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Three-Dimensional Simulation of Land Drains as a Preferential Pathway for Vapor Intrusion into Buildings

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Abstract

Preferential pathways can be significant vapor intrusion (VI) contributors, causing potentially higher inhalation risk to residents of affected buildings than that arising through traditional intrusion pathways. To assess land drains as a preferential pathway, a three-dimensional model, validated using data from a 4-yr field study, was used to study the roles of subfoundation soil permeability on soil gas flow and indoor depressurization. Results indicated that it is almost impossible for an indirect preferential pathway like a land drain ending in subfoundation soils with

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a permeability $<10^{-11} \text{ m}^2$ to affect indoor air quality if the land drain connects to a source with the same vapor concentration as that of the groundwater source beneath the building. An equation was developed to estimate the threshold permeability. We also found that even after the preferential pathway was identified using indoor depressurization (also known as controlled pressure method [CPM]) and then turned off, the influence of the preferential pathway and indoor depressurization on indoor concentration might last for months, although it may not be significant (i.e., may not exceed one order of magnitude, in this study). In the absence of such a preferential VI pathway, CPM may actually reduce indoor air concentrations of contaminants below those present under natural indoor pressure conditions, due to the emission rate limit determined by the upward diffusion rate from the vapor source. Our study highlights the role of measuring subfoundation soil permeability to soil gas flow in site investigations and warns practitioners about the possible mischaracterization of indoor air concentration after applying CPM in the absence of a preferential pathway.

VAPOR INTRUSION (VI) refers to the migration of volatile organic compounds (VOCs) from a subsurface source into the enclosed space of a building situated above (USEPA, 2016). In the traditional VI pathway, contaminant vapors released from a source such as contaminated soil or groundwater diffuse upward through soil to reach the subfoundation zone and then leak into the building through foundation slab cracks due to advection caused by indoor–outdoor pressure difference (Johnson and Ettinger, 1991). However, recent studies indicate that storm sewers, sanitary sewers, and utility tunnels could be preferential VI pathways for the migration of VOCs into buildings (McHugh et al., 2017). For example, the USEPA claims that VOCs can migrate through sewer lines into occupied homes in many circumstances (USEPA, 2012). In such scenarios, the contaminant vapor can reach the subfoundation zone or enclosed space of the building directly and at a greater concentration than by diffusion through the soil, causing a potentially higher indoor air concentration than that resulting from a traditional VI pathway. To characterize a site appropriately, key factors that determine the influence of preferential pathways on indoor air quality must be identified.

Some field studies have identified preferential VI pathways and their effects on indoor air concentrations. Riis et al. (2010) identified sewer lines as a preferential pathway after noticing an inconsistency between the plume extent and the location of houses under VI threat. They claimed that advective transport of groundwater into the sewer line was the major mechanism for the migration of contaminants, which could then vaporize into the sewer air and affect indoor air quality of houses along the sewer line by advection and diffusion. Pennell et al. (2013) also identified sewer gas as a source of tetrachloroethylene (PCE) detected in indoor air, given significant spatial variation of indoor air concentration and direct measurements in sewer pipe, and reported that direct infiltration of sewer gas into the living space could increase the indoor air concentration by almost two orders of magnitude compared with traditional pathways. Guo et al. (2015) proposed that a controlled pressure method (CPM) can be used to identify the existence of preferential pathways, such as sewer lines, in combination with subsurface soil gas measurements and screening level models. McHugh et al. (2012, 2017) suspected and then discovered the existence of a preferential pathway due to the similarity between subslab and indoor air concentrations

under indoor depressurization caused by CPM, and they suggested that measurements of sewer gas should be included in a routine vapor intrusion investigation. Although these individual case studies provide interesting information that could help practitioners identify preferential pathways and estimate their contributions to indoor air concentration, few studies have been performed to investigate the roles of environmental factors in determining the influences of such preferential pathways. For example, the role of subfoundation soil permeability in soil gas flow is not clear where vapors reach the subfoundation zone through a preferential pathway like a subsurface land drain, a pipe network built to allow rain water to rapidly drain away.

In this article, we use a three-dimensional (3-D) numerical model to study the circumstances in which a land drain that ends in subfoundation soil gas would act as an alternative VI pathway. First, we compare predictions of indoor air concentration and emission rate into the building with measured data from a field study for model validation. Then, we used this model to carry out simulations with different subfoundation soil permeabilities to investigate the temporal trends of indoor air concentration and emission rate. We simulated controls without preferential pathways to help understand the role of indoor depressurization caused by CPM in the transient process.

