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Evaluation of site-specific lateral inclusion zone for vapor intrusion based on an analytical approach

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Abstract

In 2002, U.S. EPA proposed a general buffer zone of approximately 100 feet (30 m) laterally to determine which buildings to include in vapor intrusion (VI) investigations. However, this screening distance can be threatened by factors such as extensive surface pavements. Under such circumstances, EPA recommended investigating soil vapor migration distance on a site-specific basis. To serve this purpose, we present an analytical model (AAMLPH) as an alternative to estimate lateral VI screening distances at chlorinated compound-contaminated sites. Based on a previously introduced model (AAML), AAMLPH is developed by considering the effects of impervious surface cover and soil geology heterogeneities, providing predictions consistent with the three-dimensional (3-D) numerical simulated results. By employing risk-based and contribution-based screening levels of subslab concentrations (50 and 500 $\mu\text{g}/\text{m}^3$, respectively) and source-to-slab attenuation factor (0.001 and 0.01, respectively), AAMLPH suggests that buildings greater than 30 m from a plume “boundary” can still be affected by VI in the presence of any two of the three factors, which are high source vapor concentration, shallow source and significant surface cover. This finding justifies the concern that EPA has expressed about the application of the 30 m lateral separation distance in the presence of physical barriers (e.g., asphalt covers or ice) at the ground surface.

Keywords

Vapor intrusion; lateral inclusion zone; analytical approach; surface cover; layering

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Introduction

Vapor intrusion (VI) is a process by which chemical vapors originating from subsurface sources migrate into the enclosed space of the buildings above the contamination site [1], and can induce negative effects on human health [2–4]. To identify a complete VI exposure pathway, U.S. EPA recommended screening evaluations by using sampling, mathematical models, empirical concentration attenuation factors and separation distances [5–15]. For example, 100 feet (30 m) laterally was considered as a reasonable criterion for diffusive transport in the absence of preferential pathway. Independent of site-specific characterizations, the judgment of 30 m laterally was summarized based on available information and practice experiences up to 2002. This recommended lateral separation distance is also supported by recent modelling studies [7, 16–17], which reported that a 30 meter lateral transport distance can induce at least 3 orders of magnitude attenuation in soil gas concentration, unless involving a very deep vapor source.

However, the scenarios simulated in above modelling work are limited to homogenous soil gas diffusivity and the absence of physical barrier at ground surface. In practice, especially in urban areas, the ground surface can be paved and become impervious or difficult for soil gas flow to go through. Previous studies showed that such capping effect can increase the contaminant subslab vapor concentration when source plume is beneath the building foundation [18–19]. On the other hand, the spatial variabilities of soil gas concentration identified in field studies implied a possibility that soil heterogeneities may also play a role [20–26]. In EPA's spreadsheet version of the Johnson-Ettinger (J-E) model, the van Genuchten parameters for 12 kinds of soil type (SCS soils) are provided so that they can be chosen to apply in a multilayer system [27]. Even in scenarios involving single type of soil, the spatial variability of moisture content due to capillary fringe and rainfall events could also affect the distribution of the effective diffusivity of soil gas [28–30].

Though these studies involving paved surface and soil heterogeneities focus on the influences of individual factor, and are limited to vertical soil gas transport, the results still hint at the need to examine the lateral separation needed to achieve a sufficient attenuation under the circumstances with joint influences of those factors. Moreover, EPA recommended investigating soil vapor migration distance on a site-specific basis in cases where the 30 m buffer is threatened by significant surface cover and become inappropriate to apply [5]. In this study, with the help of three-dimensional (3-D) numerical simulations and mathematical approximations, we introduce a VI screening tool (AAMLPH) as an alternative to evaluate lateral VI inclusion zones based on site-specific characterizations including surface cover and soil geology, by employing a critical subslab concentration C_{ss} and source-to-subslab attenuation factor α_s^{ss} as the screening criteria. Similar to the Analytical Approximations Methods (AAMs) developed in previous studies [17, 31–32], AAMLPH can be used independent of building operational conditions without computational efforts.

