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Estimation of contaminant subslab concentration in vapor intrusion

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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.

Keywords

Vapor intrusion; Subslab concentration; Johnson-Ettinger model; Analytical approximation; 3-D simulation

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 undertaken. 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

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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.

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, AB 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 Figure 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 E-F approximates the groundwater source at the bottom of the domain shown in Figure 1. At this boundary, the contaminant vapor concentration is taken to be at its source value $c = c_s$ as usual. The line segment A–B 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. Equation 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 is 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 Figure 1). The solution to this problem is effected using Schwarz-Christoffel mapping [21] (see appendix). The result is shown in equation (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 (Figure 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.

2.2 Compared with 3-D Simulation

The full 3-D model examined here and solved using the Comsol finite element package is essentially that presented earlier by this group [2–5, 8]. The case of interest here is the steady-state “base case” discussed in the earlier studies, i.e., a single structure built atop an otherwise flat, open field, underlain by a homogeneous soil that stretches from the ground surface to a water table which serves as an infinite source of the contaminant vapor of interest. Relevant parameters are shown in Table 2.

The results of the full 3-D simulations for a variety of conditions are shown in Figure 2. Results are shown for calculations performed here as well as by Abreu [19]. Both sets of simulation results are seen to agree reasonably closely.

The simplification of Equation (2) resulted in emergence of a characteristic length ratio,

which is the depth of the foundation to the depth of the source ($\frac{d_f}{d_s}$). Figure 2 shows the relationship between this ratio and normalized perimeter crack concentration for all 3-D simulated cases involving many different soil permeabilities, foundation footprint sizes, foundation and source depths, and other parameters. It shows clearly that this characteristic length ratio is a key factor determining subslab to source concentration to generally better than an order of magnitude.

It is seen that the analytical approximation (2) is always conservative as compared to the simulations, to an extent as much as a factor of 5. That is, the approximation of Equation (2) will always give a crack concentration estimate at least as high as any full 3-D simulation result. However, it should be noted that this approximation was based on the assumption of infinitely large foundation footprint (due to the use of a 2-D approximation). It is possible to use a correction factor to move the analytical approximation curve into better agreement with the majority of 3-D results, as shown. This involves changing the exponential factor on the characteristic length ratio in Equation (2) from 0.5 to 0.7. Figure 2 clearly shows that the analytical approximation with 0.5 exponent is a fair but conservative approximation, whereas the 0.7 exponent is a much better approximation to the 3-D simulations.

2.3 Derivation of AA method for multi-layer soil cases

At vapor intrusion sites, it is often the case that layered soil geology is present. The soil gas contaminant vapor concentration profile in a vapor intrusion scenario is analogous to the voltage distribution in a series circuit. If the soil diffusivity is constant throughout the domain, the “resistance” to vapor diffusion is proportional to the thickness of a soil layer. This is why the concentration at the subslab is mainly determined by the ratio of the foundation depth to the source depth. Of course when the impermeable foundation itself is taken into consideration, this makes the profile non-linear near the subslab.

For a system with a multi-layer soil, it is still the resistance in each layer that determines the contaminant concentration profile in the domain, as this is still based on that assumption that the contaminant vapor concentration profile within the domain is primarily determined by diffusion. Therefore it is possible to construct a homogenous diffusivity approximation to replace the true multi-layer non-homogeneous diffusivity soil case by considering equivalent series resistances. The averaged diffusivity of multi-layered soil is calculated in the same way as in the J-E model [22].

The argument of the arccosine term in equation (2) contains $1 - \frac{d_f}{d_s} = \frac{d_s - d_f}{d_s}$. This shows that this argument is effectively the fraction of resistance from foundation slab to source divided by total resistance to diffusion (soil vapor diffusion path length is proportional to resistance in a constant diffusivity case). Assuming the foundation is in the zone of diffusivity of D_1 as shown, and then the fraction of resistance from source to foundation slab is

$$\frac{\sum \text{all layers} \frac{L_i}{D_i} - \frac{d_f}{D_1}}{\sum \text{all layers} \frac{L_i}{D_i}}$$