Materials and Methods

Field Data Used for Validation

In a previous field study conducted by Guo et al. (2015), CPM was employed to investigate a land drain as a preferential VI pathway. Information from study was used to build the numerical model used in this study. Groundwater contaminated by trichloroethylene (TCE) is considered to be the vapor source, ~2.5 m below the building foundation. The dissolved TCE concentration in groundwater ranges from 10 to 50 $\mu\text{g L}^{-1}$ during a 2.5-yr period. The soil beneath the house consists mainly of fine sandy silt with fine sand stringers, except for a gravel zone in the subfoundation, which drains to a neighborhood land drain system through a lateral pipe. The study building is a two-story, split-level house with a footprint of ~85 m² (Holton et al., 2013, 2015).

Data used in this study are from site monitoring over ~4 yr. The whole field experiment could be divided into four stages. In the first stage, when it was not known that a subsurface land drain was present, the experiment was conducted under natural indoor pressure conditions, with a land drain as an active preferential pathway connecting the groundwater source and the subfoundation zone. In the second stage, indoor depressurization was introduced using CPM, which involved installing two identical dual-speed blowers in an upstairs closet that vented into the attic, which in turned vented to the atmosphere. At this stage, the presence of a land drain was identified; it was turned off at the end of this stage by installing a manual butterfly valve. In the third stage, a negative indoor–outdoor pressure difference was maintained for several months; CPM was turned off at the end of this stage. In the fourth stage, samples of indoor air, subsurface soil gas, and groundwater were collected daily under natural indoor pressure conditions and in the absence of a preferential pathway. Temporal variations of indoor–outdoor pressure difference, air exchange rate, and rate of contaminant emission into the building were also recorded (Holton et al., 2013).

Measured indoor–outdoor pressure differences and exchange rate were used in the numerical modeling to predict temporal variations of contaminant emission rate and indoor air concentration, which were then compared with field observations to validate the model. Readers interested in other details of that field experiment are directed to the original references (Holton et al., 2013, 2015; Guo et al., 2015).

Numerical Model

In a scenario involving preferential VI pathways such as a land drain, which allows the contaminant vapor to reach a building's subfoundation zone directly from the source, not only the indoor air concentration but also the soil gas concentration profile is affected. Due to such complexity, a full 3-D finite element model is used to study the influences of such a preferential pathway on both of these measures. The 3-D numerical model applied here was developed with COMSOL Multiphysics and has been presented in previous publications (Bozkurt et al., 2009; Pennell et al., 2009; Yao et al., 2011, 2012, 2013a, 2013b, 2013c, 2015c, 2017a, 2017b). The numerical model includes two modules, Darcy's law and chemical transport in porous media. The governing equations and the boundary conditions for two modules are shown in Table 1. The soil gas specific discharge field can be obtained by solving Darcy's law and then substituting it into the module of chemical transport in porous media as input to obtain the soil gas concentration profile. In previous studies, this model was used to simulate subsurface soil gas transport and fate through advection, diffusion, adsorption, and biodegradation in VI scenarios, whereas in this paper, the model was used to simulate transient scenarios involving nonbiodegradable chemicals. The settings are the almost same as those in the previous studies, except for the opening of the lateral pipe, where a flux boundary condition is used similar to that for the perimeter crack in Abreu and Johnson (2005). Moreover, it is assumed that the lateral pipe was directly connected to the vapor source, with atmospheric pressure and the same vapor concentration as that of the groundwater source beneath the building.

Given the characterization of the field site (Guo et al., 2015; Holton et al., 2013, 2015), we employed a model domain of $16 \times 17 \times 2.8$ m. A building foundation with a footprint of 7.4×11.4 m is located in the middle of the domain, with a depth below ground surface of 0.3 m. Below the foundation is a gravel zone 0.6 m thick, whereas the rest of domain consists of the sandy clay soil. To simplify the modeling work, most parts of the lateral pipe used as the land drain were not simulated except for the end of the pipe with an upward opening, the size of which is 10×10 cm, 20 cm below the foundation slab; the other possible openings along the land drain are not included either. The temporal variations of subsurface environmental factors, such as moisture content and temperature, are not considered here. The contaminant vapor migrates into the building's enclosed space through a perimeter crack with a width of 0.005 m. By assuming that the opening of the land drain is located at the axis of symmetry, only a half domain is actually simulated for the efficiency of computation, as shown in Fig. 1.

For the subfoundation gravel zone, the permeability to soil gas and effective diffusivity are assumed to be uniform. For the rest part of the domain, the moisture content distribution is approximated using the van Genuchten equation (van Genuchten, 1980):

$$s_{ew} = \frac{\theta_w - \theta_r}{\theta_t - \theta_r} = \left[1 + (\alpha z)^N \right]^{1/N-1} \quad [1]$$

where s_{ew} is the effective fluid saturation (dimensionless); α is the point of inflection in the water retention curve where $d\theta_w/dz$ is maximal (L^{-1}); θ_t , θ_w , and θ_r are the total porosity, water content, and residual soil water content (dimensionless), respectively; N is the van Genuchten curve shape parameter; and z is the vertical coordinate (L).