Methods

3-D numerical model

The development, validation and applications of the 3-D finite element model examined here were already presented in former studies [18–20, 28–33]. In the present study, the model is applied only in a steady-state mode for non-degradable contaminants. The scenarios studied consist of a single square 10 m × 10 m footprint structure built on a field of 100 m × 50 m, with a vapor source plume (10 m × 10 m). Since all scenarios studied here are symmetrical, only a half domain is actually simulated. Impervious boundary conditions are employed at parts of ground surface between the building and the vapor source to simulate the physical barrier such as asphalt, concrete, or frozen soil, though in some studies the concrete slab was considered permeable to soil gas flow but of higher resistance compared to soil [34–35]. For readers who are interested in the differences between impervious and low-permeability slabs, a comparison is provided in the discussion section below. In the present study, the thickness of the pavements and the base course layer are not considered here, either. The non-flux boundary conditions are also applied at planes of symmetry, the groundwater surface and the foundation (except for the crack). The open ground surface is taken to be at atmospheric reference pressure and is a sink of zero contaminant concentration. A negative pressure of -5 Pa and a contaminant flux equation is assigned at the crack, the same as in the former studies [28–33]. The detailed parameters are shown in Table 1. Though permeability and diffusivity are both related to the porosity of the soil, permeability is assumed to be constant here because advection does not have a significant impact on soil gas transport [36].

Scenarios simulated

The simulated scenarios can be divided into three groups. The first is the cases with (partially) paved ground surface and uniform soil geology, the second involves heterogeneous soil and the absence of surface cover, and the last includes (partially) paved ground surface and heterogeneous soil. In cases examining the capping effect on lateral soil gas transport, pavements of different location and size are assumed between building and vapor source. The pavement is in stripe shape and perpendicular to source-building separation, with a length equal to the width of the model domain. Take the cases with lateral source-building separation as 60 m for example, the separation distance between paved ground and building varies from 0 m to 50 m, and the width ranges from 10 m to 60 m, as shown in Figure 1. To study the heterogeneities of soil geology on lateral soil gas transport, different horizontal soil layers are employed. The scenarios involve three-layer and two-layer systems, simulating the influences of the vertical geologic variation and capillary fringe, respectively. For the former, the thickness of the top layer is 3 m, the middle layer is from 3 m below ground surface (bgs) to 6 m bgs, and the remain is the bottom layer. In the two-layer ones, the thickness of bottom layer (capillary fringe) depends on the soil type above the groundwater, and is obtained from the EPA's spreadsheet of the J-E model. In both kinds of scenarios the source depth is 8 m below ground surface (bgs). For the last group of scenarios involving both pavements and soil heterogeneities, the arrangements are similar to the second group involving only soil heterogeneities, except that pavements of different size and location are employed.

AAMs upon which AAMLPH is based

In 2012, Yao *et al.* proposed a simple equation to estimate non-degradable contaminant subslab concentration for cases with homogenous source distribution and soil geology [31]:

$$\frac{C_{ss}}{C_s} \approx \sqrt{\frac{d_f}{d_s}} \quad (1)$$

where C_s is the source vapor concentration [M/L³]; d_f and d_s are the foundation depth and source depth below ground surface [L], respectively. For scenarios involving multilayer soil geology, equation (1) was modified as

$$\frac{C_{ss}}{C_s} \approx \sqrt{\frac{\frac{d_f}{D_n}}{\sum \frac{L_i}{D_i}}} \quad (2)$$

where n is the total number of layers, L_i and D_i are the thickness [L] and the effective diffusivity in i layer counted from the bottom [L²/T]. For cases involving laterally displaced source, uniform soil geology and pure open ground surface except building foundation, equation (1) was modified as [17]:

