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Investigating the Role of Soil Texture in Vapor Intrusion from Groundwater Sources

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Abstract

Soil texture is believed to play a significant role in the migration of subsurface volatile chemicals into buildings at contaminated sites, an exposure process known as vapor intrusion (VI). In this study, we investigated the role of soil texture in determining the attenuation of contaminant soil gas concentration from groundwater source to receptor building. We performed soil column experiments, numerical simulations, and statistical analysis of the USEPA's VI database. The soil column experiments were conducted with commercial sand and soils with sand and sandy loam textures. Measured one-dimensional soil gas concentration profiles were compared with numerical predictions. Good agreement between experiments and model results supports the use of the classical multiphase chemical transport equation for simulating contaminant vapor transport from groundwater through the vadose zone. A full three-dimensional numerical model was then used to simulate typical VI scenarios with groundwater sources. Results indicate that, although soil particle texture can play a role in determining slab-to-indoor air concentration attenuation,

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there is no obvious relationship between soil particle size and groundwater source-to-subslab except in the case of a shallow contaminant source. This conclusion is consistent with results reported in USEPA's VI database, in which variation in soil particle size does not affect source-to-subslab attenuation factors but does influence subslab-to-indoor air concentration attenuation factors by an average of about 0.4 order of magnitude. This finding suggests that an appropriate focus of VI site investigation should include the shallow soil beneath the building foundation.

Vapor intrusion (VI) refers to the migration of volatile chemicals from subsurface sources through the vadose zone into the enclosed space of an affected building. This process can be a major human exposure pathway at sites built on top of contamination. In many cases of practical importance, the vapors are from contaminated groundwater, although the possibility of free product in the vadose zone also needs to be considered if in proximity to the original source such as leaking underground storage tank (Rivett, 1995). As the major medium between the subsurface vapor source and a building, soil can play a significant role in contaminant vapor concentration attenuation factors in VI. These factors refer to the fraction of source concentration observed at a particular location above the contaminant source. In some VI guidelines (ITRC, 2007), soil type is believed to be one of the key environmental factors that influence vapor migration, and others (USEPA, 2015) suggest that information on soil conditions below the foundation should be collected during site investigation to develop a reliable conceptual site model. Soil type is a proxy for a suite of properties that influence volatile organic contaminant transport in soil, and these properties include porosity, moisture content, soil permeability, effective diffusivity, and sometimes organic carbon adsorptive capacity (Johnston and Gibson, 2013). Hence, accurate characterization of the subsurface vapor migration route requires a good understanding of the role of soil properties in contaminant transport processes.

Some studies have addressed the influence of soil texture in VI (Johnston and Gibson, 2011, 2013; USEPA, 2012; Johnston et al., 2014). Several reviews of the USEPA's VI database (USEPA, 2012; Johnston and Gibson, 2013) have suggested that greater groundwater source-to-indoor air attenuation can be observed in cases with finer-grained soils, but it was not reported how soil texture affects the indoor air concentration. In the Johnson–Ettinger model (JEM), the most commonly applied one-dimensional (1-D) VI risk screening model, users are allowed to estimate soil vapor permeability based on soil type (Johnson and Ettinger, 1991). In cases involving groundwater sources, USEPA spreadsheet implementation of the JEM (USEPA, 1997) divides the domain into capillary fringe and unsaturated zone based on soil types and treats them as two separate, but uniform, layers. However, Shen et al. (2013a, 2013b) have argued, according to numerical simulations, that such a simplified characterization of soil moisture content profiles underestimates contaminant concentration attenuation by two orders of magnitude. This can result in significantly different predictions of subfoundation soil gas concentration profiles than those with a more realistic continuous variation of moisture content. This concern is further confirmed by a newly published study (Yao et al., 2017), which reported that the predictions of USEPA spreadsheet are higher than the full three-dimensional (3-D) simulations by one to two orders of magnitude in scenarios involving groundwater sources. Although the above studies provided some interesting insights into the influence of soil properties such as

moisture content and permeability in VI, there has been no comprehensive investigation of the role of soil texture in the soil gas concentration attenuation processes in scenarios involving groundwater sources.