Given the moisture content distribution, the effective diffusivity (D_e) in the sandy clay is approximated using the Millington and Quirk model (Millington and Quirk, 1961) as:

$$D_e(z) = D_g \frac{\theta_g^{10/3}}{\theta_t^2} + \frac{D_w}{K_H} \frac{\theta_w^{10/3}}{\theta_t^2} \quad [2]$$

where D_g and D_w are the molecular diffusivity in gas and water phase, respectively ($L^2 T^{-1}$), θ_g is the air filled porosity, and K_H is the Henry's law constant. The relative permeability ($k_{r,g}$) could be calculated according to Parker et al. (1987):

$$k_{r,g} = (1 - s_{ew})^{0.5} \left[1 - s_{ew}^{N/(N-1)} \right]^{2(1-1/N)} \quad [3]$$

All parameters used in the simulations are shown in Table 2.

The measured and simulated temporal variations of indoor air exchange rate and outdoor–indoor pressure difference are shown in Fig. 2. The duration of the field experiment can be divided into four sections according to the operational conditions of preferential pathways and indoor pressurization caused by CPM. The outdoor–indoor pressure difference fluctuated between 3 and -0.2 Pa under natural conditions and was maintained at approximately -11 Pa during the period when CPM was applied.

The numerical simulations can be divided into three groups. For the first group, with parameters obtained from the site investigation, the numerical simulation was performed to reproduce what happened during the field investigation so that the simulated results could be compared with field data for the validation of the model. For the second group, hypothetical soil permeabilities on soil gas flow were substituted for the subfoundation zone, and the other settings were the same as those in the first group. The settings in the third group were similar to those in the second group, except that the land drain was off the whole time.

Results and Discussion

Comparison with Field Data

Parameters are shown in Table 2, and Fig. 2, 3, and 4 show the simulated indoor air concentrations and emission rates, respectively, during the 1200-d experiment. Generally, the

numerical predictions match field observations reasonably well for both indoor air concentration and emission rate.

In Stage 1 (Days 100–740), when the preferential pathway was on and the indoor pressure was not controlled, significant fluctuations (about three orders of magnitude) were observed for simulated indoor air concentration and emission rate, whereas the indoor pressure difference and exchange rate were comparatively steady. In Stage 2 (Days 750–1050), when the preferential pathway was still on and the indoor pressure was controlled, the simulated indoor air concentration and emission rate rose to a steady value, which was maintained during this section.

In Stage 3 (Days 1060–1170), when the preferential pathway was closed and the indoor air was still depressurized by CPM, the simulated indoor air concentration and emission rate dropped by roughly two orders of magnitude. Then, the simulated indoor air concentration and emission rate continued to decay by depleting the subfoundation zone, but at a rate slower than the observations in the field experiment. This might be because we assume that the whole subfoundation zone is a reservoir of contaminants, whereas in reality, the size of such reservoir could be much smaller, causing a faster decay rate.

In Stage 4 (Days 1170–1300), when the preferential pathway was closed and the indoor pressure was not controlled, both simulated and measured indoor air concentration and emission rate continued to decay, except for an initial rise of indoor air concentration due to the decrease of indoor air exchange rate by stopping CPM. For measured indoor air concentration and emission rate, a fluctuation of one order of magnitude could be observed, with an upper limit similar to the simulated values. This could be caused by the drastic changes of outdoor–indoor pressure difference, even within a day, during the field experiment, although there was no significant variation of daily averaged values, which we employed in the simulations. A similar phenomenon is also observed in Stage 1, where there was about one order of magnitude variation in both measured indoor air concentration and emission rate within a short time, although the long-term temporal trends of the measurements were well captured by the simulations.

Scenarios with Different Subfoundation Soil Permeability to Soil Gas Flow

By substituting different soil permeability to soil gas flow in the subfoundation zone, we can examine the influences of the soil permeability to soil gas flow in determining indoor air quality in scenarios involving a land drain as a preferential pathway. Figures 5 and 6 show the simulated temporal variations of indoor air concentration and emission rate of TCE, respectively, with hypothetical subfoundation soil permeabilities of 10^{-8} , 10^{-9} , 10^{-10} and 10^{-11} m². All other settings of the simulations are the same as those in the former section.

