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Modeling Quantification of the Influence of Soil Moisture on Subslab Vapor Concentration

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Abstract

The U.S. EPA has developed a database of field data obtained from vapor intrusion sites throughout the United States. Large variations in reported subsurface contaminant vapor concentration ratios (*e.g.* building subslab to groundwater source) present challenges for the analysis of subsurface vapor transport processes. Meanwhile, numerical models have been used by the U.S. EPA and others to describe the transport processes governing vapor intrusion. The influence of the capillary fringe has often been ignored in these models. In this manuscript, the influence of soil moisture content on the subslab vapor concentration is analyzed in the context of mathematical models. Results are compared to those from other modeling methods that do not account for the soil moisture content. The slab capping effect is observed to interact with the effect of soil moisture in determining the subslab contaminant vapor concentration. The slab capping effect is observed to be significant when the building-source separation distance is less than half of the slab size.

Introduction

In 2012, the U.S. EPA¹ published a document showing results from a series of runs of a three-dimensional numerical model that simulated vapor transport processes. This series of results summarized and explained various factors that affect vapor intrusion. These analyses are based on use of two sets of assumptions. The “baseline model” assumed an infinite vapor source that was located at the top of the capillary fringe, in which case, the source vapor concentration was assumed uniform beneath a domain that held a structure of interest. This is distinct from another common assumption, that the vapor source is groundwater, which is uniformly distributed just beneath the domain. The distinction (*i.e.* whether the domain starts at the groundwater table or top of the capillary fringe) can be important, as it affects where a zone of uniform vapor concentration exists (above or below the capillary fringe).

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A relatively higher contaminant vapor concentration is normally present beneath a building slab than at comparable depths outside the building footprint. This has been attributed to the slab capping effect ², in which the (usually concrete) building slab serves as a largely impermeable barrier to upward diffusion of contaminant vapor. This capping effect on contaminant concentration also extends deeper into the soil, and may lead to higher contaminant vapor concentrations at the top of the capillary fringe directly beneath the building than away from its footprint. This would render questionable an assumption of constant contaminant vapor concentration at the top of the capillary fringe, even when the underlying groundwater concentration is uniform. This effect has not been considered previously in the literature. It is worth mentioning that the groundwater table elevation is often used to represent the elevation of the vapor source. This means the capillary fringe thickness is also not taken into account. This will be considered further below.

Also in the above-cited U.S. EPA document, an “alternative model” was used to examine the influence of various factors that affect vapor intrusion, including different soil moisture contents. In these scenarios, the soils were divided into distinct relatively wet and relatively dry soil layers. The soil moisture was assumed to be constant within each of these soil layers. This kind of layered soil approach has been used in other modeling work ³ though not explicitly focusing on soil moisture effects. Several other studies of vapor intrusion have noted the importance of soil moisture distribution ^{4–12}. For example, Tillman and Weaver ¹² showed the impact of the temporal and spatial variation of near-surface soil moisture content on indoor air vapor concentration, but the capillary fringe was not explicitly considered. Sanders and Talimcioglu ¹⁰ and Picone *et al.* ⁹ simplified the vapor intrusion scenario into one-dimensional (1D) form and studied transient processes, as related to soil moisture. While this previous work has contributed to the understanding of vapor intrusion and the general role of moisture, as distinct from these above studies, this manuscript assesses the influence of soil moisture on the subslab contaminant vapor concentration.

The modeling in this manuscript was developed from a 1D model ¹³ of vapor transport in soils that has been validated through comparison with experimental results, and extends it into multi dimensional settings, in order to evaluate the effect of soil moisture on subslab vapor concentration. Several models using different methods to describe or account for soil moisture are then compared with field measured data in the U.S EPA vapor intrusion database. The interaction between different factors in determining the subslab vapor concentration is examined.