$$\left. \frac{C_{ss}}{C_s} \right|_{max} \approx \sqrt{\frac{d_f}{d_s}} \exp\left(-\frac{\pi d_h}{2d_s}\right) \quad (3)$$

where $\left. \frac{C_{ss}}{C_s} \right|_{max}$ is normalized contaminant subslab crack concentration at the location most close to the vapor source plume and d_h is the horizontal separation distance between the

source plume and building edges [L]. Equation (3) consists of two parts, $\sqrt{\frac{d_f}{d_s}}$, representing vapor concentration attenuation during vertical transport, and $\exp\left(-\frac{\pi d_h}{2d_s}\right)$, the attenuation during horizontal transport. This implies two assumptions, the independence of vapor concentration attenuations in both directions and exponential decay with the lateral transport distance in the absence of surface cover.

Development of AAMLPH

For cases with surface cover, the decay rate along the horizontal diffusion pathway is decreased. Therefore an “effective lateral diffusion distance” is defined as follows:

$$L_e = L_o + rL_p \quad (4)$$

where L_e , L_o , and L_p are effective lateral diffusion distance, the lateral transport distance below open ground surface and the distance with surface cover [L], respectively; r is the coefficient, meaning the decay of soil gas concentration along the lateral diffusion distance L_p below surface cover equals that along a distance as $r \times L_p$ beneath open ground surface. It should be noted that equation (4) is based on the assumption that the location of the surface

cover between building and vapor source plays an insignificant role in determining $\frac{C_{ss}}{c_s} \Big|_{max}$. In such way, equation (3) can be modified to apply in scenarios with the presence of impervious surface cover and uniform soil gas diffusivity.

$$\frac{C_{ss}}{c_s} \Big|_{max} \approx \sqrt{\frac{d_f}{d_s}} \exp \left(-\frac{\pi(L_o + rL_p)}{2d_s} \right) \quad (5)$$

As for a multilayer system in the absence of surface cover, $\frac{C_{ss}}{c_s} \Big|_{max}$ can be obtained by employing an approximation technique of mass conservation (details are shown in Appendix A):

$$\frac{C_{ss}}{c_s} \Big|_{max} \approx \sqrt{\frac{\frac{d_f}{D_n}}{\sum \frac{L_i}{D_i}}} \exp \left(-\frac{\pi d_h}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_i}{D_j} - \sum_i \frac{L_i}{D_j} \right) \right)}} \right) \quad (6)$$

where the number of layer is counted from the bottom and $\sum_0 \frac{L_j}{D_j} = 0$. It should be noted that equation (3) can be obtained by assuming a uniform diffusivity in equation (6). By

combing equations (5) and (6), $\frac{C_{ss}}{c_s} \Big|_{max}$ for a multilayer system involving soil heterogeneities is proposed as follows:

$$\frac{C_{ss}}{c_s} \Big|_{max} \approx \sqrt{\frac{\frac{d_f}{D_n}}{\sum \frac{L_i}{D_i}}} \exp \left(-\frac{\pi (L_o + rL_p)}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_i}{D_j} - \sum_i \frac{L_i}{D_j} \right) \right)}} \right) \quad (7)$$

where $\sum_0 \frac{L_j}{D_j} = 0$. The value of r in equation (5) and (7) can be obtained through fitting the 3-D simulations, by employing a trial-and-error method. Equation (7) could be named as Analytical Approximation Method involving Lateral soil gas transport, Paved ground surface and Heterogeneous soil (AAMLPH).

Results and discussions

3-D simulations

Figure 2 shows simulated concentration profiles for different assumptions of pavements (impervious and low-permeability), and Figure 3 presents the simulated concentration profiles for different arrangements of pavements of the same size in total. The result indicate that the characteristics and the arrangements of pavements would not cause more than one

order of magnitude difference in $\frac{C_{ss}}{c_s} \Big|_{max}$ in the simulated scenarios. Therefore, the following discussions focus on scenarios with continuous impervious pavements.