In the presence of an active preferential VI pathway in the subfoundation and natural indoor pressure conditions (Stage 1), Fig. 5 suggests that the simulated fluctuation of indoor air concentration becomes smaller with the decrease of soil permeability to soil gas flow (e.g., the peak values are linear to the soil permeability to soil gas flow). As a result, in the 10^{-11} m² case, the temporal variation is insignificant. On the other hand, the lower limits of these curves are quite similar, regardless of three-orders-of-magnitude difference in the soil

permeability to soil gas flow, indicating the absence of indoor depressurization and advective soil gas flow into the building. In Stage 2, when CPM was applied to cause a significant and steady indoor depressurization, the indoor air concentration increased significantly except in the case of subfoundation soil permeability to soil gas flow of 10^{-11} m^2 . In this case, the indoor air concentration dropped by $\sim 70\%$ (from 0.017 to 0.005 g d^{-1}) immediately after CPM was activated, because the increase in air flow into the building was greater than the increase in vapor entry at that time (McHugh et al., 2012). Moreover, for the 10^{-11} m^2 case, it took about a month to reach steady state. Similar to the peak values in Stage 1, indoor air concentrations in steady state after applying CPM are also linear to the soil permeability to soil gas flow.

When the preferential pathway was closed, the indoor air concentrations in all four cases immediately fell into a small range with a variation less than one order of magnitude, regardless of the three-orders-of-magnitude variation in subfoundation soil permeability to soil gas flow. The indoor air concentration in four cases continued to decrease with time in Stage 3, caused by the depletion of the contaminant in the subfoundation. It is worth noting that the differences in indoor air concentration among the four cases were observed to be temporally constant. In the final stage, the indoor air concentration in all cases rose immediately after the CPM was turned off, due to the decrease of indoor air exchange rate. However, it then continued to decrease in a general trend—indicating the effects caused by the depletion of subfoundation, desorption, or both—after the preferential pathway was turned off a few months earlier.

The simulated temporal variations of emission rate into the building (Fig. 6) are similar to those of indoor air concentration (Fig. 5), except for the continuous decay trend of emission rate after the preferential pathway was turned off in Stages 3 and 4, independent of building operational conditions. The slopes of these curves are identical, regardless of different soil permeability to soil gas flow.

Although the simulations suggest that the preferential pathway is unlikely to play a significant role in determining indoor air concentration with a subfoundation soil permeability to soil gas flow of $<10^{-11} \text{ m}^2$, such a conclusion is based on the assumption that the vapor concentrations were the same for the source zone beneath the building and that connecting to the land drain. In reality, the source plume could be spatially heterogeneous. In such scenarios, to define the threshold of subfoundation soil permeability to soil gas flow above which the preferential pathway could play a role in determining indoor air concentration, we can assume that the advective contaminant soil gas flow from the preferential pathway is larger than the diffusion flux from the source beneath the building with outdoor–indoor pressure difference of 1 Pa :

$$\frac{k}{\mu} \frac{\partial p}{\partial x} \bigg|_{\text{opening}} A_p c_{p,s} > A_f D_{\text{eff},T} \frac{c_s}{L_T} \quad [4]$$

which can be written as

$$k > \frac{A_f D_{\text{eff},T} c_s \mu}{\vec{\nabla} p|_{\text{opening}} A_p c_{p,s} L_T} \quad [5]$$

where k is the permeability to soil gas flow (L^2), μ is the viscosity ($L^2 T^{-1}$), c_s is the source vapor concentration ($M L^{-3}$), $\vec{\nabla} p|_{\text{opening}}$ is the pressure gradient at the opening of the pipe, A_p is the size of the pipe opening, $c_{p,s}$ is the vapor concentration of the source connecting to the land drain, A_f is the size of building footprint, $D_{\text{eff},T}$ is the total effective diffusion coefficient between building foundation and vapor source at bottom (Johnson, 2002), and L_T is the vertical separation distance between building foundation and source.

$\vec{\nabla} p|_{\text{opening}}$ could be estimated using the following equation:

$$\frac{d}{dr} \left(\frac{dp}{dr} r \right) = 0 \quad [6]$$

with boundary conditions as

$$\begin{cases} p=0 \text{ at } r=R/2 \\ p=-1 \text{ Pa at } r=L_{o-c} \end{cases} \quad [7]$$

where r is distance from the pipe opening, R is the diameter of the pipe opening, and L_{o-c} is the distance between perimeter crack and pipe opening.

In this study, we assume that $c_s = c_{p,s}$ and substitute $R = 0.1$ m, $L_{o-c} = 1.6$ m, $D_{\text{eff},T} = 7.5 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$, $A_f = 84.4 \text{ m}^2$, $A_p = 0.01 \text{ m}^2$, $\mu = 1.8 \times 10^{-5} \text{ Pa s}$ and $L_T = 2.5$ m into Eq. [5] to obtain:

$$k > 7.9 \times 10^{-11} \text{ m}^2 \quad [8]$$

which is in accordance with numerical results. Figure 7 shows the relationship between the threshold subfoundation soil permeability to soil gas flow and total effective diffusivity in cases with different $c_{p,s}/c_s$.