Modeling Methodology

The modeling configuration that is used to describe a typical ^{11, 14–17} vapor intrusion scenario is shown in Figure 1. The governing equations, boundary conditions, and constitutive equations (in full 3D form) for this scenario are shown in Table 1. This model is primary physically based and assumes a steady state, so temporal effects are ignored. The building slab is assumed to be impermeable. A finite element code, COMSOL, is used for solving the partial differential equations in either two- or three-dimensional (2D or 3D) settings. Tetrachloroethylene (PCE) is chosen as a typical contaminant, while comparison with other chemical in the context of human health aspect is not discussed here. PCE is

assumed to be uniformly distributed in the groundwater (as opposed to assuming uniform distribution at the capillary fringe interface). Contaminant diffusion through soil gas has been earlier shown to be the controlling process determining subsurface concentration profiles, even in the presence of the typical small pressure difference between indoor air and outdoor air which promotes a small amount of near subslab advection^{18, 19}. Also, near-water table vertical dispersion by groundwater flow has been shown as a minor process^{13, 20} for contaminant transport within the unsaturated zone.

In the cases considered below in which soil gas advection is allowed to contribute to contaminant entry into the structure, the foundation slab, which is assumed to be impermeable, is assumed to be 0.15 m, and to have a 0.01 m wide crack running along the perimeter of the foundation which permits entry of contaminant vapor into the 5 Pa depressurized basement. It has been shown that this particular assumption regarding the entry crack gives results quite similar to those using other assumptions of crack configuration and so is a good general description of crack entry¹⁸.

We first compare previously obtained modeling predictions with field measurements from the U.S. EPA database. Then we use a simplified 2D numerical model, based on those used in modeling other transport processes in dry soils^{21–24}, to analyze the influence of soil moisture on the subslab vapor concentration. Then, we incorporate the soil moisture calculation into a full 3D numerical vapor intrusion model, examining three soil types as examples.

Results and Discussion

Comparing field data and predictions from the models assuming uniform soil moisture

The U.S. EPA vapor intrusion database includes field measurements of subslab contaminant vapor concentrations c_{ss} , soil gas contaminant vapor concentrations from non-subslab areas c_{sg} , and contaminant vapor concentration in equilibrium with groundwater c_{gw} . Considering the subslab vapor concentration, c_{ss} data are plotted as a function of c_{gw} in Figure 2. Although the data points spread out over orders of magnitude, there appears to be a correlation between these values, *i.e.*, c_{ss} increases with c_{gw} .

Also shown in this figure are the averaged values of c_{ss}/c_{gw} from 30 sets of 3D simulations obtained from a previous numerical modeling study²⁵. These are added as the dashed line. These 30 sets of modeling scenarios have tested a range of soil gas permeabilities and different building construction characteristics, including a single building, a building with a parking lot or detached garage, a building with a porous sub-base, and separate adjacent buildings scenarios. These modeling scenarios all assumed uniform soil moisture and constant effective diffusivity. The basement depth l_{slab} was 2 m and the assumed groundwater depth l was 8 m. These modeling results of c_{ss}/c_{gw} all fall towards the higher end of the actual field data, and their averaged value is about 20 times larger than the median of the field data. What was not included in the above analyses was the influence of the capillary fringe, as discussed below.

From a previous study ², which also assumed a uniform soil, the subslab vapor concentration has been shown to be approximated by:

$$\frac{c_{ss}}{c_1} = 1 - \frac{l - l_{slab}}{l} \frac{1}{\pi} \arccos \left\{ 1 - \frac{8 \exp\left(\frac{\pi \beta}{2(l - l_{slab})}\right)}{\left[\exp\left(\frac{\pi \beta}{2(l - l_{slab})}\right) + 1\right]^2} \right\} \quad \text{Equation (3)}$$

where c_1 is the source vapor concentration, which was assumed to be uniformly distributed along a horizontal plane at a depth l below the groundwater table. This really corresponds to an assumption of uniform vapor concentration above a capillary fringe whose top is at a depth l . In general, $c_1 < c_{gw}$ due to the influence of the diffusion resistance of the capillary fringe (and it needs to be kept in mind that c_{gw} refers to the vapor in equilibrium with the groundwater). Here, disregarding for the moment the above and assuming $c_1 = c_{gw}$, the calculated subslab results using Equation (3) are shown in Figure 3(a), for different basement depths l_{slab} . Note that Figure 3(a) shows that for most conditions, the subslab concentrations are of comparable order of magnitude to groundwater source concentrations. Properly accounting for the capillary fringe resistance can reduce c_1 by several orders of magnitude, relative to c_{gw} .

