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Vapor intrusion in urban settings: effect of foundation features and source location

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Abstract

In many urban settings, groundwater contains volatile organic compounds, such as tricholoroethene, tetrachloroethene, benzene, etc., at concentrations that are at or slightly below non-potable groundwater standards. Some non-potable groundwater standards do not protect against human health risks that might result from vapor intrusion. Vapor intrusion is a process by which vapor phase contaminants present in the subsurface migrate through the soil and ultimately enter a building through foundation cracks. The end result is a decrease in air quality within the building. Predicting whether or not vapor intrusion will occur at rates sufficient to cause health risks is extremely difficult and depends on many factors. In many cities, a wide-range of property uses take place over a relatively small area. For instance, schools, commercial buildings and residential buildings may all reside within a few city blocks.

Most conceptual site models assume the ground surface is open to the atmosphere (i.e. green space); however the effect that an impervious surface (e.g. paving) may have on vapor transport rates is not routinely considered. Using a 3-D computational fluid dynamics model, we are investigating how the presence of impervious surfaces affects vapor intrusion rates. To complement our modelling efforts, we are in the initial stages of conducting a field study in a neighborhood where vapor intrusion is occurring.

Keywords: Vapor intrusion; urban; capping; perimeter crack; wall crack

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1. Introduction

Since the first identification of the probable Vapor Intrusion (VI) pathway into a building in 1987[1], there have been many VI simulation or modeling studies [2-19]. However, among these previous studies, only a few involve examining the VI problem in simulated urban areas [15,17], which is where most people live, and where exposure concerns are greatest. Through use of a 3-D computational Fluid Dynamic (CFD) model, we have examined a few factors that may play important roles in determining VI exposures within urban areas.

2. The model

The full 3D model developed here is based on the model presented earlier by Pennell et al. [15] and Bozkurt et al. [16-17]. In the present implementation, the assumed domain size was smaller than it was previously, but this is of no consequence to the present results. Also, the earlier "Characteristic Entrance Region (CER)" approximation to crack geometry was not employed here, but again, this has no significant impact on results.

2.1 Research scenario

The situation that is modeled in this paper is illustrated in Figure 1. It consists of a single square 10m x 10 m footprint structure built either on an open field (uncapped) or with an impermeable cap of 5 m wide surrounding the structure footprint. The assumed domain size (24m x 24m) is sufficiently large such that the domain boundaries do not substantially affect the solution within the domain. The structure has a basement foundation (or it is built on a slab) that has a 0.005 m wide perimeter crack or a 0.005 m perimeter wall crack at the joint of wall and cap, running along the entire edge of the foundation. Different types of foundation and surrounding features are the focus of this paper, and the following cases have been simulated:

The "Perimeter Crack" case without any capping around the building, with 0.1 and 2m deep foundation;

The "Perimeter Crack" case with 5 m wide capping around the building with 0.1 and 2m deep foundation;

The "Wall Crack" case with 5 m wide capping around the building with 2m deep foundation, and a crack where the surface capping intersects the foundation wall. (See Figure 1(c))

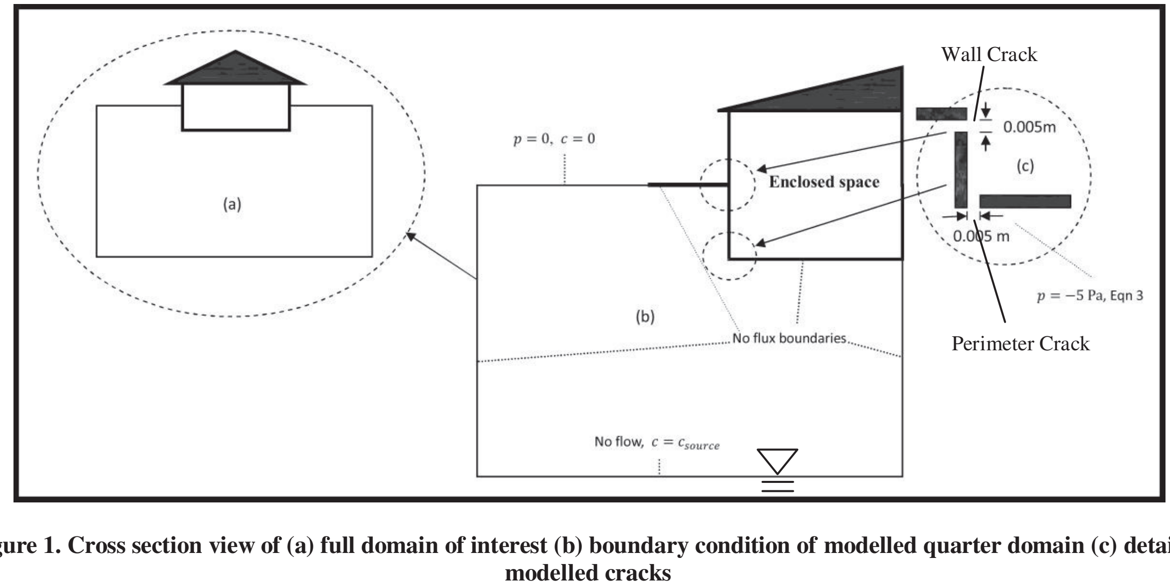


Figure 1. Cross section view of (a) full domain of interest (b) boundary condition of modelled quarter domain (c) detail of modelled cracks