In this study, we investigated the role of soil type in contaminant vapor concentration attenuation by performing soil column experiments, numerical simulations, and then extending the understanding gained to statistical analysis of USEPA's VI database. First, we conducted soil column experiments for three types of mediums and compared the measured soil gas concentration profiles with simulated results. Then, we simulated 3-D VI scenarios involving a groundwater source and different soil types. From this, we obtained the relationship between contaminant vapor concentration attenuation and soil type. Finally, such a relation was used to reexamine entries in USEPA's VI database and offer new conclusions regarding the role of soil texture in those results.

Materials and Methods

Soil Column Experiments

Chemicals—Trichloroethylene (TCE) (99%) was obtained from Sinopharm Chemical Reagent Company.

Column Design—Three kinds of mediums—sand, sand soil, and sandy loam soil—were used in this study. Sand was commercially obtained, whereas sand soil and sandy loam were taken from two different places on the west side of the Zijingang Campus of Zhejiang University. The samples were collected from a 0- to 20-cm depth using a shovel. These samples were first air dried and then sieved to establish the particle size distributions. These particle size distributions of the three soil types are shown in Table 1. Three soil column systems were built of glass and supported by a steel frame. The soil columns were all of 1.2-m height and 0.2-m inside diameter. A partition made of Teflon was placed in each column below a layer of gravel to retain the soils at the bottom of the column. The soil gas and soil sampling ports were designed and manufactured as a whole with the column. The distance between the nearby sampling ports is 10 cm. The soil gas sampling ports were sealed before and after sample collections. The dried and weighed soil was packed carefully in 5-cm increments into the glass columns to a known bulk density (a vibrator was used to ensure that soil was packed uniformly).

A known volume (50 mL) of TCE solution was then injected into 2000 mL deionized water and stirred for 5 h. The resulting TCE-saturated aqueous solution was introduced to the bottom of the columns as vapor source, as shown in Fig. 1. For the sand and sand soil column, the water level was maintained at 1 m below the surface of the soil column, and for the sandy loam column, the water level was 0.95 m below the surface. The moisture content profiles were measured by weighing soil samples taken from sampling port of the column with a stainless-steel spoon before and after heating at 106°C for 8 h. Each time, three to four spoonfuls of soil were collected for moisture tests. The surface of the soil column was open during all experiments, defining a zero concentration at the top of the column. The experiments were performed at room temperature (25°C). It took 2, 5, and 9 mo before columns reached equilibrium for sand, sand soil, and sandy loam soil, respectively. The

equilibration time was initially estimated using numerical modeling and further confirmed or revised by obtaining constant soil gas concentration profile without temporal variation. Replicate water, soil, and soil gas samples were collected to test the reproducibility of the data, whereas a column test was performed only once for each media. The soil samples were taken for moisture test 2 to 3 d after the soil gas sampling. The TCE-saturated aqueous solution at the bottom of the column was kept at a constant level during the experiment.

Analytical Methods—Soil gas samples (0.5 mL) were collected from the unsaturated zone in the soil column (see below) using 1.0-mL gastight syringes, and these samples were analyzed directly on an SHIMADZU 2010 gas chromatograph equipped with a flame ionization detector and a capillary column (DB-624, Agilent, 30 m × 0.53 mm i.d., film thickness = 3.0 μm). The column was maintained at 70°C. The injector was operated in the split mode (5:1) and was maintained at 200°C. High-purity helium (99.999%) was used as the carrier gas at the constant flow rate of 40.0 mL min⁻¹.

Aqueous samples (5 mL) were collected from the saturated zone in the soil column using 10-mL syringes. These samples were placed in 50-mL glass vials fitted with a rubber stopper and diluted to 20 mL, then allowed to equilibrate for 1 h. According to preliminary tests, equilibration between the aqueous phase in the vials and the headspace could be achieved within 30 min. A 0.5-mL sample of headspace gas was then drawn from the vial using a 1-mL gastight syringe and analyzed by gas chromatography. All the gas samples and liquid samples were analyzed in duplicate. The glass vials were cleaned with methanol and rinsed with deionized water prior to use. The concentration of TCE in the solution was not directly measured, since the focus is the relative differences, rather than quantitative predictions of absolute values in different soils.

Numerical Model

The full 3-D finite element model applied here was COMSOL Multiphysics and has been presented in previous publications (Bozkurt et al., 2009; Pennell et al., 2009; Yao et al., 2011, 2013, 2015). The simulations were performed for a steady-state scenario assuming nonbiodegradable contaminants. Two scenarios were simulated.