Figure 3(b) plots paired field data for subslab and groundwater, obtained from the U.S. EPA database. What is plotted is the ratio c_{ss}/c_{gw} as a function of the subslab to groundwater table distance. The building slab to source vertical separation distance ($l - l_{slab}$) mostly varies from 1 m to 10 m. While information on the building slab size was not provided in the database, we might assume that a reasonable building slab characteristic size β in North America is normally of order 10 m. Applying Equation (3) with this assumption and assuming again $c_1 = c_{gw}$, the calculation results are added to Figure 3(b) and fall within the shaded area. The range of c_{ss}/c_{gw} so estimated is again at the higher end of the actual field data. In other words, taking c_{gw} as an estimate of c_1 again leads to an overprediction of c_{ss} . This may again be due to ignoring a significant resistance of the capillary fringe to vapor transport.

The results from the models with consideration of soil moisture

The above modeling results have demonstrated some of the limitations of vapor intrusion models in predicting the subslab vapor concentration, particularly when these assume soil moisture content is uniform and the contaminant vapor source is the well-mixed groundwater table. In the U.S. EPA vapor intrusion database ²⁶, the major portion of the sources at different sites were indeed dissolved contaminant in groundwater. The capillary fringe right above the groundwater however acts as a large resistance to diffusion, because the diffusivity of contaminant in this zone is much lower than its diffusivity in air-filled soil porosity. The capillary fringe cannot be assumed to be well-mixed with the underlying groundwater, so there is a significant concentration gradient across the capillary zone.

For analyzing the effect of non-uniform soil moisture distribution, including the existence of a capillary fringe, on the subslab vapor concentration, a 2D numerical model is now used here. A concentration profile calculated using this model (governed by the equations in Table 1), considering both vapor diffusion and soil gas advection, is shown in Figure 4. In

this first case, the soil was divided into two soil layers: a relatively wet soil layer (thickness l_1 , total effective diffusivity $D_1 = \text{constant}$) immediately above the groundwater table, and a relatively dry soil layer (thickness l_0 , total effective diffusivity $D_0 = \text{constant}$) above this. The wet layer is a surrogate for the capillary fringe, reflecting an approach used in some other modeling²⁷. The calculated concentration contours beneath the slab show an upturn, with higher contaminant concentrations underneath the slab as is quite commonly predicted by most 2D and 3D models. This is a result of the slab capping effect *i.e.* the slab acts as diffusion barrier. Note, however, that this capping effect extends all the way downward to the top of capillary fringe (Point C).

As noted above, previously published vapor intrusion models have typically assumed either a constant contaminant vapor source at the groundwater table interface (at a concentration equal to the vapor concentration in equilibrium with the groundwater), or a constant vapor concentration at the top of the capillary fringe. In Figure 4, the former was assumed, and demonstrated that this assumption is inconsistent with the latter. As noted above, the U.S. EPA baseline model¹ has used the latter method. The advantage of not including modeling of a capillary layer explicitly is that it avoids the cost of adding many more complexity and thus incurring longer modeling time and effort, but as this result shows, it may lead to results that are not accurate, near the building.