This result can be applied to equation (2):

$$\frac{c_{ck}}{c_s} \approx \frac{\arccos \left(2 \left(\frac{\sum \text{all layers} \frac{L_i}{D_i} - \frac{d_f}{D_1}}{\sum \text{all layers} \frac{L_i}{D_i}} \right)^2 - 1 \right)}{\pi} \approx \sqrt{\frac{\frac{d_f}{D_1}}{\sum \text{all layers} \frac{L_i}{D_i}}} \quad (3)$$

or using the empirically corrected exponent.

$$\frac{c_{ck}}{c_s} = \left(\frac{\frac{d_f}{D_1}}{\sum \text{all layers} \frac{L_i}{D_i}} \right)^{0.7} \quad (4)$$

Where L_i are the thicknesses of layers, and D_i are the effective diffusivities in the layers.

Table 3 gives a comparison of the full 3-D simulation and the above analytical approximation for four different cases. The first case is a three-layer soil in which layer 1 is medium diffusivity and layer 2 has diffusivity a factor of 4 higher, and layer 3 has a diffusivity a factor of 4 lower than the upper layer. The second through fourth cases are used to describe a capillary zone with much lower diffusivity just above the water table due to high moisture content. As shown, with greater deep layer diffusion resistance, the analytical approximation tends to predict lower subslab crack concentration, consistent with full 3-D simulation.

Table 3 shows the use of the approximation with “corrected” exponent of 0.7, giving excellent agreement with the full 3-D simulation results is excellent.

2.4 Calculation of indoor air concentrations

Ultimately, the indoor air contaminant concentration is of greatest practical interest for assessing human health risks. For this reason, the results of the AA method concentration predictions are now explored using the usual kinds of assumptions regarding indoor air volume and air exchange rate.

Based on the assumption of enclosed space as one single continuous stirred flow through volume (CSTV), the indoor air contaminant concentration is determined by contaminant mass flow rate into the enclosed space and air exchange rate of the indoor volume [1]

$$c_{indoor} = \frac{J_s + V_b A_e c_{atm}}{V_b A_e + Q_s} \approx \frac{J_s}{V_b A_e} \quad (5)$$

Where c_{indoor} is the indoor air concentration of the contaminant $[M/L]$, J_s is the contaminant mass flow rate into the enclosed space $[M/T]$, V_b is the volume of the enclosed space $[L]$,

c_{atm} is the contaminant concentration in atmosphere [M/L] and Q_s is the volumetric flow rate in the enclosed space [L/T].

J_s is determined from c_{ck} (from the AA method) and Q_s is the advection soil gas flow rate determined by the Nazaroff equation[6] or any other method:

$$J_s = \begin{cases} \frac{c_{ck} Q_s}{1 - \exp(-\frac{Q_s d_{ck}}{A_{ck} D^{ck}})}, & Q_s \neq 0 \\ \frac{c_{ck} A_{ck} D^{ck}}{d_{ck} V_b A_e}, & Q_s = 0 \end{cases} \quad (6)$$

Where A_{ck} is the area of the crack [L^2] and $c_{indoor} \ll c_{ck}$ is assumed.

Therefore the attenuation factor relative to a source concentration c_s becomes:

$$\alpha = \frac{c_{indoor}}{c_s} \approx \begin{cases} \frac{\frac{c_{ck}}{c_s} \frac{U_s}{V_b A_e}}{1 - \exp(-\frac{Q_s d_{ck}}{A_{ck} D^{ck}})}, & Q_s \neq 0 \\ \frac{\frac{c_{ck}}{c_s} A_{ck} D^{ck}}{d_{ck} V_b A_e}, & Q_s = 0 \end{cases} \quad (7)$$

In the J-E model, the Nazaroff equation is applied to calculate Q_s [1] but the use of a

parametric value for $\frac{Q_s}{V_b A_e}$ is a recently recommended alternative approach for this calculation [23].

3. Results and Discussion

3.1 Comparison with 3-D simulation

The cases shown in table 4 were drawn from the thesis of Abreu [19], where the subslab crack contaminant concentration, although not directly shown in the thesis, is back-calculated from the simulation results of indoor air attenuation factor and other model parameters. The results from the J-E and AA methods are also presented for the purpose of comparison. Some parameters in the J-E model used here are different from those in the EPA J-E screening tool. Specifically the in-crack diffusivity of the contaminant used here is the contaminant diffusivity in air instead of its soil diffusivity, and secondly the soil gas entry rate obtained from the Abreu and Johnson 3-D simulation replaced the Nazaroff equation, which is no longer recommended by Johnson [23].