The first involved the soil column experiments in which the contaminant vapor released from the simulated groundwater source diffused through the soil column to reach the atmosphere at the open end of the column. Because of the configuration of the experiment, this was effectively a 1-D simulation. The relevant governing equation of simulated contaminant vapor transport is

$$\frac{d}{dz} \left[D_e(z) \frac{d}{dz} c_g \right] = 0 \quad [1]$$

where z is the vertical coordinate (L); c_g is the contaminant vapor concentration (m L⁻¹); $D_e(z)$ is the contaminant effective diffusion coefficient (L² T⁻¹) which can be calculated using the Millington and Quirk model (Millington and Quirk, 1961) as:

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

where D_g is the diffusivity of contaminant in the gas phase (air) ($L^2 T^{-1}$), D_w is the diffusivity of contaminant in the water phase ($L^2 T^{-1}$), θ_g is the soil air-filled porosity, K_{aw} is partition coefficient between gas and water phase in the soil and is dimensionless; θ_t is the saturated soil water content, dimensionless; and θ_w is the soil water-filled porosity and is dimensionless. The latter can be calculated using the van Genuchten (1980) equation:

$$s_{ew} = \frac{\theta_w - \theta_r}{\theta_t - \theta_r} = \left[1 + (\alpha z)^N \right]^{1/N-1} \quad [3]$$

where s_{ew} is the effective total fluid saturation, dimensionless; α is the point of inflection in the water retention curve where $d\theta_w/dz$ is maximal (L^{-1}); θ_r is the residual soil water content, dimensionless; and N is the van Genuchten curve shape parameter. The fitted parameters α , θ_r and N are obtained with the Levenberg–Marquardt algorithm (Levenberg, 1944; Marquardt, 1963) according to observed moisture content profiles of the soil column.

The boundary conditions of the 1-D simulation are shown as:

$$c_g = \begin{cases} 0 & \text{Top} \\ 1 & \text{Bottom} \end{cases} \quad [4a] \quad [4b]$$

The parameter values (e.g., the diffusion coefficients of TCE) used here are shown in Table 2.

The other simulation performed here involved a full 3-D VI scenario, assuming a single, square, 10-m $\times$ 10-m footprint structure built on otherwise open (uncapped) field of 24 $\times$ 24 m. Since this scenario is symmetrical, only a quarter of domain was actually simulated. The governing equations of soil gas velocity and chemical transport are:

$$\begin{cases} \nabla u = \nabla \left(\frac{k_{in} k_{r,g}}{\mu} \nabla p \right) = 0 \\ \nabla (D_e \nabla c_g) + \nabla (u c_g) = 0 \end{cases} \quad [5a] \quad [5b]$$

where p is the pressure ($m L^{-1} T^{-2}$), u is the soil gas velocity ($L T^{-1}$), c_g is the soil gas concentration ($m L^{-3}$), and k_{in} and $k_{r,g}$ are the soil intrinsic permeability (L^2) and relative permeability. It may be observed that Eq. [5b] is the same as Eq. [1] but extended to the full 3-D coordinate system and allowing for advection. Equation [5a] determines the advective flow of soil gas under the usual assumption of incompressible flow. Equations [2] and [3] are used to calculate the effective diffusivity and moisture content distribution in the 3-D

simulations as they were in the column simulations. The value of $k_{r,g}$ could be calculated according to the following equation (Parker et al., 1987):

$$k_{r,g} = (1 - s_{ew})^{0.5} \left[1 - s_{ew}^{N/(N-1)} \right]^{2(1-1/N)} \quad [6]$$

The indoor air concentration is estimated with the simulated contaminant entry rate into the building.

$$c_{in} = \frac{J_e}{Q_b A_e}$$

where c_{in} is the indoor air concentration (m L^{-3}); J_e is the simulated contaminant entry rate (m L^{-1}) and could be obtained from the numerical simulations; Q_b is the volume of the enclosed space (L^3); and A_e is the indoor air exchange rate (T^{-1}). The parameters and boundary conditions used in the 3-D simulations are shown in Tables 2 to 4.

USEPA's VI database

The USEPA has compiled a database of measurements at VI sites across the United States. The entries in the database include measurements of contaminant concentrations in indoor air, subslab soil gas, exterior soil gas, and groundwater. The database was reported to contain 2929 paired measurements, such as paired groundwater and indoor air measurements, paired exterior soil gas and indoor air measurements, paired subslab soil gas and indoor air measurements, and paired crawlspace and indoor air measurements. Approximately 97% of the collected data involved chlorinated chemicals, and the rest petroleum hydrocarbons. Besides the information on sample concentrations, the database also includes other site information regarding geologic settings (e.g., hydrogeologic setting, soil type, and aquifer type), contaminant history (e.g., chemical of concern, source types, and depth) and a few other data from the VI investigation (e.g., sample time, building use, and foundation type).