Employing the model inputs shown in Table 1, the 3-D simulated soil gas concentration profiles are presented for cases with the presence of surface cover and layering in Figure 4, examining the individual or joint influences of impervious surface cover and layering on the soil gas concentration attenuation during lateral diffusive transport. Generally, the presence of surface cover will decrease the decay of soil gas concentration, while the layering can provide either positive or negative effects on the required lateral buffer zone, depending on the arrangements of soil layers. The simulations suggest that in the absence of surface cover, the most significant attenuation is observed for the arrangement shown in Figure 4 (c), the

low-med-high one, while $\left. \frac{C_{ss}}{c_s} \right|_{max}$ is highest in Figure 4(d), with an opposite high-med-low arrangement, with a variation of 2–3 orders of magnitude. Similar finding was also reported by a previous modelling study involving only vertical soil gas transport [20]. Moreover, the presence of capillary fringe can induce a similar effective diffusivity distribution as shown in Figure 4(c), indicating the conservative predictions by previous lateral transport models in the absence of surface cover [7, 16–17]. It should be noted that the significant decay in Figure 4(c) might be partly offset by the increase of soil gas entry rate into the building due to high permeability in top layer, though in the simulations the permeability is assumed to be independent of effective diffusivity.

Figure 5 shows the dependence of normalized subslab vapor concentration on the lateral soil gas transport distance beneath the impervious cover and open ground surface. The simulated results suggests that the attenuation is more sensitive with shadow sources, the decrease of vapor concentration is exponential to the lateral transport distance with open ground surface, and the influence of building foundation types is not significant. All of these are in agreement with previous studies involving lateral soil gas transport and the absence of surface cover [7, 16–17]. In the absence of soil heterogeneities, the influence of surface cover is quite significant, inducing up to 4 and 12 orders of magnitude variation in soil gas concentration attenuation for cases with d_s as 3 m and 8 m, respectively.

Though the scenarios studied are limited to idealized surface cover and simple geologic heterogeneities, the 3-D simulations do provide some insights in the evaluation of lateral site-specific VI buffer zone. For example, the influences of surface cover on soil gas concentration attenuation are found to be dependent on the soil geology. Usually, the role of surface cover is more significant for cases where the soil geology is in favor of soil gas

concentration decay, and the greatest difference of $\left. \frac{C_{ss}}{c_s} \right|_{max}$ is observed between (d) and (f) in Figure 4. This requires the consideration of both soil geology and surface cover to estimate lateral vapor migration distance, providing the justification to develop AAMLPH. Moreover, the simulations suggest it is the size of the surface cover instead of location that

determines soil gas $\left. \frac{C_{ss}}{c_s} \right|_{max}$, and the straight nature of the fitting curves in Figure 5 implies an exponential decay of soil gas concentration during the lateral transport even beneath the surface cover. Both findings offer a theoretical basis for AAMLPH.

Identification of “r” in AAMLPH

As discussed above, the value of r in AAMLPH can be obtained through fitting the 3-D simulations. Employing a trial-and-error method, different values in the range of 0–1 were substituted into equation (7) to make the best agreement between predicted maximum subslab concentrations and those from the 3-D simulations. Finally, the semi-empirical subslab concentration approximation is shown as follows:

$$\frac{C_{ss}}{c_s} \Big|_{max} \approx \sqrt{\frac{\frac{d_f}{D_n}}{\sum \frac{L_i}{D_i}}} \exp \left(- \frac{\pi \left(L_o + \frac{L_p}{6} \right)}{\sqrt[2]{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i=1}^{j-1} \frac{L_i}{D_i} - \sum_{i=j+1}^n \frac{L_i}{D_i} \right) \right)}} \right) \quad (8)$$

