assume that a subslab concentration of 10^{13} times the source concentration is measured. The question could then be asked whether a lateral separation from the contaminant plume at the presumed contaminant concentration could be responsible for such a low subslab value. From Fig. 5, the value of r would need to be between 3 and 4, meaning that the lateral separation from the edge of the contaminated plume would need to be 12 to 16 m. Other site data could help establish whether or not this was plausible, and from that, whether other explanations of the low subslab concentration should be sought.

There remains an issue with the above analysis that warrants attention. In some cases, especially in urban areas, the area between the vapor source and the building might be a paved impermeable surface, as opposed to an open surface. In this case, the present analytic method will also underestimate subslab concentrations. In other words, dense paving will tend to minimize the effects of foundation–source separation. Moreover, a differential moisture content outside the building slabs may reduce permeability and lead to the same result.

CONCLUSIONS

Based on the newly developed AAM, the potential impact of groundwater source inhomogeneity on subslab contaminant concentration is easily assessed. Based on a diffusion-dominated mechanism, the AAM indicates that lateral source–building separation may play an important role in groundwater-to-subslab concentration attenuation factors. In general, as a screening tool, the AAM can be conveniently used not only to examine the influence of lateral source–building separation but also to help characterize groundwater plume sources.

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Abbreviations

AAM analytical approximation method

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Figure 1.
Scheme of vapor intrusion (USEPA, 2008).

Figure 2.

Cross-sectional view of (a) full domain of interest; (b) boundary conditions of modeled half domain; (c) details of modeled perimeter crack in 3-D simulation; (d) the 2-D scenario used for obtaining the approximation for subslab perimeter crack concentration (Yao et al., 2012).

Figure 3.

The modeling scenario with lateral source–building separation.

Figure 4.

Transform for an isolated building with a finite source laterally separated from the building foundation: (a) approximation considering half structure; (b) after transform of the situation in (a).

Figure 5.

The ratio of measured subslab concentration (c_{ck}) to measured vapor concentration of groundwater source (c_s) as a function of the ratio of foundation depth to source depth (d_f/d_s). Based on EPA vapor intrusion database for perchloroethylene and trichloroethylene, assuming different contaminant source-building separations (USEPA, 2012b; Yao et al., 2012). $r = d_h/d_s$, the ratio of source-edge-to-building distance (d_h) to source depth (d_s). Solid and dashed lines are simulated results based on Eq. [6].

Table 1

Input parameters used in the three-dimensional simulations.

Building and foundation parameters
Indoor air depressurization: ± 5 Pa
Domain cross-sectional size: 100 by 70 m
Contaminant source size: 30 by 30 m
Foundation foot print: 10 by 10 m
Depth of foundation: 0.2 or 2 m
Crack/foundation slab thickness (d_f): 0.152 m
Crack width (w_{ck}): 0.005 m
Depth to groundwater/source (d_s): 3, 8 m bgs
Lateral building-source separation (d_h): 1, 2, 5, 8, 16 m bgs
Three-dimensional finite element analysis parameters
Size of the grid elements: 0.001–1 m
Number of elements: 2×10^5 to 1×10^6
Contaminant vapor source properties
Contaminant: trichloroethylene
Diffusivity of trichloroethylene in crack (D^{ck}): $7.4 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$
Effective diffusivity of trichloroethylene in soil (D^{ck}): $1.04 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$
Soil gas flow properties
Viscosity of air/soil gas (μ_g): $1.8648 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$
Density of air/soil gas (ρ_g): 1.1614 kg m^{-3}
Soil permeability (k): 10^{-11} m^2
Total soil porosity (Φ_t): 0.35
Soil porosity filled with gas (Φ_g): 0.296

Table 2

Comparison of predicted normalized subslab crack concentrations (c_{ck}/c_s) from the analytical approximation method (AAM; Ea. [9]) with results from full three-dimensional (3D) simulations.

d_h (m)	AAM	3D(M)	3D(A)	3D(A)/3D(M)	AAM/2
$d_t = 2$ m, $d_s = 8$ m					
1	4.11E-01	2.55E-01	1.42E-01	0.56	2.06E-01
2	3.38E-01	2.24E-01	1.22E-01	0.54	1.69E-01
5	1.87E-01	1.38E-01	7.22E-02	0.52	9.35E-02
8	1.04E-01	7.89E-02	4.04E-02	0.51	5.20E-02
16	2.16E-02	1.59E-02	8.03E-03	0.51	1.08E-02
$d_t = 0.2$ m, $d_s = 8$ m					
1	1.30E-01	5.63E-02	3.28E-02	0.58	6.50E-02
2	1.07E-01	4.90E-02	2.80E-02	0.57	5.35E-02
5	5.92E-02	3.00E-02	1.65E-02	0.55	2.96E-02
8	3.29E-02	1.70E-02	9.21E-03	0.54	1.65E-02
16	6.83E-03	3.42E-03	1.83E-03	0.54	3.42E-03

Table 3

Comparison of predicted average perimeter crack subslab concentrations (c_{ck}/c_s) from the analytical approximation method (AAM) with results from full three-dimensional simulations [3D(A)].[‡]

d_h (m)	$d_s = 3$ m		$d_s = 8$ m	
	$d_f = 2$ m			
	3D(A)	AAM(A)	3D(A)	AAM(A)
0	2.62E-01	4.05E-01	1.75E-01	2.50E-01
5	2.75E-02	2.98E-02	8.20E-02	9.37E-02
10	2.41E-03	2.17E-03	3.20E-02	3.51E-02
20	1.82E-05	1.16E-05	4.03E-03	4.93E-03
	$d_f = 0.2$ m			
	3D(A)	AAM(A)	3D(A)	AAM(A)
0	1.03E-01	1.22E-01	7.08E-02	7.91E-02
5	1.11E-02	9.42E-03	—	—
10	9.39E-04	6.87E-04	1.22E-02	1.11E-02
20	8.39E-06	3.66E-06	1.67E-03	1.56E-03

[‡] Results from the AAM are divided by 2 to obtain the averaged subslab concentration [AAM(A)], as shown in Eq. [10] (Abreu, 2005).