In this study, the datasets with groundwater, subslab measurements, and indoor measurements were employed to calculate attenuation factors, which were divided into different groups based on two soil types (i.e., coarse or very coarse and fine textures), respectively. The textural parameters noted above are often all that are available in the datasets, and these will be used here as a surrogate for more definitive soil type characterization. Calculated contaminant concentration attenuation factors with different soil types were compared to identify the relative influences of moisture content distribution attributable to different soil particle sizes. This is done using the Student's t test, which is often used to determine if there are statistically significant differences between two groups. Effects are considered statistically significant at the $p = 0.05$ level (95% confidence intervals) with two-sided tests. Data analyses were performed using SPSS statistical package (IBM, 2011).

Results and Discussion

Simulation of Groundwater-through-Vadose-Zone Transport

At steady state, the vapor concentration profile across the vadose zone is dependent on the soil moisture content distribution, at least a portion of which is determined by the capillary-fringe effect. For the case with uniform moisture content, the vertical concentration profile of contaminant would naturally be linear from source to atmospheric sink in steady state, because the resistance across the soil layer is uniform with depth. When there are diffusive resistance variations with depth, this will no longer be the case. The effects of the capillary fringe are dependent on soil types.

In this study, sand, sand soil, and sandy loam soil were chosen as examples to investigate the effects. In the left panel of Fig. 2, measured soil moisture retention curves are compared with the simulated results using the van Genuchten (1980) equation, for which the fitting parameters are shown in Table 1. According to the calculated moisture content profile, the Millington and Quirk equation (Millington and Quirk, 1961) was used to estimate the effective diffusivity profile (left panel of Fig. 2). The calculated effective diffusivity was then substituted into the transport equation (Eq. [1]) to obtain the vapor concentration profile to be compared with the measured soil gas concentration, as shown in the right panel of Fig. 2.

Of the three textures, the moisture content curve break was the most abrupt for the sand column, as the fitted van Genuchten parameter N is the largest in that case. As the effective diffusivity of soil gas is dependent on the moisture content according to the Millington and Quirk equation, a significant decline of soil gas concentration is observed across a very short distance from the groundwater level. On the other hand, in the case of the sandy loam soil, the moisture content curve was the smoothest among three textures due to the smallest value of the van Genuchten parameter N ; this suggests that there would not be a very drastic change in effective diffusivity. As a result, the vertical profile of soil vapor concentration in the sandy loam soil case is also the smoothest, which is in accordance with our observations.

For all three soil columns, both measurements and predictions show that the capillary fringe can cause three to four orders of magnitude attenuation in soil gas concentration below the open ground surface, in accordance with previous studies (McCarthy and Johnson, 1993; Atteia and Hohener, 2010). This is also consistent with a similar observation by Shen et al. (2013a), in which 1-D numerical simulations were performed to study soil gas concentration profiles in columns of sand, sandy loam, and clay soils. Moreover, the good agreement between the predicted and the measured contaminant vapor concentration profiles indicates that the classical transport equation can be used to simulate contaminant transport from groundwater through the vadose zone.

Groundwater Source-to-Subslab Attenuation

A numerical model was used to simulate 3-D VI scenarios involving groundwater sources. Four cases (i.e., soil with uniform moisture content distribution, sand, sandy loam, and clay soils) were studied to investigate the role of the moisture content distribution, which is affected by the capillary fringe, in determining soil gas concentration profiles. For the first

case, the moisture content is assumed to be homogenous in the domain, whereas for the latter three, the vertical variation of effective diffusivity due to the moisture content variation is considered. The relevant van Genuchten parameters are shown in Table 3.

Figure 3 shows predicted contaminant vapor concentration profiles normalized by the contaminant vapor concentration in equilibrium with the groundwater source. The results for two vertical source-building separation distances (2 and 6 m) are shown. It suggests that the subslab concentration profiles are quite dependent on soil types for the shallow source cases. In the simulated scenarios of 2-m vertical separation, one to two orders of magnitude attenuation is observed for soil gas concentration from source to subslab for the case of sand, around one order of magnitude for the case of sandy loam, and less than one order of magnitude attenuation for the cases of uniform soil and clay. When the vertical distance increases to 6 m, the source-to-subslab attenuation factors become one to two orders of magnitude lower for all cases, except in the case of uniform soil, where the attenuation remains virtually unchanged.