The comparison of predicted subslab concentrations for non-degradable contaminant vapors, obtained by using equation (8) and the 3-D model is shown in Figure S1 in supplemental information. For two-layer and three-layer systems, equation (8) can be written as:

$$\frac{C_{ss}}{c_s} \Big|_{max} \approx \begin{cases} \sqrt{\frac{\frac{d_f}{D_n}}{\frac{L_1}{D_1} + \frac{L_2}{D_2}}} \exp \left(- \frac{\pi \left(L_o + \frac{L_p}{6} \right)}{\sqrt[2]{L_1^2 + L_2^2 + 2 \frac{D_1}{D_2} L_1 L_2}} \right) & \text{for two-layer cases} \\ \sqrt{\frac{\frac{d_f}{D_n}}{\frac{L_1}{D_1} + \frac{L_2}{D_2} + \frac{L_3}{D_3}}} \exp \left(- \frac{\pi \left(L_o + \frac{L_p}{6} \right)}{\sqrt[2]{L_1^2 + L_2^2 + L_3^2 + 2 \frac{D_2}{D_3} L_2 L_3 + 2 \frac{D_1}{D_3} L_1 L_3 + 2 \frac{D_1}{D_2} L_1 L_2}} \right) & \text{for three-layer cases} \end{cases} \quad (9)$$

AAMLPH can also be employed to estimate a conservative indoor air concentration C_{in} by using a generic subslab-to-indoor air concentration attenuation factor α_{ss}^{in} as 0.02 [37–38].

Figure 6 shows sensitivity test of $\frac{1}{r}$ in predicting the maximum subslab soil gas concentration. Assuming a homogenous soil gas effective diffusivity, the change of r from

1/4 to 1/8 can produce half order of magnitude difference in $\frac{C_{ss}}{c_s} \Big|_{max}$ in scenarios with $d_s=8m$ and $L_p=30m$.

VI screening criteria

Though C_{in} is still considered as the major indicator for a complete VI pathway, EPA also recommended the assessments by using multiple lines of evidence, including employing soil vapor concentrations, to determine which buildings to include in VI investigation [5]. For example, 50 and 100 $\mu g/m^3$ have been employed as the risk-based screening levels for soil vapor concentration of benzene [39]. Besides the risk-based screenings, a contribution-based screening was proposed recently to identify the dominant sources responsible for the indoor air contaminants [37]. It was reported that there is a greater likelihood that C_{in} is determined by VI instead of background sources if $C_{ss} > 500 \mu g/m^3$ [37]. In the present study, independent of contaminant types, 50 and 500 $\mu g/m^3$ are chosen as the typical risk-based and contribution-based thresholds of C_{ss} for chlorinated chemicals (CHCs), respectively.

Moreover, the source-to-subslab concentration attenuation factor (α_s^{ss}) can also be used as an alternative to evaluate the required separation distance besides C_{ss} . Figure 7(a) shows the

distributions of the α_s^{ss} datasets remaining after screening out samples for which C_{ss} were reported less than 500 and 50 $\mu\text{g}/\text{m}^3$, respectively, for CHCs in EPA's VI database. It is found that most observed α_s^{ss} are above 0.01 and 0.001, respectively. This is most likely because most predicted groundwater source vapor concentrations C_s recorded in the database fall in a range between 325 and 820,000 $\mu\text{g}/\text{m}^3$, as shown in Figure 7(b). Since EPA's VI database represents the most comprehensive compilation of VI data for CHCs available up to now, it is reasonable to believe that 0.001 and 0.01 can be employed as the risk-based and contribution-based thresholds of α_s^{ss} appropriate for most VI sites impacted by CHCs.