In practice, the availability of soil gas samples taken just above the capillary fringe can decrease the uncertainties associated with the modeling of this low diffusivity layer. However, the actual contaminant vapor concentration distribution at the top of the capillary fringe has not been considered in previous analyses. The capping effect propagates to this interface (Point C), and so assumption of uniform vapor source concentration at the top of the capillary fringe is again not necessarily consistent with a uniform groundwater vapor source, despite these sometimes being equated. It follows that a soil gas sample taken just above the capillary zone, but outside the building footprint, might not accurately reflect the value beneath the building.

Next, **four** different numerical modeling scenarios have been used to evaluate the influence of high soil moisture content layers without yet explicitly modeling the structure of the capillary fringe. To simplify the analysis, soil gas advection is neglected here since its influence is not visible anywhere but immediately adjacent the slab, and even then, generally only visible near a crack. The **first** scenario involves simulating a lower wet soil layer that is not quite as effective a diffusive barrier as an actual capillary layer (thickness $l_1 = 0.5 l_0$, effective diffusivity $D_1 = 0.1 D_0$) beneath the upper “dry” soil layer. The **second** scenario involve modeling a thick “capillary fringe” ($l_1 = 0.5 l_0$, $D_1 = 0.01 D_0$), in which a typical capillary fringe vapor diffusivity is assumed. The **third** scenario involves a thinner lower wet soil layer of only slightly reduced diffusivity ($l_1 = 0.05 l_0$, $D_1 = 0.1 D_0$) beneath the dry soil layer. The **forth** scenario ($l_1 = 0.05 l_0$, $D_1 = 0.01 D_0$) involves a thinner capillary-like zone characterized by the usual capillary fringe vapor diffusivity. Therefore, this may be the most likely to occur of these four scenarios. All four scenarios are simulated considering different non-dimensional slab sizes (β/l_0), in order to explore the interaction between slab capping and capillary effects.

For these four sets of models, vapor concentrations at three points (see Figure 4) were evaluated: c_{ss_C} at Point C, which is underneath the center of the slab and at the interface between the two soil layers; c_{sg_D} at Point D, which is also at the interface between soil layers but horizontally far away from the building; and c_{ss} right beneath the center of the subslab. The slab capping effect on Point C and the subslab are immediately seen in Figure 5(a) and (b), respectively.

Figure 5(a) compares the concentrations at Point C to Point D. The building slab capping effect leads to the difference between these concentrations in which the concentration $c_{ss_C} > c_{sg_D}$. If there is no building on the soil surface, the vapor concentrations at Point C and Point D would be the same. The larger the non-dimensional building slab (β/l_0), the larger the capping effect on Point C. In the cases modeled here, these concentration differences can be up to an order of magnitude. Figure 5(b) shows the slab capping effect on the subslab vapor concentration compared to c_{sg_D} . There are two effects visible in Figure 5(b). Since contaminant concentration decreases with height above the groundwater source, the deeper the groundwater, the lower the ratio of c_{ss}/c_{sg_D} . On the other hand, the greater the capping effect, the closer the values of c_{ss} and c_{sg_D} should be. Finally, the greater the capping effect, the less important the resistance of the capillary fringe between beneath the building, and the value of c_{ss} approaches c_{gw} (which can be significantly greater than c_{sg_D}). The larger the capillary diffusion resistance, the larger the capping effect on c_{ss_C} and c_{ss} .

From Figure 5(a) and (b), the first and the forth sets of results overlap each other, which can be understood by considering the ratio of l_l/D_l . Both the bottom layer thickness and diffusivity decrease by an order of magnitude in the fourth case relative to the first, so the ratio of l_l/D_l remains the same. Since this moist soil layer is that which is most critical in determining c_{ss_C} and c_{ss} , it is not surprising that these sets of results overlap.

