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Estimation of contaminant subslab concentration in vapor intrusion

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HIGHLIGHTS

- ▶ A new vapor intrusion (VI) hazard assessment tool has been developed.
- ▶ The new VI tool permits computationally easy estimates of subslab and indoor air concentrations.
- ▶ This new VI tool highlights the role of key parameters that need to be measured in the field.

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ABSTRACT

This study is concerned with developing a method to estimate subslab perimeter crack contaminant concentration for structures built atop a vapor source. A simple alternative to the widely-used but restrictive one-dimensional (1-D) screening models is presented and justified by comparing to predictions from a three-dimensional (3-D) CFD model. A series of simulations were prepared for steady-state transport of a non-biodegradable contaminant in homogenous soil for different structure construction features and site characteristics. The results showed that subslab concentration does not strongly depend on the soil diffusivity, indoor air pressure, or foundation footprint size. It is determined by the geometry of the domain, represented by a characteristic length which is the ratio of foundation depth to source depth. An extension of this analytical approximation was developed for multi-layer soil cases.

1. Introduction

Mathematical models are important tools for characterizing soil vapor intrusion into structures. They are widely used to predict indoor air contaminant concentrations in structures built on contaminated sites before more detailed site characterization is under-taken. In the U.S., the most widely used modeling tool is based on the work of Johnson and Ettinger [1], as now implemented by the US EPA in a spreadsheet. Predicted indoor air concentrations are determined by considering the building's enclosed volume, air exchange rate and contaminant mass flow rate into the structure. The air exchange rate depends on details related to the building, its design and its operating conditions and cannot be reflected with certainty in most current vapor intrusion models. Even the relevant building volume may be difficult to properly characterize. All other things being the same, the mass flow rate of contaminant into the building is the key factor influencing indoor vapor concentration; it has been recommended as an alternative indoor air quality indicator in some studies [2–5]. This contaminant mass flow rate is linearly related to indoor air concentration and by focusing on this quantity, one avoids arbitrary choices of air exchange rate and volume of enclosed space.

The contaminant mass flow rate into an enclosed space depends on volumetric flow rate of soil gas into the structure and the concentration of contaminant vapor beneath the slab on which the structure is built. One possible way to calculate the volumetric soil gas flow rate into the structure is based on an equation by Nazaroff [6]. This equation has been validated by comparison with site experimental data and simulation [7,8], and it has been shown reasonably accurate for a perimeter crack scenario [8]. The other key factor determining mass entry rate is contaminant concentration beneath the foundation slab, at entrance cracks in the slab which allow soil gas entry into the structure [2,3,9]. In 1991, the Orange County Health Care Agency (OCHCA) vapor intrusion model [10] assumed zero subslab contaminant concentration to simplify the calculation of diffusive contaminant transport rate, while in the same year Johnson and Ettinger [1] introduced a simple one-dimensional model in which a perimeter crack was the main entry route into an enclosed space, and in which the assumption of a non-zero subslab concentration is implicit. In this paper, a new method, the analytical approximation method, is provided for estimating subslab crack concentrations.

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Soil vapor intrusion rates vary depending on the nature of the building foundation. Generally, building construction foundation types include crawl space, basement and slab-on-grade. The latter two cases are the main focus of this work. Models to simulate crawl space scenario include CSOIL [11], VOLASOIL [12] and those based Jury et al.'s work [13–15].

There have been numerous 1-D analytical models of the basement and slab-on-grade situations based on the Johnson–Ettinger (J–E) model [16–18]. In 2005, a 3-D model developed by Abreu and Johnson also used the same coupling of advection (described by Nazaroff's equation [6]) and soil gas diffusion to obtain subslab concentration [9,19,20]. Our group developed another 3-D model [2–5,8] that was similar in form to that by Abreu and Johnson, but solved by a different method. A recent study based on this latter work showed that the three dimensionality of the problem causes potentially important differences from the predictions of subslab concentration obtained from simple 1-D models [8]. 3-D simulation, although powerful in its ability to better describe physical processes, requires considerably greater effort than simple 1-D modeling, and is therefore much less attractive for quick screening. The purpose of this investigation is to see if more of the essential physics of the process can be captured without resorting to a full 3-D numerical simulation.