In general, the AA method fits the 3-D simulation results quite well except in isolated cases, shown in both Figure 3 and Table 4. The results from the J-E model are also within an order of magnitude of those from 3-D simulation in most cases, although the AA method predictions are closer. The majority of the data fall within a factor of two of the results predicted by the full 3-D model.

Beyond agreement with the 3-D model results, the AA model is advantageous over the J-E model for estimation of subslab contaminant concentrations because Q_s is not needed as input into the AA method, while it is a requirement for the J-E model. Johnson et al. suggested the ratio $(Q_s/V_b A_e)$ be input instead of Q_s and $V_b A_e$ separately [23]. That does not solve the problem, and it just leaves the problem of selecting the soil gas entry rate as part of another parameter. Of course, the AA method does not allow the calculation of attenuation factor (or indoor air contaminant concentration), without selecting some Q_s , but at least the subslab perimeter crack concentration can be obtained without this requirement.

3.2 Comparison with lab experiment

The main purpose of this study was not to provide a full validation of any particular VI modeling approach, but to provide an analytical approximation to subslab concentration. To address questions regarding how accurate the predictions of the AA method are, below we offer a comparison to laboratory experiment simulation of vapor intrusion.

The validation is based on results which show that the crack size can be a significant factor in vapor intrusion only if it is big enough, and that the degree of depressurization of indoor air is only significant in terms of dilution at higher rates of flow [24]. The experiment studied the TCE concentration inside an artificial basement with different crack sizes, depressurizations, and soil types. To maintain a steady negative pressure in the basement, it required the outflow to be equal to the soil gas entry rate, which makes the TCE concentration inside the basement also the subslab concentration. The crack size ranges from 0.0794 cm^2 to 0.794 cm^2 , while the pressure 0 to -50 Pa . More details are given in the original paper [24]. Table 5 shows the comparison of AA method predictions with this lab simulation data.

The point to be made here is that for this set of cases involving very different soil types and a range of advection rates, the subslab to source concentration ratio is relatively constant, as the AA method would predict, and its magnitude is well predicted by the AA method.

4. Conclusion

In summary, this study provides an analytical method that approximates well the predictions of subslab contaminant concentrations obtained from two widely used 3-D numerical models of vapor intrusion. Unlike 3-D numerical models, the AA method is simple and does not require the significant effort associated with using the full 3-D CFD codes. This means that with characterization only of source and foundation depth, and source vapor concentration, a field estimate of expected subslab contaminant concentration can be obtained.

Appendix

Conformal transformation

Schwarz–Christoffel mapping is a conformal transformation of the upper half-plane onto the interior of a simple polygon. A significant advantage of this method is that the Laplace equation can still be applied after transform [21].

To illustrate this, a simple example is as follows. It represents an open field (no building) with a source on plane CD and a sink on plane AB. The plane BC is just a plane of symmetry defining a semi-infinite domain.

After the application of Schwarz–Christoffel mapping, the above case becomes an upper half-plane and the points on the boundary before transform are made to fall on the real axis in the new coordinate system. For example, in previous domain, $A(\infty,1)$, $B(0,1)$, $C(0,0)$ and $D(\infty,0)$ become the $A'(-\infty,0)$, $B'(-1,0)$, $C'(0,0)$ and $D'(\infty,0)$ after transform. The

boundary conditions are still the same, $c = 1$ for $C'D'$, $c = 0$ for $A'B'$ and $\frac{\partial c}{\partial Y} = 0$ for $B'C'$.