The key working equations are summarized in Table 1. Incompressible soil gas flow is assumed, as is typical in VI modeling. All contaminant vapor originates from the groundwater surface. There are no contaminant sources within the soil itself. The pressure driving force for soil gas advection arises from the "chimney effect" in the structure itself, transmitted to the soil through the foundation crack, which is also the main pathway for contaminant vapor entry into the building.

Table 1. Summary of model equations for steady state simulation [15]

Equation 1: Soil gas continuity $$q = -\frac{\kappa\rho_g}{\mu_g}\nabla\phi$$ $$\phi = gz + \int_{p_0}^{p}\frac{\nabla p}{\rho_g}$$	Where: q = Soil gas velocity (L/t) κ = Intrinsic permeability (L^2) ρ_g = Density of soil gas (M/L^3) μ_g = Dynamic Viscosity of soil gas (M/L/t) g = Gravitational acceleration (L/t^2) z = Elevation (L) p = Pressure of soil gas ($M/L/t^2$) ϕ = Potential (L^2/t^2)
Equation 2: Chemical transport $$J_T = q\mathrm{c} - D_{eff}\nabla c$$ $$D_{eff} = D^g\frac{\phi_g^{\frac{10}{3}}}{\phi_T^2} + \frac{D^w}{H}\frac{\phi_w^{\frac{10}{3}}}{\phi_T^2} \approx D^g\frac{\phi_g^{\frac{10}{3}}}{\phi_T^2}$$	Where: J_T = Bulk mass flux of chemical ($M/L^2/T$) D_{eff} = effective diffusivity coefficient of chemical in soil gas phase (L^2/T) D^g = molecular diffusion coefficient for chemical in gas (L^2/T) D^w = molecular diffusion coefficient for chemical in water (L^2/T) c = Concentration of chemical in soil gas (M/L^3) H = Air:water partition (Henry's) coefficient (L^3_{air}/ L^3_{water}) ϕ_g = Porosity filled by gas (L^3_{air}/ L^3_{soil}) ϕ_w = Porosity filled by water(L^3_{water}/ L^3_{soil}) ϕ_T = Total porosity (L^3_{pores}/ L^3_{soil})
Equation 3: Chemical mass flux through the crack $$J_{ck} = q_{ck}\frac{exp\left(\frac{q_{ck}d_{ck}}{D^g}\right)c_{ck} - c_{indoor}}{exp\left(\frac{q_{ck}d_{ck}}{D^g}\right) - 1} \approx \frac{q_{ck}\,exp\left(\frac{q_{ck}d_{ck}}{D^g}\right)c_{ck}}{exp\left(\frac{q_{ck}d_{ck}}{D^g}\right) - 1}\ (q_{ck} \neq 0)$$	Where: J_{ck} = Mass flux of chemical ($M/L^2/T$) q_{ck} = Soil gas velocity at the crack (L/T) d_{ck} = Thickness of the crack (L) c_{ck} = Concentration of chemical at the crack (M/L^3)

Table 2 gives the key input parameters explored in this study. Though permeability and diffusivity can both be related to the porosity of the soil, this is not necessarily always the case. Here, small variations in diffusivity do not have a significant impact on the solutions. For purposes of presenting a consistent comparison, as well as for reasons of simplicity, a constant effective soil porosity and diffusivity were therefore assumed here; small changes in these values has little effect on the conclusions. It should also be noted that the simulations were carried out for a "typical" contaminant (Trichloroethylene-TCE). For many volatile organic compounds (VOCs) of concern for vapor intrusion, diffusivity values are similar to the value of TCE.

3. The discussion

3.1 Concentration profile

The contaminant in the soil is represented by the concentration normalized to the source soil vapor concentration

$$.C = \frac{c}{c_{source}} \tag{4}$$

Figure 2 (a), (b) and (c) show simulation results of cases with a 2 m deep foundation for permeability of 10^{-11} m^2, while Figure 2 (e) and (f) represent those with 0.1m deep foundation for the same permeability. The location of the crack is unimportant in determining the concentration profile, while the effect of the cap is significant. This is reasonable because diffusion dominates contaminant transport in the soil, and the effect of soil gas flow on concentration profiles is negligible for soil with permeabilities less than approximately 10^{-11} m^2 [8].