Scenarios with No Preferential Pathway

The influences of land drain as a preferential VI pathway could also be shown by comparing with controls, the predictions in scenarios without such a preferential pathway. Figures 5 and 6 show the simulated results of indoor air concentration and emission rate in controls, respectively. The numerical simulations show that the temporal trends of both indoor air concentration and emission rate are identical independent of soil permeability to soil gas flow.

Under natural indoor pressure conditions (Stage 1), the temporal trends of indoor air concentration and emission rate in scenarios with the absence of a preferential pathway are almost identical to the 10^{-11} m² case with a preferential pathway, as shown in Fig. 5 and 6. After the application of CPM to cause indoor depressurization, the emission rate increased by about 50% (from 0.001 to 0.0015 g d⁻¹, Fig. 6), whereas the indoor air exchange rate increased by almost 200% (from 4 to 11 m³ min⁻¹) in the absence of a preferential pathway (Fig. 2). As a result, the indoor air concentration under CPM conditions is about half of that under natural conditions (from 0.016 to 0.007 µg m⁻³, Fig. 5) in such scenarios.

The reason behind this phenomenon is that, in the absence of a preferential pathway, the application of CPM cannot increase the emission rate higher than the indoor air exchange rate (McHugh et al., 2012). In this case, the upper limit of the emission rate into the building is determined by the upward diffusion rate of TCE from the groundwater source, the latter of which could be considered as a constant in the absence of significant advection in the source zone and temporal variation of the source plume. If the emission rate was already very close to the upward diffusion rate of source plume beneath the building foundation like in this field site, the application of indoor depressurization would not increase the emission rate significantly, as it is against the law of mass conservation. In Guo et al. (2015), without a land drain as a preferential pathway, the application of CPM does not cause an indoor air concentration higher than that under natural indoor pressure conditions. Similar results were also observed by McHugh et al. (2012), who reported that the introduction of indoor negative pressure condition reduced the indoor air concentration of TCE and PCE from subsurface sources by ~30% in two rounds of tests for the building at Moffett Field.

In Stage 3, for simulations without a preferential pathway all the time, Fig. 5 and 6 show that there are small temporal variations for the indoor air concentration and emission rate, both of which were ~1 to 1.5 orders of magnitude lower than those with a preferential pathway that was closed in the middle of the simulation. Such differences, however, decreased with time in both Stages 3 and 4. The indoor air concentration rose and the emission rate dropped moderately immediately after CPM was turned off, but the curves remained horizontal in the control.

These comparisons with scenarios without a preferential pathway further confirm that the preferential pathway can still play a role, although not a significant one (no more than one order of magnitude vs. those in cases with a land drain in this study), in determining indoor air concentration and emission rate after the drain was identified by CPM and turned off a few months earlier. Additionally, the numerical simulations show that CPM might cause lower instead of higher indoor air concentrations than those under natural indoor pressure conditions if it does not lead to a higher emission rate than the indoor air exchange rate. In the case studied here, for example, in the absence of a land drain as a preferential pathway, the emission rate was already close to the upward diffusion rate under natural indoor pressure conditions, and the application of CPM did not cause a significantly higher emission rate into the building.

Implications

At sites where a contaminant vapor source was identified in the subsurface, it is possible that the vapor could migrate into the enclosed space of a building via a preferential pathway, creating a more significant threat to the residents than that from the traditional pathway. Our study indicated that a preferential VI pathway like a land drain, through which the contaminant vapor can reach the subfoundation directly from the source, would not play an important role in determining indoor air concentration unless the soil permeability to soil gas flow in the subfoundation zone was significantly higher than the upper limit of classical soil type (i.e., 10^{-11} m² for scenarios involving uniform source plumes). Otherwise, the threshold subfoundation soil permeability to soil gas flow could be estimated using the equation developed in this study. One way or another, the importance of measuring subfoundation soil permeability to soil gas flow is highlighted in identifying the potential influences of preferential pathways, like land drains, that do not directly vent into indoor air but end in subfoundation soils.

Once the preferential pathway was identified with CPM and then turned off, the influence of such a pathway on indoor air concentration could still last for months, although not significantly (no higher than one order of magnitude vs. those in cases with a land drain in this study). Moreover, both numerical results and field data suggest that the application of CPM may cause a lower indoor air concentration in the absence of preferential pathways like a land drain if it does not lead to a higher emission rate than the indoor air exchange rate (e.g., due to the limit of upward diffusion rate from the vapor source). Such results could warn the practitioner about the potential consequences of CPM in certain cases.