Assume $z(x,y) = x + yi$ and $s(X,Y) = X + Yi$, and the transform formula is

$$\frac{dz}{ds} = \frac{c_1}{s^{0.5}(s+1)^{0.5}} \quad (A1)$$

Where C_1 is a constant. The solution of equation (A1) is

$$z = \frac{\ln \left(\left(\sqrt{s} + \sqrt{s+1} \right)^2 \right)}{\pi} \quad (A2)$$

And for points on BC: $z(0,y) = yi$ and its correspondent $B'C'$: $s(Y,0) = Y$, $0 < y < 1$ and in $-1 < Y < 0$ in Figure A1. Applying equation (A2) with these conditions:

$$y = \frac{\arccos(2Y+1)}{\pi} \quad (A3)$$

As noted above, the concentration distribution on BC in the untransformed plane is:

$$c = 1 - y \quad (A4)$$

Therefore, the concentration distribution on $B'C'$ is obtained by substituting (A4) into (A3)

$$c = 1 - \frac{\arccos(2Y+1)}{\pi} = \frac{\arccos(-2Y-1)}{\pi} \quad (A5)$$

This relates the non-dimensional concentration to any transformed value Y . The solution in non-transformed space is already known for this simple case, and is equation (A4). The greater value of (A5) is seen in the next example.

Isolated building with homogenous source

Another scenario is now constructed to approximate the case of an isolated building with homogenous source beneath it.

The boundary conditions are also similar to what was presented above: EF is the source ($c = 1$), AB is a sink ($c = 0$) and BCD is an impermeable wall. What is described is the concentration at the corner point C and as the analytical distribution on $B'C'$ is shown in equation (A5), the exact location of C' is the key.

According to Carslaw and Jaeger [21], if the coordinates in (b) are $A(\infty, d_s)$, $B(0, d_s)$, $C(0, d_s - d_f)$, $D(-\infty, d_s - d_f)$, $E(-\infty, 0)$ and $F(0, \infty)$, the new transformed coordinates in (c) would be

$$A'(-\infty, 0), B'\left(-\left(\frac{d_s}{d_s - d_f}\right)^2, 0\right), C'(-1, 0), D'(E')(0, 0) \text{ and } F'(0, \infty).$$

Using the previously developed solution in equation (A5), the concentration at point C is

$$c(\text{point C or } C') = \frac{\arccos\left(2\left(1 - \frac{d_f}{d_s}\right)^2 - 1\right)}{\pi} \approx \sqrt{\frac{d_f}{d_s}} \quad (A6)$$

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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

FIGURE 1.

Cross sectional view of (a) full domain of interest; (b) boundary conditions of modeled half domain; (c) details of modeled perimeter crack in 3-D simulation; (d) the 2-D scenario used for obtaining the approximation for subslab perimeter crack concentration.

FIGURE 2.

The influence of source depth on the normalized subslab crack concentration (including cases with different soil permeabilities, foundation footprint sizes, foundation depths and source depths) (The 3-D simulation data are from this group and from the Abreu & Johnson model, as noted) [19]

(a)

(b)

FIGURE 3.

Error of J-E model [1] and AA method compared with the Abreu and Johnson 3-D simulation results [19–20]: (a) Error on a linear scale; (b) Error on a $\log_{10}$ scale.

FIGURE A1. Schwarz–Christoffel mapping example (a) before and (b) after transform

In Figure A1(a), two parallel semi-infinite plates AB and CD are connected by a vertical segment BC . The Laplace Equation applies to describing steady state contaminant concentration profiles on this domain. The boundary condition at CD is a uniform source of $c = 1$, while $c = 0$ for AB , and an impermeable boundary condition is assumed for BC . Obviously, at steady state the concentration distribution on BC is linear, as it must be in the entire semi-infinite domain.

FIGURE A2. Transform for an isolated building with uniform source (a) approximation considering half structure (b) after transform of the situation in (a)

In Figure A2, (a) is taken as an approximation to 3-D case, and (b) is the coordinate system after Schwarz–Christoffel mapping. The approximation (a) considers only half the structure and would clearly be adequate in the symmetrical case

TABLE 1

Comparison of the J-E and AA methods [1]

	J-E model	AA method
Dimensions presented	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 determining 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

TABLE 2

Input parameters used in 3-D simulation (unless otherwise noted in the figures and table)