Evaluating lateral VI inclusion zone

Employing the screening level of C_{ss} as 500 and 50 $\mu\text{g}/\text{m}^3$, Figures 8(a) and 8(b) reports the calculated effective lateral diffusion distance for VI inclusion as a function of C_s , respectively. The capillary fringe effects for different soil types are considered by employing the calculated thickness and corresponding soil gas effective diffusivity according to the EPA spreadsheet of the J-E model, except for the "homogenous" scenarios. The results show that a buffer zone of 30 m laterally can serve well for cases with shallow sources with $c_s < 10^8 \mu\text{g}/\text{m}^3$ in the absence of significant surface cover, regardless of the source strength. But for the scenarios with deep vapor sources, the 30 m lateral separation distance can barely provide enough soil gas concentration attenuation in the presence of a strong vapor source, even if most area of the ground surface is open to the atmosphere.

Table 2 showed the predicted $\left. \frac{C_{ss}}{c_s} \right|_{max}$ by AAMLPH for basement cases with single soil type. "Homogenous" means that the soil gas effective diffusivity is uniform in the whole domain, while in the other three scenarios the influences of capillary fringes on soil gas effective diffusivity are included just as in Figure 8. Again, the source depth plays a significant role. In scenarios with a constant lateral source-building separation ($d_h=30\text{m}$) and a shadow vapor source ($d_s=3\text{m}$), both screening levels of soil gas concentration attenuation (0.01 and 0.001) can be achieved for all types of soil even if impervious pavements occupied two thirds of the ground surface area. For cases with a deep vapor source ($d_s=8\text{m}$), the screening level as 0.001 can be barely achieved for a 30m lateral source-building seapartion in the presence of little surface cover.

Conclusions

In sum, based on the assumption diffusion is the major mechanism of soil gas transport, AAMLPH suggests that the three key factors that determine the soil vapor migration distances are source strength, source depth and surface cover. Generally the 30 m VI inclusion zone can serve well in the presence of one of the three factors, which are high source vapor concentration, deep source and significant surface cover. For sites involving all three, the soil vapor migration distance will certainly be extended to be longer than 30 m in most cases. In cases with the joint effects of two, the application of 30 m lateral separation is likely to be inappropriate, and additional professional judgments are recommended based on site-specific characterizations, such as the strength of the vapor source, the type of vapor

source, the soil types and layering in the vadose zone. This finding justifies the concern that EPA has expressed about the application of the 30 m lateral separation distance in the presence of physical barriers (e.g., asphalt covers or ice) at the ground surface. In such scenarios, AAMLPH can be employed as an alternative to investigate soil vapor migration distance on a site-specific basis, just as EPA suggested for cases where the 30 m lateral screening distance may not be appropriate [5].

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix

The mathematical approximation of the attenuation along lateral soil gas transport when involving vertical soil heterogeneities

Based on the assumption that the attenuations in vertical and horizontal directions are independent of each other, the vertical soil gas concentration profile can be approximated to be determined by the layer thickness and effective thickness of each layer. As shown in Figure A1, the contaminant concentration $c(x,y)$ normalized to $c(x,0)$ can be expressed as

$$\frac{c(x,y)}{c(x,0)} \approx \frac{\sum_{below} \frac{L_i}{D_i}}{\sum \frac{L_i}{D_i}} \quad (A1)$$

where n is the number of layers, L_i and D_i are the thickness [L] and the effective diffusivity in i layer from the bottom [L^2/T].

Then the diffusive flux through open ground surface is

$$J_y = -D_1 \frac{c(x,0)}{L_1} * \frac{\frac{L_1}{D_1}}{\sum \frac{L_i}{D_i}} = -\frac{c(x,0)}{\sum \frac{L_i}{D_i}} \quad (A2)$$