The analytical approximation (AA) method uses an analytical approximation of the contaminant perimeter subslab concentration. Table 1 shows several aspects of the comparison of the AA and J–E methods. In the AA method, entry into the house is also based on perimeter crack assumption, but the very restrictive J–E assumption that all contaminant vapors must pass through the structure is not invoked [1]. This means that what happens inside the enclosed space does not affect concentration beneath the building. The net effect is that the empirical effective source area, A_B required in the J–E model becomes unnecessary, since there is no artificially forced conservation of contaminant mass transport from the source through the enclosed building.

The AA method explicitly recognizes what has become generally accepted by investigators in this field; that is, the subslab contaminant concentration profiles are largely determined by diffusion processes. The role of diffusion as a dominant transport mechanism has also been demonstrated with the use of models [3,20]. Also, steady state contaminant concentration profiles do not depend on diffusivity, even if the overall rate of diffusion does. Further, the "stack effect" of the structure (i.e. indoor depressurization) is almost never sufficiently strong to influence soil gas profiles. Therefore, advective transport does not need to be accounted for, and consequently soil permeability is not needed to predict the general contaminant profiles in the subslab. It should quickly be added that very near a subslab crack, the competition between advection and diffusion can certainly result in advection locally influencing contaminant concentration. These are, however, often transient effects which are not considered in steady state screening models. Alternatively, they may exist at steady state when the soils are of unusually high permeability.

2. The "Analytical Approximation" method (AA method)

2.1. Method development

The main objective of the AA method is to establish a simple way to approximate true subslab crack concentration without resorting to the laborious numerical 3-D solution. To achieve this goal, a simple 2-D approximation to the full 3-D situation has been first developed, based upon the scenario shown in Fig. 1.

This approximation rests upon the assumption that transport of contaminant in the soil is dominated by diffusion processes, as is also assumed in the J–E model [1]. The line EF approximates the groundwater source at the bottom of the domain shown in Fig. 1. At this boundary, the contaminant vapor concentration is taken to be at its source value $c = c_s$ as usual. The line segment AB represents the ground surface at which the contaminant vapor concentration is $c = 0$. The line segments BC and CD represent the outside boundaries of a building foundation, taken to be impermeable, as usual (except of course at the perimeter crack at the corner C). The assumed contaminant concentration at corner C or anywhere in the soil can be calculated analytically by solving

$$\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} = 0 \quad (1)$$

on the domain. Eq. (1) simplifies the full 3-D to an analytically more tractable 2-D representation that still captures the details of lateral concentration variation. Lateral concentration variation is not accounted for in the J–E model, which a strict 1-D model. The key parameters of interest are d_f, the depth of the foundation, and d_s, the depth of the source (see Fig. 1). The solution to this problem is effected using Schwarz–Christoffel mapping [21] (see appendix). The result is shown in Eq. (2):

$$\frac{c_{ck}}{c_s} = \frac{\arccos\left(2\left(1 - \frac{d_f}{d_s}\right)^2 - 1\right)}{\pi} \approx \sqrt{\frac{d_f}{d_s}} \quad (2)$$

where C_{ck} is the soil vapor concentration at point C (Fig. 1d). In most cases, this analytical approximation can be simplified, for typical values of interest, to the square root of the characteristic length ratio, as shown.

Table 1
Comparison of the J–E and AA methods [1].

	J–E model	AA method
Dimensions represented	1-D	2-D analytical solution, 3-D approximation
The contaminant transport mechanism in the soil	Diffusion dominated	Diffusion dominated
The theoretical basis	The contaminant released by the source must equal its mass inflow rate into the building via subslab cracks which equals the rate of contaminant purge from the building	Approximates soil gas concentration profile from a pure diffusion model, knowing source depth and foundation depth.
The role of building	Affects the soil gas flow rate into the crack via Nazaroff's equation and this determines contaminant entry rate which equals source release rate over a semi-empirical effective source area A_B	The foundation and source depths are the keys for predicting subslab crack concentration. The Nazaroff equation can be applied later, but has no role in determining subslab concentration.
The normalized contaminant concentration profile in the domain	Changes with foundation crack boundary conditions, such as indoor pressure and soil permeability	Determined by source and atmospheric sink; not influenced by indoor parameter choices or soil permeability.
Dependence of subslab concentration on soil gas flow rate into the building	Yes	No