Building/foundation parameters	Contaminant vapor source properties
Domain cross section size: 24 m × 24 m or 50 m × 50 m	Contaminant: TCE
Foundation foot print: 5 m × 5 m, 10 m × 10 m, or 20 m × 20 m.	Diffusivity of TCE in crack (D^k): $7.4 \times 10^{-6} \text{ m}^2/\text{s}$
	Effective diffusivity of TCE in soil (D_{eff}): $1.04 \times 10^{-6} \text{ m}^2/\text{s}$
Depth of foundation (d_f): 0.1 m, 0.5 m, 1 m or 2 m	Soil gas flow properties
Crack/foundation slab thickness (d_{ck}): 0.152 m	Viscosity of air/soil gas (μ_g): $1.8648 \times 10^{-5} \text{ kg/m/s}$
Crack width (w_{ck}): 0.005 m	Density of air/soil gas (ρ_g): 1.1614 kg/m^3
Depth to groundwater/source (d_g): 3, 5, 8, 11, 14, or 18 m bgs	Soil permeability (k): 10^{-10} , 10^{-11} , 10^{-12} , 10^{-13} or 10^{-14} m^2
3-D Finite Element Analysis Parameters	Total soil porosity (ϕ): 0.35
Size of the grid elements: 0.001 m – 1 m	Soil porosity filled with gas (ϕ_g): 0.296
Number of elements: 200k – 1,000k	

TABLE 3

Comparison between 3-D simulation and analytical approximation for multi-layer soil cases

$d_f = 2 \text{ m and } k = 10^{-11} \text{ m}^2$ $10 \text{ m} \times 10 \text{ m footprint}$	$(c_{ck}/c_s)_{3D} \left(\frac{\frac{d_f}{D_1}}{\frac{L_i}{D_i}} \right)^{0.7}$	
$d_1 = 3 \text{ m}, D_1 = 1.04 \times 10^{-6} \text{ m}^2/\text{s}$		
$d_2 = 3 \text{ m}, D_2 = 4 \times 1.04 \times 10^{-6} \text{ m}^2/\text{s}$		
$d_3 = 2 \text{ m}, D_3 = \frac{1}{4} \times 1.04 \times 10^{-6} \text{ m}^2/\text{s}$	0.27	0.29
$d_1 = 7.5 \text{ m}, D_1 = 1.04 \times 10^{-6} \text{ m}^2/\text{s}$		
$d_2 = 0.5 \text{ m}, D_2 = \frac{1}{10} \times 1.04 \times 10^{-6} \text{ m}^2/\text{s}$	0.29	0.25
$d_1 = 7.5 \text{ m}, D_1 = 1.04 \times 10^{-6} \text{ m}^2/\text{s}$		
$d_2 = 0.5 \text{ m}, D_2 = \frac{1}{100} \times 1.04 \times 10^{-6} \text{ m}^2/\text{s}$	0.07	0.09
$d_1 = 7.5 \text{ m}, D_1 = 1.04 \times 10^{-6} \text{ m}^2/\text{s}$		
$d_2 = 0.5 \text{ m}, D_2 = \frac{1}{1000} \times 1.04 \times 10^{-6} \text{ m}^2/\text{s}$	0.01	0.02

TABLE 4
Comparison of the AA method results and the J-E model [1] with Abreu and Johnson 3-D simulation [19–20]

(All the parameters in Abreu & Johnson's 3-D model are the same as shown in Table 2, except that here a constant footprint size of 10m X 10m, air exchange rate as $0.5h^{-1}$ and enclosed space volume of $174 m^3$ were assumed. This table shows all of the calculation results from the Abreu thesis, except for those that assumed indoor pressures higher than ambient and those for exceptionally high soil permeability or pressure difference.)

$$(E_{AA} = \left| \frac{\left(\frac{d_f}{d_s}\right)^{0.7} - \left(\frac{c_{ck}}{c_s}\right)^{3-D}}{\left(\frac{c_{ck}}{c_s}\right)^{3-D}} \right|, E_{J-E} = \left| \frac{\left(\frac{c_{ck}}{c_s}\right)^{J-E} - \left(\frac{c_{ck}}{c_s}\right)^{3-D}}{\left(\frac{c_{ck}}{c_s}\right)^{3-D}} \right|)$$