In Figure 5(b), an analytical solution for a uniform soil with $D_l = D_0$, calculated using Equation (3), has been added. Here, c_l in Equation (3) is equal to the soil gas vapor concentration at Point D, instead of c_{gw} that had been used in Figure 3(b). The analytical solution is the lower bound (limiting case) of the subslab vapor concentration shown in Figure 5(b). The curves that fall above this analytical curve show an enhanced capping effect attributable to the fact that c_l in Equation (3) depends on position. Comparing this analytical result with the above numerical simulations for different soil layer configurations, larger differences are found for larger β/l_0 , though when $\beta/l_0 < 2$, relatively small differences are seen. If the low diffusivity layer exists nearer to the slab than $\beta/2$ (i.e. $\beta/l_0 > 2$), the capping effect on the concentration at the soil layer interface cannot be ignored. The assumption of a uniform vapor concentration along the soil layer interface¹ will thus lead to underestimation of the subslab vapor concentration. For example, if a building has a characteristic footprint size of 10 m, and a groundwater source is 10 m below the surface, then the assumption of a uniform concentration at the edge of the capillary fringe is quite good. On the other hand, if the source is 2 m below ground surface and the building is surrounded by paving such that $\beta = 16$ m, then $\beta/l_0 = 8$ and the contaminant concentration at the top of the capillary fringe beneath the building might be almost an order of magnitude greater than it is away from the building (keeping in mind that l_l depends upon soil type).

The layered soil assumption has also been incorporated into a full 3D model of a building with a basement (again, using the Equation of Table 1). Figure 6 shows the cross-section plots of vapor concentrations from this calculation. Here, Figure 6(a) employed the van Genuchten relations in calculating the true soil moisture distribution instead of assuming two distinct (wet and dry) soil layers as was used above, while Figure 6(b) assumed the two soil layers as in the above 2D model. In this case, the U.S. EPA Johnson and Ettinger built-in default values for the soil moisture were used for each layer and capillary fringe thickness. A 2 m basement was included in this scenario and soil gas advection was considered, though comparing with the no soil gas advection case (results not shown), advection again played a minor role in determining the subsurface vapor concentration. The assumed building slab size β was 10 m and the depth of groundwater vapor source l was 4 m bgs.

Comparing Figure 6(a) and (b), the contaminant vapor concentration distributions are quite different when using these two methods, and the results depend on the soil type, soil moisture distribution and the building slab capping effect. For clay and sand, (a) and (b) show large differences.

Using the van Genuchten relations to describe the actual moisture profile for clay, Figure 6(a) shows a gradual decrease in contaminant concentration with height. This is a result of the soil moisture content that drops smoothly from groundwater to ground surface. The effective diffusivity for contaminant vapor gradually increases with height above the groundwater table. It is worth mentioning that this figure looks like the profile that is obtained assuming uniform soil, such as in Figure 2(a), and c_{ss} is of the same order of magnitude (about 50%) of the source concentration in this case.

Assuming instead a two-layer (wet and dry) soil for clay, Figure 6(b) shows very different behavior. The lower soil layer ($l_l = 0.7 l_0$, $D_l = 0.006 D_0$) becomes a much larger resistance to contaminant diffusion than the upper soil layer, *i.e.*, the effective diffusivity in the capillary fringe is only 0.6% of that for the soil layer above. Thus, the contaminant concentration gradient falls almost entirely into the capillary fringe. Thus the two-layer approximation underpredicts subsurface values.

For sandy loam, there exist much smaller concentration differences regardless of the choice of assumptions regarding soil moisture profiles. The concentration gradient is mostly confined to the capillary fringe in both (a) and (b).

For sand, using the van Genuchten relations, the soil moisture content decreases very fast from saturation as the height above the groundwater table increases, resulting in a diffusivity increase from $8.2 \times 10^{-10} \text{ m}^2/\text{s}$ to $8.9 \times 10^{-8} \text{ m}^2/\text{s}$ through a very small height of capillary fringe (0.32 m). This confines a large concentration gradient to that zone and leads to the result in the lowest panel of Figure 6(a). The representation of an actual soil moisture content distribution in this case leads to an effective capillary fringe resistance that is much higher than that in the simple two soil layer representation of Figure 6(b), in which the upper dry soil layer represents more of the total diffusive resistance for sand. In Figure 6(b), $l_l = 0.1 l_0$, $D_l = 0.04 D_0$. the calculation result shows $c_{ss_C} = 1.7 c_{sg_D}$ and $c_{ss} = 1.5 c_{sg_D}$. In

this case, there is a relatively smaller slab capping effect on the top of the capillary fringe than that for clay in Figure 6(b). If one uses a deep soil gas vapor concentration at Point D as a hypothetical vapor source concentration, and assumes a constant concentration along the horizontal line at the same elevation of Point D, the calculation result will be almost the same as the prediction obtained by modeling the soil layer below Point D.

