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Examining the role of sub-foundation soil texture in chlorinated vapor intrusion from groundwater sources with a two-layer numerical model

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ABSTRACT

In this study we investigate the role of the sub-foundation soil texture in determining groundwater source-to-indoor air attenuation factors. A three-dimensional numerical model was used to simulate a series of two-layer scenarios, involving different sub-foundation and deep soil textures, foundation types and groundwater source depths. The results indicate that if the sub-foundation soil permeability is larger than 10^{-11} m^2, the convection dominates the soil gas transport into the building, and the indoor air concentration increases by half an order of magnitude with one order of magnitude increase of the sub-foundation soil permeability. Otherwise, diffusion plays a more important role and the sub-foundation soil texture does not cause significant variation of indoor air concentration. We found that, independently from the deep soil texture, the capillary fringe offers the main resistance to vapor transport. In these cases, the deep soil texture could induce at most half an order of magnitude of variation in total effective diffusion coefficient in deep soil as well as groundwater source-to-indoor air attenuation factors. Finally, we found that, as the thin capillary zone represents the higher resistance to upward soil gas flow, groundwater source depth has little influence in determining the chlorinated vapor intrusion risk.

1. Introduction

At contaminated sites, it is common to observe volatile organic compounds (VOCs) rising from subsurface sources and migrating into the building of concern [1]. Such process is called vapor intrusion (VI), a key migration pathway that should be considered when conducting risk assessment or determining groundwater clean-up level [2]. The VOCs involved in VI are typically divided into two groups, chlorinated solvents and petroleum hydrocarbons, and the VI processes involved are usually named as chlorinated vapor intrusion (CVI) and petroleum vapor intrusion (PVI), respectively [3,4]. The major difference between CVI and PVI is that petroleum hydrocarbons could be aerobically biodegraded in soil while biodegradation is usually not considered in the risk assessments of CVI, which therefore could induce a higher threat to human health.

In CVI investigations, groundwater is much more common to be observed as the vapor source than other forms, like soil and non-aqueous phase liquid (NAPL), as it can expand the contaminant plume far away from the release point. In United States Environmental Protection Agency (USEPA)'s VI database, the current largest collections of CVI data from sites across U.S.A., only contaminant groundwater concentration were recorded as the vapor source data [5].

The CVI process could be divided into two relatively independent parts, groundwater source-to-subslab and subslab-to-indoor air [6], in both of which, soil texture plays an important role in determining the concentration attenuations. In CVI from groundwater sources, the effective diffusivity of soil gas is determined by the moisture content distribution, which is greatly affected by the presence of the capillary fringe [7]. At steady state, the soil gas concentration profile (and groundwater source-to-subslab soil gas concentration attenuation) for low or non-biodegradable chemicals, such as chlorinated solvents, is largely determined by the soil texture above the groundwater level (in this study we refer to this zone as deep soil texture). In the USEPA's spreadsheet for modelling subsurface vapor intrusion, such influence

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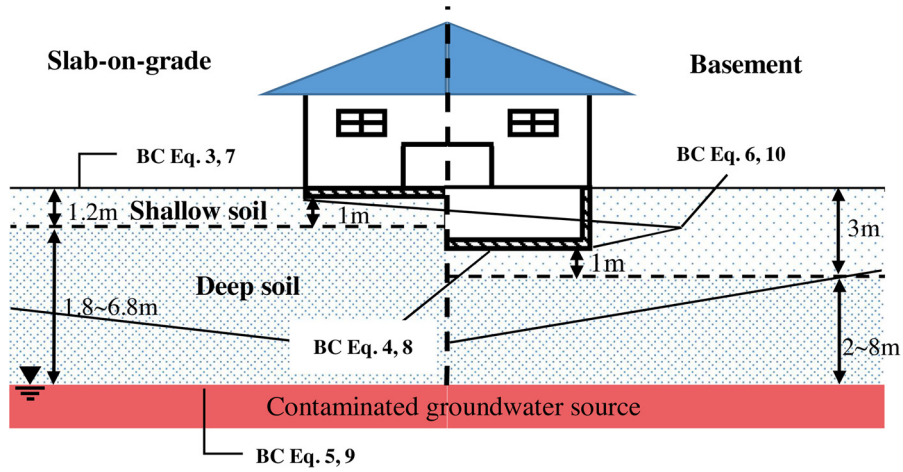

Fig. 1. The scheme of the two-layer system and its boundary conditions (BC).

was included by dividing the soil below the building foundations into two uniform but separate layers, the capillary zone and the unsaturated zone above the capillary fringe [8]. Shen et al. 2013 argued that the way USEPA handled the capillary fringe effect could underestimate the attenuation during the upward diffusion of contaminant vapors [7].