#	d_s (m)	d_f (m)	$Q_{air(3-D)}$ (L/min)	$a_{3-D} = \frac{c_{indoor}}{c_s}$	$\left(\frac{c_{ck}}{c_s}\right)^{3-D}$	$\left(\frac{c_{ck}}{c_s}\right)^{AA}$	$\left(\frac{d_f}{d_s}\right)^{0.7} = \left(\frac{d_f}{d_s}\right)^{J-E}$	$E_{AA}(\%)$	$E_{J-E}(\%)$
1	3	2	12.36	5.50E-03	0.65	0.75	0.48	15	26
2	3	2	6.18	3.21E-03	0.75	0.75	0.65	0	13
3	3	2	3.09	1.75E-03	0.82	0.75	0.78	9	5
4	3	2	1.54	9.08E-04	0.86	0.75	0.88	13	2
5	3	2	0	7.80E-05	0.82	0.75	0.99	9	21
6	3	2	1.25	7.35E-04	0.85	0.75	0.9	12	6
7	3	2	0.31	2.07E-04	0.87	0.75	0.97	14	11
8	3	2	0	7.80E-05	0.82	0.75	0.99	9	21
9	3	2	0.12	1.20E-04	0.85	0.75	0.98	12	15
10	3	2	0.03	8.60E-05	0.82	0.75	0.99	9	21
11	3	2	0	7.60E-05	0.8	0.75	0.99	6	24
12	8	2	15.89	3.93E-03	0.36	0.38	0.11	6	69
13	8	2	7.95	2.19E-03	0.4	0.38	0.19	5	53
14	8	2	3.97	1.17E-03	0.43	0.38	0.32	12	26
15	8	2	1.99	6.08E-04	0.44	0.38	0.48	14	9
16	8	2	0	3.99E-05	0.42	0.38	0.93	10	121
17	8	2	1.6	4.99E-04	0.45	0.38	0.54	16	20
18	8	2	0.4	1.33E-04	0.46	0.38	0.82	17	78
19	8	2	0	3.99E-05	0.42	0.38	0.93	10	121
20	8	2	0.16	6.99E-05	0.44	0.38	0.86	14	95

$$(E_{AA} = \left| \frac{\left(\frac{d_f}{d_s} \right)^{0.7} - \left(\frac{c_k}{c_s} \right) \frac{3-D}{3-D}}{\left(\frac{c_k}{c_s} \right) \frac{3-D}{3-D}} \right|, E_{J-E} = \left| \frac{\left(\frac{c_k}{c_s} \right) \frac{J-E}{J-E} - \left(\frac{c_k}{c_s} \right) \frac{3-D}{3-D}}{\left(\frac{c_k}{c_s} \right) \frac{3-D}{3-D}} \right|)$$

#	d_s (m)	d_f (m)	$Q_{soil(3D)}$ (L/min)	$\alpha_{3-D} = \frac{c_{indoor}}{c_s}$	$\left(\frac{c_k}{c_s} \right) \frac{3-D}{3-D}$	$\left(\frac{c_k}{c_s} \right) \frac{AA}{AA} = \left(\frac{d_f}{d_s} \right)^{0.7}$	$\left(\frac{c_k}{c_s} \right) \frac{J-E}{J-E}$	$E_{AA}(\%)$	$E_{JE}(\%)$
21	8	2	0.04	4.57E-05	0.42	0.38	0.9	10	114
22	8	2	0	3.90E-05	0.41	0.38	0.91	7	122
23	8	2	0.004	1.12E-05	0.45	0.38	0.96	16	113
24	8	2	0.04	1.82E-05	0.45	0.38	0.96	16	113
25	8	2	0.38	1.20E-04	0.46	0.38	0.83	17	80
26	8	2	2.35	7.14E-04	0.44	0.38	0.44	14	0
27	8	2	4.95	1.45E-03	0.43	0.38	0.31	12	28
28	8	2	5.56	1.65E-03	0.43	0.38	0.29	12	33
29	8	2	3.69	1.09E-03	0.43	0.38	0.34	12	21
30	8	2	21.26	5.04E-03	0.34	0.38	0.1	12	71
31	8	2	0.004	3.77E-05	0.39	0.38	0.87	3	123
32	8	2	0.04	4.57E-05	0.42	0.38	0.9	10	114
33	8	2	0.4	1.33E-04	0.46	0.38	0.82	17	78
34	8	2	3.97	1.17E-03	0.43	0.38	0.32	12	26
35	8	2	36.16	7.65E-03	0.31	0.38	0.06	23	81
36	8	2	0.004	1.14E-04	0.24	0.38	0.58	58	142
37	8	2	0.04	1.42E-04	0.29	0.38	0.67	31	131
38	8	2	0.4	2.22E-04	0.36	0.38	0.67	6	86
39	8	2	4	1.19E-03	0.43	0.38	0.32	12	26
40	8	2	0.4	2.95E-04	0.27	0.38	0.54	41	100
41	8	2	0.004	1.73E-04	0.12	0.38	0.31	217	158
42	8	2	0.04	2.36E-04	0.16	0.38	0.41	138	156
43	8	2	0.4	3.40E-04	0.22	0.38	0.45	73	105
44	8	2	4	1.21E-03	0.38	0.38	0.29	0	24
45	8	2	40.16	8.40E-03	0.3	0.38	0.05	27	83