Generally, in diffusion-dominated scenarios of steady-state VI, the subslab concentration can be estimated based on the vertical distribution of the resistance to soil gas diffusion (i.e., $1/D_e$) (Yao et al., 2012). For cases involving shallow sources in sand, the effective diffusivity of contaminant vapor just beneath the slab is about three orders of magnitude higher than that toward the bottom of the capillary fringe, as shown in Fig. 4. This implies that, in sand, the resistance just below the slab is relatively small compared with that further below the foundation at the capillary fringe, leading to low concentrations of contaminant right below the subslab. By contrast, in the “uniform soil” and “clay soil” cases, the effective diffusivity of contaminant vapor adjacent the slab is the same or no more than one order of magnitude higher than its diffusivity near the water table. This leads to high subslab contaminant concentrations because, in the absence of a diffusivity gradient, what dominates the concentration gradient is the existence of the diffusion pathway blockage presented by the slab. For the case of sandy loam, a moderate source-to-subslab attenuation can be observed, as the contaminant vapor effective diffusivity adjacent the slab is one to two orders of magnitude higher than that in the capillary fringe. Hence, the behavior is intermediate between that seen for the sand and clay.

When the vertical source-building separation is increased to 6 m, Fig. 3 shows there is no significant change of the subslab concentration for the uniform soil and sand cases, compared with those that have vertical separation distance of 2 m. This is because the distribution of effective contaminant vapor diffusivity in the cases with 6 m separation are similar to those in cases with 2 m separation in the sense that, again, the majority of the soil beneath the structures has uniform diffusivity. However, for clay and sandy loam cases, Fig. 4 shows that there is continually increasing effective diffusivity with vertical distance much higher into the vadose zone, or alternatively, that the diffusivity in the vadose zone remains lower than in the case of sand much higher into the vadose zone. Thus, the extra height above the capillary zone represents a greater fraction of the total resistance to diffusion, and as a result, the source-to-subslab attenuation is significantly enhanced by the extra separation distance, in those two cases.

Figure 5a shows the responses of 3-D simulated source-to-subslab (geometric mean) attenuation factors to the arithmetic mean of soil particle size (i.e., mean grain diameter in Table 3) for different water table source depths below the surface for slab-on-grade scenarios. It is found that the predicted variation of source-to-subslab attenuation factors for different soil types is up to 0.5 order of magnitude. There is no explicit relationship between the soil particle size and the source-to-subslab attenuation, except for cases involving shallow sources, in which the subslab concentration decreases with soil particle size if the mean grain diameter is >0.25 mm.

The above conclusion is consistent with a statistical analysis of entries in USEPA's VI database, as shown in Table 5, which suggests that there is no statistically significant difference between the groundwater source-to-subslab concentration attenuation factors in cases with fine-grained soils versus those with soil types characterized as "coarse" or "very coarse." This analysis, based on fairly crudely characterized soils, is therefore not inconsistent with what is concluded here on the basis of our models.

Subslab-to-Indoor Attenuation

Although we conclude that the groundwater source-to-subslab soil gas concentration attenuation is not affected by soil particle size except for in cases involving shallow sources, previous studies suggest that coarse-grained soil can increase indoor air concentration by an average of 0.5 to 1 order of magnitude (USEPA, 2012; Johnston and Gibson, 2013). In this study, statistical analysis of entries in the USEPA database (Table 5) also suggests that the average source-to-indoor air concentration attenuation factor with "fine" soil type is about 0.6 order of magnitude lower than that with "coarse" or "very coarse" soil type.

To investigate this point further, we examined the results of the same numerical simulations presented above with respect to the source-to-indoor attenuation. Our results shown in Fig. 5c suggest that the predicted source-to-indoor air contaminant concentration attenuation factors are higher (i.e., there is less attenuation of contaminant) in coarse-grained soils, such as sand and loamy sand. Considering that we have shown that soil particle size does not play an important role in determining the source-to-subslab attenuation except for shallow (e.g., <6 m) source cases, it is reasonable to conclude that the subslab-to-indoor air concentration attenuation is affected by soil particle size.