On the other hand, the decay rate of contaminant flux in x direction can be written as:

$$J_x = -\frac{1}{2} \frac{d^2 c(x,0)}{dx^2} \left(D_1 L_1 \frac{\sum \frac{L_i}{D_i} + \sum \frac{L_i}{D_i} - \frac{L_1}{D_1}}{\sum \frac{L_i}{D_i}} + D_2 L_2 \frac{\sum \frac{L_i}{D_i} - \frac{L_1}{D_1} + \sum \frac{L_i}{D_i} - \frac{L_1}{D_1} - \frac{L_2}{D_2}}{\sum \frac{L_i}{D_i}} + \dots + D_n L_n \frac{\sum \frac{L_i}{D_i} - \sum_{n-1} \frac{L_j}{D_j} - \sum \frac{L_i}{D_i} - \sum_{n-1} \frac{L_j}{D_j}}{\sum \frac{L_i}{D_i}} \right) = -\frac{1}{2 \sum \frac{L_j}{D_j}} \frac{d^2 c(x,0)}{dx^2} \sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right) \quad (A3)$$

where $\frac{1}{2}D_n L_n \frac{\sum \frac{L_i}{D_i} - \sum_{n-1} \frac{L_j}{D_j} - \sum \frac{L_i}{D_i} - \sum_{n-1} \frac{L_j}{D_j}}{\sum \frac{L_i}{D_i}}$ is the average contaminant concentration in layer n relative to $c(x,0)$.

To make a mass conservation, $J_x=J_y$,

$$-\frac{c(x,0)}{\sum \frac{L_i}{D_i}} = \frac{1}{2 \sum \frac{L_j}{D_j}} \frac{d^2 c(x,0)}{dx^2} \sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right) \quad (A4)$$

Substitute $c(0,0)=1$ and $c(\infty,0)=0$, and we have

$$c(x,0) = \exp \left(- \frac{\sqrt{2}x}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right)}} \right) \quad (A5)$$

As the attenuation is assumed to be independent in two directions, the normalized contaminant subslab concentration could be written as:

$$\frac{C_{ck}}{c_s} \Big|_{max} \approx \sqrt{\frac{d_f}{D_n}} \exp \left(- \frac{\sqrt{2}x}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right)}} \right) \quad (A6)$$

3-D simulations show that it is more appropriate to use

$$\exp \left(- \frac{\frac{\pi}{2}x}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right)}} \right) \text{ rather than}$$

$$\exp \left(- \frac{\sqrt{2}x}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right)}} \right) \text{ as the attenuation part in horizontal}$$

direction, and equation (S6) becomes:

$$c(x,0) = \exp \left(- \frac{\frac{\pi}{2}x}{\sqrt{\sum \left(D_i L_i \left(2 \sum \frac{L_j}{D_j} - \sum_{i-1} \frac{L_j}{D_j} - \sum_i \frac{L_j}{D_j} \right) \right)}} \right) \quad (A7)$$

which also makes it consistent with equation (3) in the manuscript, if $D_1 = D_2 = \dots = D_n$.

It should be noted that only the mass conservation in the whole soil layer is considered, and the mass conservation in individual layer is actually not balanced, because the mass flux in y direction is assumed to be the same in each layer, which is in contradiction to the decay during the lateral diffusion in each layer. This was ignored in order to obtain an

analytical solution, and the comparisons with 3-D simulations show that this approximation is acceptable.

FIGURE A1. A two-dimensional schematic scenario of soil gas transport

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Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

(a)

(b)

Figure 8.