$$(E_{AA} = \left| \frac{\left(\frac{d_f}{d_s} \right)^{0.7} - \left(\frac{c_{ck}}{c_s} \right)^{3-D}}{\left(\frac{c_{ck}}{c_s} \right)^{3-D}} \right|, E_{J-E} = \left| \frac{\left(\frac{c_{ck}}{c_s} \right)^{J-E} - \left(\frac{c_{ck}}{c_s} \right)^{3-D}}{\left(\frac{c_{ck}}{c_s} \right)^{3-D}} \right|)$$

#	d_s (m)	d_f (m)	$Q_{soil(3D)}$ (L/min)	$\alpha_{3-D} = \frac{c_{indoor}}{c_s}$	$\left(\frac{c_{ck}}{c_s} \right)^{3-D}$	$\left(\frac{c_{ck}}{c_s} \right)^{AA} = \left(\frac{d_f}{d_s} \right)^{0.7}$	$\left(\frac{c_{ck}}{c_s} \right)^{J-E}$	$E_{AA}(\%)$	$E_{JE}(\%)$
46	18	2	16.31	2.17E-03	0.19	0.22	0.04	16	79
47	18	2	8.15	1.12E-03	0.2	0.22	0.08	10	60
48	18	2	6.12	8.50E-04	0.2	0.22	0.1	10	50
49	18	2	4.08	5.75E-04	0.2	0.22	0.15	10	25
50	18	2	2.04	2.89E-04	0.21	0.22	0.26	5	24
51	3	0.2	19.78	3.62E-03	0.27	0.15	0.1	44	63
52	3	0.2	9.89	2.12E-03	0.31	0.15	0.18	52	42
53	3	0.2	4.94	1.17E-03	0.34	0.15	0.31	56	9
54	3	0.2	2.47	6.08E-04	0.36	0.15	0.47	58	31
55	3	0.2	0.49	1.29E-04	0.37	0.15	0.82	59	122
56	18	0.2	20.42	1.10E-03	0.08	0.04	0.02	50	75
57	18	0.2	10.21	5.62E-04	0.08	0.04	0.03	50	63
58	18	0.2	5.1	2.84E-04	0.08	0.04	0.06	50	25
59	18	0.2	2.55	1.40E-04	0.08	0.04	0.12	50	50
60	18	0.2	0.51	2.83E-05	0.08	0.04	0.4	50	400

TABLE 5

Comparison of lab simulation data and AA method [24]

Soil type	Permeability (cm ²)	$\frac{c_{subslab}}{c_s}$	d_f (inches)	d_s (inches)	$\left(\frac{d_f}{d_s}\right)^{0.5}$	$\left(\frac{d_f}{d_s}\right)^{0.7}$
Acid-washed sand	6.02×10^{-7}	0.42–0.90				
Cohansey sand	3.59×10^{-7}	0.42–0.78	4	10	0.63	0.53
Neshaminy clay loam	6.53×10^{-9}	0.18–0.48				

The point to be made here is that for this set of cases involving very different soil types and a range of advection rates, the subslab to source concentration ratio is relatively constant, as the AA method would predict, and its magnitude is well predicted by the AA method