In Fig. 5b, numerical simulations indicate that the predicted subslab-to-indoor attenuation factor in coarse-particle soil is higher than the attenuation factors in fine-grained soil, especially for cases of shallow sources. This is because that coarse particle soil allows for enhanced soil gas advection in the vicinity of the slab, and advection is believed to be the dominant mechanism for the entry of contaminated soil gas through breaches in the building foundation (Robinson and Sextro, 1997; McHugh et al., 2012). The analysis of USEPA database shown in Table 5 also suggests that an average of 0.4 order of magnitude more attenuation is observed in the subslab-to-indoor process if the soil type is "fine" instead of "coarse" or "very coarse."

Implications

For VI involving chlorinated chemicals such as tetrachloroethylene (PCE) and TCE, contaminated groundwater is commonly the vapor source (USEPA, 2012), as groundwater plumes can typically affect a larger area than isolated free product vapor sources in the vadose zone. In such cases, soil is the major medium between groundwater source and the building of concern. Our study indicates that the texture of the shallow soil below the building foundation is important because it determines the soil gas entry rate into the enclosed space, whereas the vapor concentration profile outside of this subsurface advective zone is generally independent of soil particle size, except for cases of shallow sources (e.g., <6 m). In other words, the properties of deep soil are generally of limited concern, as they play an insignificant role in determining the source-to-subsurface and thus the groundwater-to-source soil gas contaminant concentration attenuation. Our findings strongly suggest that there is high value in obtaining soil borings beneath a building to establish subsurface soil texture, but there is less value in exploring in detail the texture of deeper soil (unless it represents a significant barrier to diffusion, such as a clay lens [see below]). The value of characterizing subsurface soil permeability during subsurface soil gas sampling has been indicated by other studies (McAlary et al., 2009). Moreover, the results of this study suggest that the equation used in USEPA's VI spreadsheet to describe the vapor transport through the capillary fringe does not correlate with observations in the column experiment and could be revised to avoid misjudgment of the risk.

It should be noted, however, that only steady-state conditions and single-layered soils have been considered in this research. In reality, vertical variability of subsurface soil types (i.e., layering) would also affect the soil gas concentration attenuation in the subsurface (Abreu and Schuer, 2012), and events such as rainfall and snow can cause a dynamic response of moisture content profile in soil (Shen et al., 2012; Hers et al., 2014). Biodegradation is also not included here, so the results for petroleum contaminants need to be considered in light of that possibility as well.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

1-D	one-dimensional
3-D	three-dimensional
JEM	Johnson–Ettinger model
TCE	trichloroethylene

VI vapor intrusion

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Core Ideas

- Soil particle size is not important in source-to-subslab processes, except for shallow sources.
- Soil particle size affects subslab-to-indoor air concentration attenuation.
- Investigators should focus on the shallow soil beneath the building foundation.

Fig. 1.
Schematic drawing of the soil column experiment.

Fig. 2.

Left: Observed soil moisture profiles (square), the effective diffusion coefficient (blue point), and its curve fit using the van Genuchten relations (line). Right: Observed trichloroethylene concentration in the soil column (square) and predicted concentration profiles (line).

Fig. 3. Simulated vertical soil gas concentration profiles through the building centerlines. The top four panels assume a source at 2.2-m depth, and the bottom four panels assume a source at 6.2-m depth, whereas the depth of the foundation is 0.2 m deep.

Fig. 4. Simulated one-dimensional profile of overall effective diffusivity for different soil types and partition coefficients in scenarios with a source depth assumed as 8 m.

Fig. 5.

The responses of three-dimensional simulated (a) source-to-subslab (the geometric mean), (b) subslab (the geometric mean)-to-indoor, and (c) source-to-indoor soil gas concentration attenuation factors in slab-on-grade scenarios to the arithmetic mean of soil particle size. S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; L, loam; SIL, silt loam; CL, clay loam; SICL, silty clay loam; SI, silt; SIC, silty clay; SC, sandy clay; C, clay; 3 m means source depth below ground surface is 3 m.

Table 1
Parameters in soil column experiments and one-dimensional numerical simulations (Fig. 2).

Soil type	Mean particle size distribution			Fitted van Genuchten parameters			
	>0.02%	0.02~0.002%	<0.002%	θ_l	θ_r	α	N
	mm						
Sand	100	0	0	0.345	0.0011	6.730	4.1879
Sand soil	4.5	7.1	88.4	0.384	0.0247	1.298	2.3791
Sandy loam soil	16.5	27.7	55.8	0.400	0.0750	2.9721	1.4524

Table 2

Parameters used in numerical simulations.