It should be noted that some conclusions made in this study are based on simplified assumptions employed in numerical simulations. For example, our study assumes a homogeneous and infinite source plume at bottom, and that only the subfoundation zone is highly permeable. If the whole building foundation is surrounded by highly permeable media, indoor depressurization may draw the clean air from the open ground surface into the subfoundation (Luo, 2009), diluting the subslab crack concentration and causing a lower indoor air concentration even in the presence of active preferential pathways such as a land drain. Biodegradation is also not considered here (per Abreu and Johnson, 2006), so results for petroleum contaminants would require further study in consideration of such conclusions.

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Abbreviations

3-D	three-dimensional
CPM	controlled pressure method
PCE	tetrachloroethylene

TCE	trichloroethylene
VI	vapor intrusion
VOC	volatile organic compound

References

- Abreu LD, Johnson PC. Effect of vapor source-building separation and building construction on soil vapor intrusion as studied with a three-dimensional numerical model. *Environ Sci Technol.* 2005; 39:4550–4561. DOI: 10.1021/es049781k [PubMed: 16047792]
- Abreu LD, Johnson PC. Simulating the effect of aerobic biodegradation on soil vapor intrusion into buildings: Influence of degradation rate, source concentrations. *Environ Sci Technol.* 2006; 40:2304–2315. DOI: 10.1021/es051335p [PubMed: 16646467]
- Bozkurt O, Pennell KG, Suuberg EM. Simulation of the vapor intrusion process for non-homogeneous soils using a three-dimensional numerical model. *Ground Water Monit Rem.* 2009; 29:92–104. DOI: 10.1111/j.1745-6592.2008.01218.x
- Guo Y, Holton C, Luo H, Dahlen P, Gorder KA, Dettenmaier EM, Johnson PC. Identification of alternative vapor intrusion pathways using controlled pressure testing, soil gas monitoring, and screening model calculations. *Environ Sci Technol.* 2015; 49:13472–13482. DOI: 10.1021/acs.est.5b03564 [PubMed: 26458025]
- Holton C, Guo Y, Luo H, Dahlen P, Gorder KA, Dettenmaier EM, Johnson PC. Long-term evaluation of the controlled pressure method for assessment of the vapor intrusion pathway. *Environ Sci Technol.* 2015; 49:2091–2098. DOI: 10.1021/es5052342 [PubMed: 25604884]
- Holton C, Luo H, Dahlen P, Gorder KA, Dettenmaier EM, Johnson PC. Temporal variability of indoor air concentrations under natural conditions in a house overlying a dilute chlorinated solvent groundwater plume. *Environ Sci Technol.* 2013; 47:13347–13354. DOI: 10.1021/es4024767 [PubMed: 24180600]
- Johnson, PC. Identification of critical parameters for the Johnson and Ettinger (1991) vapor intrusion model. *Am Petroleum Inst; Washington, DC:* 2002.
- Johnson PC, Ettinger RA. Heuristic model for the intrusion rate of contaminant vapors into buildings. *Environ Sci Technol.* 1991; 25:1445–1452. DOI: 10.1021/es00020a013
- Luo, H. PhD diss. Arizona State Univ; Phoenix: 2009. Field and modeling studies of soil vapor migration into buildings at petroleum hydrocarbon impacted sites.
- McHugh TE, Beckley L, Bailey D, Gorder K, Dettenmaier E, Rivera-Duarte I, et al. Evaluation of vapor intrusion using controlled building pressure. *Environ Sci Technol.* 2012; 46:4792–4799. DOI: 10.1021/es204483g [PubMed: 22486634]
- McHugh TE, Beckley L, Sullivan T, Lutes C, Truesdale R, Uppencamp R, et al. Evidence of a sewer vapor transport pathway at the USEPA vapor intrusion research duplex. *Sci Total Environ.* 2017; 598:772–779. DOI: 10.1016/j.scitotenv.2017.04.135 [PubMed: 28456127]
- Millington RJ, Quirk JP. Permeability of porous solids. *Trans. Faraday Soc.* 1961; 57:1200–1207. DOI: 10.1039/tf9615701200
- Parker JC, Lenhard RJ, Kuppusamy T. A parametric model for constitutive properties governing multiphase flow in porous media. *Water Resour Res.* 1987; 23:618–624. DOI: 10.1029/WR023i004p00618
- Pennell KG, Bozkurt O, Suuberg EM. Development and application of a three-dimensional finite element vapor intrusion model. *J Air Waste Manage Assoc.* 2009; 59:447–460. DOI: 10.3155/1047-3289.59.4.447
- Pennell KG, Scammell MK, McClean MD, Ames J, Weldon B, Friguglietti L, et al. Sewer gas: An indoor air source of PCE to consider during vapor intrusion investigations. *Ground Water Monit Rem.* 2013; 33:119–126.
- Riis, C., Hansen, MH., Nielsen, HH., Christensen, AG., Terkelsen, M. Vapor intrusion through sewer systems: Migration pathways of chlorinated solvents from groundwater to indoor air; *Proceedings*