It should be noted that the soil moisture retention curve can be very non-linear, such as that in the cases of sand. This can result in long simulation time in numerical modeling. For sand in Figure 6(a), the grid size is very small (< 0.01 m), in order to accurately calculate the vapor concentration gradient within the capillary fringe. The method based on assuming a layered soil linearized the vapor transport Equation (2), which greatly reduced computational time. Of course, it comes at the expense of accuracy in prediction, as Figure 6 shows.

Comparing the above results to the previous simulation results in Figure 2, shown as in the shaded area, the models that properly account for the capillary fringe are able to predict a relatively wider and more realistic range of subslab vapor concentrations ($0.01 \sim 0.5$) even for a relatively shallow source depth.

Conclusion

The prediction of subslab vapor concentrations from models of soil vapor transport is complicated, as the effects of soil moisture content interact with the slab capping effect. For subslab vapor concentration, the slab capping effect, as governed by the slab size over the slab-source vertical distance plays a key role. From the above results, the capping effect is enhanced by a capillary layer which is present within a short distance below the slab. For a deep groundwater source, a model assuming a constant source vapor concentration along the soil capillary fringe interface can provide the subslab vapor concentration that is almost the same as from a model that explicitly includes this layer.

Further, it should be noted the use of a total effective soil diffusivity^{13, 28}, especially for cases when the capillary fringe exists near the subslab, is not reliable for obtaining the subslab vapor concentration. In other words, the subslab vapor concentration is sensitive to the details of soil properties.

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Abbreviations

c	contaminant vapor concentration [$\mu\text{g}/\text{m}^3$]
c_{gw}	vapor concentration in equilibrium with groundwater concentration [$\mu\text{g}/\text{m}^3$]
c_{sg}	the soil gas vapor concentration [$\mu\text{g}/\text{m}^3$]
c_{sg_D}	the soil gas vapor concentration at Point D [$\mu\text{g}/\text{m}^3$]

c_{ss}	the subslab vapor concentration [$\mu\text{g}/\text{m}^3$]
c_{ss_C}	the subslab vapor concentration at Point C [$\mu\text{g}/\text{m}^3$]
c_w	the contaminant concentration in the water phase [$\mu\text{g}/\text{m}^3$]
D_0	the total effect diffusivity of contaminant for the top soil layer [m^2/s]
D_1	the total effect diffusivity of contaminant for the lower soil layer [m^2/s]
D_i	the molecular diffusivity of contaminant in the water or gas phase [m^2/s]
g	the acceleration due to gravity [m/s^2] acting in the vertical direction z
$H_{c,inf}$	the thickness of the capillary fringe [m]
K_H	the Henry's law constant [dimensionless]
k_s	the intrinsic soil permeability [m^2]
$k_{r,g}$	the relative soil gas permeability compared to the saturated permeability [dimensionless]
l	the thickness of soil column from open ground to the groundwater table [m]
l_0	the vertical distance from slab to the soil layer interface [m]
l_1	the thickness of the lower soil layer or capillary fringe [m]
l_{sg}	the depth of the soil gas sample bgs [m]
l_{slab}	the thickness of the lower soil layer or capillary fringe [m]
M^*	van Genuchten parameter [dimensionless]
p_c	capillary pressure [Pa]
p_i	the fluid pressure [Pa]
q	vapor flux [$\mu\text{g}/\text{m}^2/\text{s}$]
q_{crack}	vapor flux along the crack [$\mu\text{g}/\text{m}^2/\text{s}$]
u_g	the soil gas flow velocity [m/s]
z	the vertical height above the groundwater table [m]
α^*	van Genuchten parameter [1/m]
β	building slab size [m]
θ_g	volumetric soil gas content [dimensionless]
θ_r	residual soil moisture content [dimensionless]
θ_t	the total soil porosity which is either water (θ_w) or gas (θ_g) filled [dimensionless]
θ_w	volumetric soil moisture content [dimensionless]
ρ_g	the soil gas density [kg/m^3];