Table 2. Input Parameters

Building/foundation parameters	**Contaminant vapor source properties**
Foundation Length: 10 m, Width: 10 m	Contaminant: Trichloroethylene (TCE)
Depth of foundation (d_f): 0.1 and 2 m	Diffusivity of TCE in air (D^g): 7.4 x10^{-6} m^2/s
Crack/foundation slab thickness(d_{ck}): 0.152 m	Effective diffusivity of TCE in soil (D_{eff}): 1.04 x10^{-6} m^2/s
Crack width(w_{ck}): 0.005 m	**Soil gas flow properties**
Crack area(A_{ck}): 0.2 m^2	Viscosity of air/soil gas (μ_g): 1.8648 x10^{-5} kg/m/s
Depth to groundwater/source (d_{source}) 8 m bgs	Density of air/soil gas (ρ_g): 1.1614kg/m^3
3-D Finite Element Analysis Parameters	Soil permeability (k): 10^{-10}, 10^{-11} and 10^{-12} m^2
Size of the grid elements: 0.001 m – 0.5 m	Total soil porosity (ϕ_T): 0.35
Number of elements: 600k	Soil porosity filled with gas (ϕ_g): 0.296

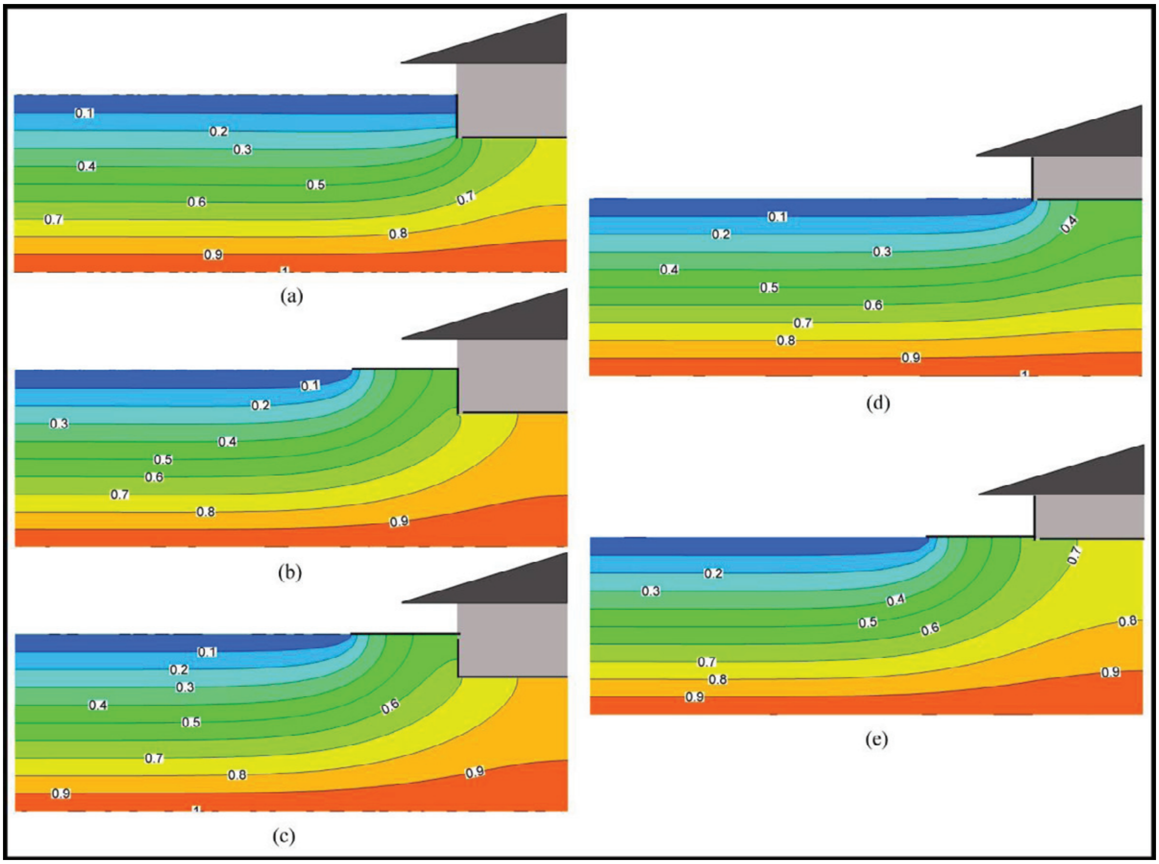
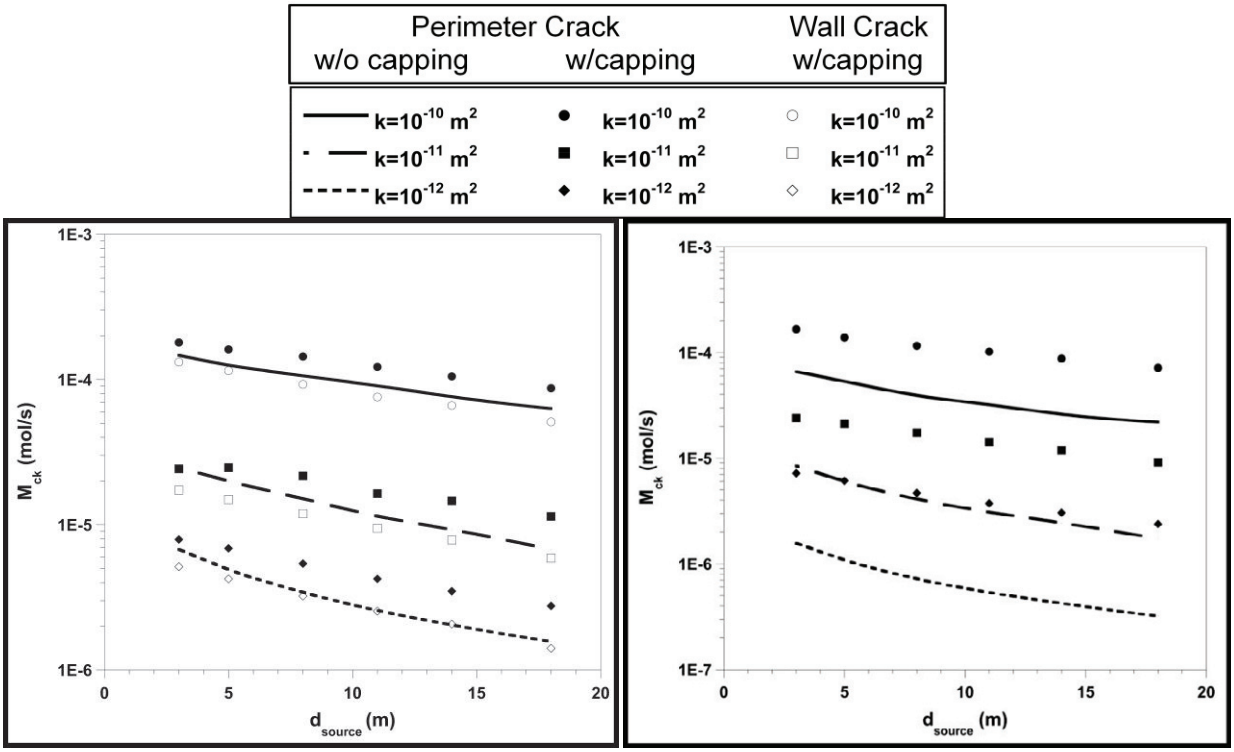