- of the 7th International Conference on Remediation of Chlorinated and Recalcitrant Compounds; Monterey, CA. 24–27 May 2010; Madison, WI: Battelle Memorial Inst; 2010.
- USEPA. USEPA Off Res Dev. Washington, DC: 2012. Fluctuation of indoor radon and VOC concentrations due to seasonal variations.
- USEPA. What is vapor intrusion?. USEPA. 2016. <https://www.epa.gov/vaporintrusion/what-vapor-intrusion> (accessed 8 Sept. 2017)
- van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci Soc Am J*. 1980; 44:892–898. DOI: 10.2136/sssaj1980.03615995004400050002x
- Yao Y, Pennell KG, Suuberg EM. Estimation of contaminant subsurface concentration in vapor intrusion. *J Hazard Mater*. 2012; 231–232:10–17. DOI: 10.1016/j.jhazmat.2012.06.016
- Yao Y, Pennell KG, Suuberg EM. Simulating the effect of slab features on vapor intrusion of crack entry. *Build Environ*. 2013a; 59:417–425. DOI: 10.1016/j.buildenv.2012.09.007 [PubMed: 23359620]
- Yao Y, Shen R, Pennell KG, Suuberg EM. Comparison of the Johnson–Ettinger vapor intrusion screening model predictions with full three-dimensional model results. *Environ Sci Technol*. 2011; 45:2227–2235. DOI: 10.1021/es102602s [PubMed: 21344848]
- Yao Y, Shen R, Pennell KG, Suuberg EM. Examination of the influence of environmental factors on contaminant vapor concentration attenuation factors using the U.S. EPA’s vapor intrusion database. *Environ Sci Technol*. 2013b; 47:906–913. DOI: 10.1021/es303441x [PubMed: 23252837]
- Yao Y, Shen R, Pennell KG, Suuberg EM. Examination of the U.S. EPA’s vapor intrusion database based on models. *Environ Sci Technol*. 2013c; 47:1425–1433. DOI: 10.1021/es304546f [PubMed: 23293835]
- Yao Y, Vergelli I, Suuberg EM. A two-dimensional analytical model of vapor intrusion involving vertical heterogeneity. *Water Resour Res*. 2017a; 53:4499–4513. DOI: 10.1002/2016WR020317 [PubMed: 29081548]
- Yao Y, Wang Y, Zhong Z, Tang M, Suuberg EM. Investigating the role of soil texture in vapor intrusion from groundwater sources. *J Environ Qual*. 2017b; 46:776–784. DOI: 10.2134/jeq2017.01.0011 [PubMed: 28783798]
- Yao Y, Wu Y, Tang M, Wang Y, Wang J, Suuberg EM, et al. Evaluation of site-specific lateral inclusion zone for vapor intrusion based on an analytical approach. *J Hazard Mater*. 2015; 298:221–231. DOI: 10.1016/j.jhazmat.2015.05.024 [PubMed: 26057584]

Core Ideas

- The influences of land drain depend on subfoundation soil permeability.
- An equation was developed to estimate the threshold soil permeability.
- The influences on indoor air may last for months after the pathway is turned off.
- CPM might cause lower instead of higher indoor concentration.

(a)

(b)

(c)

Fig. 1.

(a) Plain view, (b) cross-sectional view, and (c) three-dimensional view of the model domain.

Fig. 2.

The temporal trends of indoor depressurization and building flow rate (points: measurements; line: simulations) (Guo et al., 2015).

Fig. 3.
The temporal trends of indoor air concentration (colored: measurements; black: simulation)
(Guo et al., 2015). TCE, trichloroethylene.

Fig. 4. The temporal trends of trichloroethylene (TCE) emission rate into the building (colored: measurements, black: simulation) (Holton et al., 2015; Guo et al., 2015).

Fig. 5.

Numerical simulations of indoor air concentration with different soil permeability to soil gas flow in the subfoundation (−8 means the soil permeability to soil gas flow is 10^{-8} m^2 in the subfoundation, and −8 off means the soil permeability to soil gas flow is 10^{-8} m^2 in the subfoundation and the preferential pathway was turned off from the beginning) (Guo et al., 2015). TCE, trichloroethylene.

Fig. 6.

Numerical simulations of trichloroethylene (TCE) emission rate with different soil permeability to soil gas flow in the subfoundation (–8 means the soil permeability to soil gas flow is 10^{-8} m^2 in the subfoundation, and –8 off means the soil permeability to soil gas flow is 10^{-8} m^2 in the subfoundation and the preferential pathway is off from the beginning) (Holton et al., 2015).