Parameter	Symbol	Unit	Fig. 2	Fig. 3	Fig. 4	Fig. 5
Indoor depressurization	p	Pa		-5		-5
Source depth	d_s	m		2.2, 6.2, 4, 8	8	3, 5, 8, 11, 14, 18
Foundation footprint length		m		10		10
Foundation footprint width		m		10		10
Foundation depth	d_f	m		0.2, 2		0.2, 2
Volume of the enclosed space	V_b	m ³		366		366
Air exchange rate	A_e	h ⁻¹		0.25		0.25
Foundation crack thickness	d_{ck}	m		0.15		0.15
Foundation crack width	w_{ck}	m		0.005		0.005
Partition coefficient	K_{aw}		0.4	0.228	0.0228, 0.1, 0.228	0.228
Diffusion coefficient in air	D_g	m ² s ⁻¹	7.9×10^{-6}		8.8×10^{-6}	
Diffusion coefficient in water	D_w	m ² s ⁻¹	9.1×10^{-10}		9.8×10^{-10}	

Table 3

The van Genuchten parameters from the USEPA spreadsheet implementation of the Johnson–Ettinger model (Fig. 2–5) (USEPA, 1997).

SCS soil name	α	N	θ_l	θ_r	K_{in} m ²	Mean grain diameter mm
Silty clay	1.622	1.321	0.481	0.111	1.48×10^{-13}	3.90×10^{-2}
Silt	0.658	1.679	0.489	0.050	6.74×10^{-13}	4.60×10^{-2}
Silty clay loam	0.839	1.521	0.482	0.090	1.70×10^{-13}	5.60×10^{-2}
Clay	1.496	1.253	0.459	0.098	2.26×10^{-13}	9.20×10^{-2}
Silt loam	0.506	1.663	0.439	0.065	2.82×10^{-13}	1.10×10^{-1}
Clay loam	1.581	1.416	0.442	0.079	1.26×10^{-13}	1.60×10^{-1}
Loam	1.112	1.472	0.399	0.061	1.85×10^{-13}	2.00×10^{-1}
Sandy clay	3.342	1.208	0.385	0.117	1.74×10^{-13}	2.50×10^{-1}
Sandy clay loam	2.109	1.330	0.384	0.063	2.04×10^{-13}	2.90×10^{-1}
Sandy loam	2.667	1.449	0.387	0.039	5.93×10^{-13}	3.00×10^{-1}
Loamy sand	3.475	1.746	0.390	0.049	1.62×10^{-12}	4.00×10^{-1}
Sand	3.524	3.177	0.375	0.053	9.92×10^{-12}	4.40×10^{-1}

Table 4

Boundary conditions of the three-dimensional simulations.

Condition	Soil gas velocity	Chemical transport
Open ground surface	$p = 0$	$c = 0$
No flux	$\vec{\nabla} p = 0$ (vertical to the boundary)	$D_e(z) \vec{\nabla} c_g + \vec{u} c_g = 0$ (vertical to the boundary)
Source	$\vec{\nabla} p = 0$ (vertical to the boundary)	$c_g = c_g$
Perimeter crack	$p = p_{in}$	$D_e(z) \vec{\nabla} c_g + \vec{u} c_g = \frac{\vec{u} c_g \exp\left(\frac{\vec{u} L_{ck}}{D_g}\right)}{\exp\left(\frac{\vec{u} L_{ck}}{D_g}\right) - 1}$

Diagram

Table 5

Effects of soil type on variation in the log attenuation factors in the USEPA database.

Soil texture	No. of samples	Mean $\pm$ SD	<i>p</i> -value
$-\log(c_{in}/c_{gw})$			
Very coarse or coarse	112	3.71 $\pm$ 0.77	0.000
Fine	22	4.34 $\pm$ 0.45	
$-\log(c_{ss}/c_{gw})$			
Very coarse or coarse	112	1.15 $\pm$ 0.64	0.150
Fine	22	1.35 $\pm$ 0.48	
$-\log(c_{in}/c_{ss})$			
Very coarse or coarse	112	2.56 $\pm$ 0.70	0.010
Fine	22	2.99 $\pm$ 0.67	