TABLE 1

Input parameters used in 3-D simulations

Building/Foundation parameters	Heterogeneous soil cases:
Foundation footprint length : 10m	(1) Three-layer
Foundation footprint width : 10m	Thickness of layered soil (L_i):
Depth of foundation(d_f): 0.2 and 2 m	Top layer (L_3): 3 m
Crack width (W_{ck}): 0.005 m	Medium layer (L_2): 3 m
Thickness of crack (d_{ck}):0.152 m	Bottom layer (L_1): 2 m
Crack location : perimeter	High effective diffusivity: $1.05 \times 10^{-6} \text{m}^2/\text{s}$
Crack area (A_{ck}):0.199 m ²	Total porosity (η_T) : 0.3
Disturbance pressure (P):-5 Pa	Moisture porosity (η_W): 0.03
Depth to source (d_s): 3,5,8,11,14 m	Medium effective diffusivity : $8.68 \times 10^{-7} \text{m}^2/\text{s}$
Contaminant vapor source properties	Total porosity (η_T): 0.35
Source plume size: 10 m×10 m	
Lateral source-building Separation (d_k) 0~60 m	Moisture porosity (η_W): 0.07
Contaminant properties	Low effective diffusivity : $4.37 \times 10^{-7} \text{m}^2/\text{s}$
Source vapor concentration (c_s): 1mol/m ³	Total porosity (η_T): 0.45
Diffusivity in crack (D_{ck}): $8.81 \times 10^{-6} \text{m}^2/\text{s}$	Moisture porosity (η_W): 0.19
Diffusivity in air (D_g): $8.81 \times 10^{-6} \text{m}^2/\text{s}$	(2) Two-layer
Effective diffusivity(D_{eff}): $1.04 \times 10^{-6} \text{m}^2/\text{s}$	Sand:
Paved ground surface parameters	Effective diffusivity in upper soil: $1.42 \times 10^{-6} \text{m}^2/\text{s}$
Width of paved ground size (L_p): 10~60 m	Thickness of capillary fringe : 0.1705 m
	Effective diffusivity in capillary fringe : $5.70 \times 10^{-6} \text{m}^2/\text{s}$
Paved ground-building separation (L_o):0~50m	Sandy loam:
	Effective diffusivity in upper soil: $8.88 \times 10^{-7} \text{m}^2/\text{s}$
Soil properties	
Soil permeability (k): 10^{-11}m^2	Thickness of capillary fringe: 0.25 m
Viscosity of soil gas (μ_g): $1.8 \times 10^{-6} \text{kg/m/s}$	Effective diffusivity in capillary fringe: $8.61 \times 10^{-9} \text{m}^2/\text{s}$
	Clay:
Soil bulk density (p_b):1700 kg/m ³	Effective diffusivity in upper soil: $3.81 \times 10^{-7} \text{m}^2/\text{s}$
Homogeneous soil cases:	Thickness of capillary fringe: 0.8152 m
Effective diffusivity : $1.04 \times 10^{-6} \text{m}^2/\text{s}$	Effective diffusivity in capillary fringe: $3.70 \times 10^{-9} \text{m}^2/\text{s}$
Total porosity (η_T): 0.35	
Moisture porosity (η_W): 0.07	

TABLE 2

Calculated $\frac{C_{ss}}{C_s} \Big|_{max}$ for basement cases with a 30 m lateral source-building separation

$d_s = 3\text{ m}$							
$L_p(\text{m})$	0	5	10	15	20	25	30
No capillary fringe	1.23E-07	1.09E-06	9.66E-06	8.56E-05	7.59E-04	6.72E-03	5.96E-02
sand	3.33E-08	3.34E-07	3.34E-06	3.34E-05	3.34E-04	3.35E-03	3.35E-02
Sandy-loam	1.04E-08	1.11E-07	1.19E-06	1.27E-05	1.35E-04	1.45E-03	1.54E-02
clay	2.72E-10	4.46E-09	7.32E-08	1.20E-06	1.97E-05	3.23E-04	5.31E-03
$d_s = 8\text{ m}$							
$L_p(\text{m})$	0	5	10	15	20	25	30
No capillary fringe	1.38E-03	3.13E-03	7.10E-03	1.61E-02	3.65E-02	8.27E-02	1.87E-01
sand	9.96E-04	2.30E-03	5.29E-03	1.22E-02	2.81E-02	6.48E-02	1.49E-01
Sandy-loam	5.61E-04	1.31E-03	3.03E-03	7.06E-03	1.64E-02	3.81E-02	8.87E-02
clay	2.20E-04	5.45E-04	1.34E-03	3.32E-03	8.20E-03	2.03E-02	5.00E-02