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Perimeter crack: B.Cs. (1) or (2b); (4a) or (4b)

Fig 1.

The vapor intrusion modeling scenario. The boundary conditions that are not explicitly shown are B.Cs. (3) and (7) of Table 1

Fig 2.

Field measurements in the U.S. EPA vapor intrusion database. The subsurface vapor concentration as a function of corresponding the paired groundwater vapor concentration

Fig 3.

(a) The calculation results for c_{ss}/c_{gw} from Equation (3) with different basement depths. (b) the field data of c_{ss}/c_{gw} plotted with absolute elevation above the groundwater table

Fig 4.

An example of the concentration profile from 2D numerical simulation. The soil is divided into two layers as described in the text. The building is of slab-on-grade type

Fig 5.
Modeling results for scenarios with two soil layers. (a): Vapor concentration at Point C compared to that at Point D. (b): Vapor concentration beneath the subslab compared to that at Point D

Fig 6. 3D modeling results: cross-section plots of vapor concentration. (a) The true soil moisture profile was calculated using van Genuchten relations; (b) Soil moisture content is adapted from the U.S. EPA version of the Johnson and Ettinger model, and described by two distinct soil layers

Table 1

Equations and boundary conditions (nomenclature defined in the Abbreviations table)

Governing equations		
Soil gas flow	$\nabla \cdot \left[\frac{k_s k_{r,g}}{\mu_g} (\nabla p_g + p_g g z) \right] = 0$	Eq.(1)
Contaminant transport without advection	$\nabla \cdot (D \nabla c) = 0$	Eq.(2a)
Contaminant transport with advection	$\nabla \cdot (D \nabla c) - \nabla \cdot (u_g c) = 0$	Eq. (2b)
Boundary conditions		
Soil gas flow	$p_g = -\rho_g g z$	B.C.(1)
	$u_{g=0}$	B.C.(2a)
	$P_g = -\rho_g g z - 5pa$	B.C.(2b)
	$u_g = 0$	B.C.(3)
Contaminant transport	$Q_{crack} = 0$, when $u_g = 0$	B.C.(4a)
	$q_{crack} = \frac{u_g c \exp(\frac{u_g}{D_{air}} l_{slab})}{1 - \exp(\frac{u_g}{D_{air}} l_{slab})}$, when $u_g \neq 0$	B.C.(4b)
	$c = 0$	B.C.(5)
	$c = 1$	B.C.(6)
	$q = 0$	B.C.(7)
Constitutive equations		
van Genuchten relations	$\frac{\theta_w - \theta_r}{\theta_t - \theta_r} = [1 + (\alpha^* z)^{1/(1-M^*)}]^{-M^*}$	
	$\theta_g = \theta_t - \theta_w$	
Relative soil gas permeability	$K_{r,g} = (1 - se_w)^{1/3} (1 - se_w^{1/M^*})^{2M^*}$	
Effective in-soil diffusivity using Millington – Quirk equation	$D = D_g \frac{\theta_g^{10/3}}{\theta_t^2} + \frac{D_w}{K_H} \frac{\theta_w^{10/3}}{\theta_t^2}$	
Henry's law	$c = k_H c_w$	
Thickness of the capillary fringe	$H_{c,inf} = \frac{1}{\alpha^*} \left(\frac{1}{M^*} \right)^{1-M^*}$	