Fig. 7.

The responses to the threshold soil permeability to the total effective diffusivity with different $c_{p,s}/c_s$ (1 means $c_{p,s}/c_s = 1$, $R = 0.1$ m, $L_{o-c} = 1.6$ m, $A_f = 84.4$ m², $A_p = 0.01$ m², $\mu = 1.9 \times 10^{-5}$ Pa s, and $L_T = 2.5$ m are assumed). See Table 2 for definition of variables.

Table 1

Governing equations and boundary conditions used in the simulations.[†]

	Darcy's law	Chemical transport
Governing equation	$\vec{\nabla} \left(\frac{k}{\mu} \vec{\nabla} p \right) = \vec{\nabla} (\vec{u}) = 0$	$\left(\theta_g + \frac{\theta_g}{K_H} + K_{oc} f_{oc} \right) \frac{\partial c_g}{\partial t} = - \vec{\nabla} \left(c_g \frac{k}{\mu} \vec{\nabla} p \right) + \vec{\nabla} \left(D_{eff} \vec{\nabla} c_g \right)$
Open ground surface	$p = 0$	$c = 0$
Vertical planes of symmetry and foundation boundaries	$\vec{\nabla} p = 0$	$D_e(z) \vec{\nabla} c_g + \vec{u} c_g = 0$
Groundwater level	$\vec{\nabla} p = 0$	$c_g = c_s$
Perimeter crack	$\vec{u} = \frac{w_{ck}^2}{12 \mu d_{ck}} (p - p_{in})$	$D_e(z) \vec{\nabla} c_g + \vec{u} c_g = \frac{\vec{u} c_g \exp \left(\frac{\vec{u} L_{ck}}{D_g} \right)}{\exp \left(\frac{\vec{u} L_{ck}}{D_g} \right) - 1}$
Opening of the pipe	$\vec{u} = \frac{w_{ck}^2}{12 \mu d_{ck}} p$	$D_e(z) \vec{\nabla} c_g + \vec{u} c_g = \vec{u} \frac{c_s \exp \left(\frac{\vec{u} L_p}{D_g} \right) - c_g}{\exp \left(\frac{\vec{u} L_p}{D_g} \right) - 1}$

[†] See Table 2 for definition of variable. p is the pressure of soil gas, $\vec{u}$ is the velocity of soil gas, and c_g is the soil gas concentration.

Table 2

Parameters used in the simulations (Holton et al., 2013, 2015; Guo et al., 2015).

Parameter		Symbol	Unit	Value
Contaminant		–	–	TCE
side length of land drain opening		L_o	m	0.1
Pipe length		L_p	m	100
Indoor depressurization		–	Pa	See Fig. 2
Source depth		d_s	m	2.8
Foundation footprint length		–	m	11.4
Foundation footprint width		–	m	7.4
Foundation depth		d_f	m	0.3
Indoor air exchange rate		A_E	$\text{m}^3 \text{min}^{-1}$	See Fig. 2
Foundation crack thickness		d_{ck}	m	0.15
Foundation crack width		w_{ck}	m	0.005
Soil permeability to soil gas flow	Subfoundation	k	m^2	5×10^{-8} (first) and $10^{-8}, 10^{-9}, 10^{-10}, 10^{-11}$ (second and third)
	The rest		m^2	See Eq. [3]
Effective diffusivity	Subfoundation	D_{eff}	$\text{m}^2 \text{s}^{-1}$	1.43×10^{-10}
	The rest		$\text{m}^2 \text{s}^{-1}$	See Eq. [2]
Total soil porosity	Subfoundation	θ_t	–	0.375
	The rest			0.385
Residual soil moisture content	Subfoundation			0.053
	The rest	θ_r	–	0.117
van Genuchten parameters for sandy clay		a	m^{-1}	3.342
		N	–	1.208
Maximum permeability for sandy clay		$K_{s,c,m}$	m^{-2}	1.74×10^{-13}
Henry's law constant		K_H		0.403
Diffusion coefficient in air		D_g	$\text{m}^2 \text{s}^{-1}$	7.9×10^{-6}
Diffusion coefficient in water		D_w	$\text{m}^2 \text{s}^{-1}$	9.1×10^{-10}
Concentration in groundwater		c_s	$\mu\text{g L}^{-1}$	23
Mass fraction of organic carbon in the in sandy clay		f_{oc}	$\text{kg oc kg}^{-1} \text{soil}$	0.001
Sorption coefficient of contaminant to organic carbon		K_{oc}	$\text{kg kg}^{-1} \text{oc}$	0.0617
Soil bulk density		ρ_b	kg m^{-3}	1700
Viscosity of soil gas		μ	$\text{m}^2 \text{s}^{-1}$	1.8×10^{-5}