On the other hand, it is generally believed that the contaminant soil gas enters the enclosed space of concerned building by advection due to the indoor-outdoor pressure difference [9,10], and the advective soil flow rate is determined by the soil permeability below and adjacent to foundations [11]. Thus the second process, the subslab-to-indoor air concentration attenuation, is greatly affected by the soil texture in the upper location (here we refer to the 1-meter soil below the foundation slab as sub-foundation or shallow soil texture). In the USEPA's spreadsheet, such influences are simulated by employing the soil permeability of top soil layer in the Nazaroff equation to estimate the soil gas entry rate into the building. It should be noted that the Nazaroff equation is based on the perimeter crack assumption [11], and in the newest version of the spreadsheet, USEPA allows users to enter an empirical subslab-to-indoor air concentration attenuation factor, which should also be a function of the shallow soil texture, to estimate indoor air concentration [8].

In a previous study, we employed a three-dimensional (3-D) numerical model to simulate VI from groundwater source in single-layer scenarios, and the results indicate that the soil texture has more influence in determining subslab-to-indoor air concentration attenuation while does not play a significant role in general subfoundation soil gas concentration profiles, if the vertical source-building separation distance is larger than 5 m [12]. However, in reality, the soil condition could not be uniform, as the construction of the foundation pit would usually form a different soil layer in the shallow depth. In this study, we will employ a two-layer system (shallow and deep soil layers) to study the role of sub-foundation soil texture in such conditions. Specifically, the use of a two-layer model allows to examine the role of the diffusion-dominated transport expected in the soil near to the source zone compared to the advection-dominated transport expected in the shallow zone at the building to soil interface. On the other hand, the use of a two-layer model can be used to evaluate how the presence of the sub-foundation layer, which is typically different from the natural soil present in the site, can influence the intrusion of vapors into the building.

In this paper, we first simulate scenarios with different shallow soil textures assuming the same deep soil texture, and investigate the trend of indoor air concentration. Then we will do the opposite way to show the influence of the deep soil texture on indoor air concentration. At last, we compare their influences and draw some conclusions for future site investigation of VI from groundwater sources. In all cases, the vapor source is assumed to be in dissolved phase, and located at the groundwater table.

2. Methods

2.1. 3-D numerical model

The 3-D finite element model employed in this study was developed and applied in many previous studies [14–21]. Readers interested are directed to those references. Here we only present a brief introduction of the model. The 3-D model was developed based on Comsol Multiphysics, and consisted of two modules, Darcy's law and Convection & Diffusion. In the first module, the soil gas flow field was calculated based on the pressure profile:

$$u = \frac{k}{\mu}\nabla p \tag{1}$$

where k is the soil permeability to vapor flow [L^2], μ the soil gas dynamic viscosity [M/L/T], p the pressure in the vapor phase [M/L/T^2] and u the vapor-phase mass-average velocity [L/T].

Then the soil gas velocity u was substituted into the second module as input to obtain the soil gas concentration distribution in the domain.

$$\frac{\partial c_g}{\partial t} = -\vec{\nabla}\bullet u c_g + \vec{\nabla}\bullet(D_e\vec{\nabla}c_g) \tag{2}$$

where c_g is the contaminant vapor concentration in the soil matrix [M/L^3], D_e the effective porous medium diffusion coefficient of contaminant in soil [L^2/T], $\vec{\nabla}$ the vector del operator [1/L] and t the time [T].

As shown in Fig. 1, the simulated scenarios refers to a single square 10 m × 10 m footprint structure, built on an open field of 24 m × 24 m, overlying an infinite groundwater source at the domain bottom. Because the scenarios studied is symmetric in horizontal directions, only a quarter of domain was actually simulated. As in previous studies, a perimeter foundation crack was employed in this work, with a width of 0.001 m. The 3-D model boundary conditions are shown in Fig. 1. No flux boundary conditions were applied at the foundation slab and wall, vertical planes of symmetry, and vertical domain boundaries. At open ground surface surrounding the foundation, an atmospheric pressure and zero concentration were assumed. Flux boundary conditions were used to estimate the volumetric flow rate and mass entry rate through the crack. No soil gas flow was assumed to penetrate through the bottom boundary, where a constant vapor concentration was assigned. The detailed information of the boundary conditions is shown in Fig. 1 and Table 1.

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