Figure 2. Cross sectional views of normalized concentration profile for scenarios (k=$10^{-11}$$m^2$ and d_{source}=8m) (a. "Perimeter crack" case of 2m deep foundation without capping around the building; b. "Perimeter crack" case of 2m deep foundation with capping; c. "Wall crack" case of 2m deep foundation with capping; d. "Perimeter crack" case of 0.1m deep foundation without capping; e. "Perimeter crack" case of 0.1m deep foundation with capping)

3.2 Contaminant mass flow rate

To better understand the effect of capping and crack location on vapor intrusion, the most important parameter to consider is mass flow rate through the crack (M_{ck}). Higher M_{ck} values result in higher indoor air concentrations. Figure 3 gives the contaminant mass flow rate comparison between cases with different construction and surrounding features. For the 2 m deep foundation in the "Perimeter Crack with capping" cases M_{ck} is the greatest, while M_{ck} for the "Wall Crack with capping" case is lowest. For the cases with 0.1 m deep foundation (i.e., slab), the results are quite similar, except that the effect of capping becomes more significant. Figure 3 also shows the influence of different source depths, ranging from 3 to 18 m bgs. These results show the expected trend in which the deeper the source, the lower the mass flow rate of contaminant into the structure.



(a) (b)

Figure 3. Comparison of contaminant mass flow rate into the house (a. 2 m deep foundation; b. 0.1 m deep foundation)

4. Conclusions

Indoor air concentration is proportional to contaminant mass flow rate into a foundation crack. The latter is an alternative indoor air quality index to the commonly used indoor air attenuation factor, and is preferred because its value does not depend upon indoor air exchange rate. The present steady state simulation shows how building/foundation and capping all influence soil gas contaminant concentration profiles around a building. In the presence of paved surroundings, contaminant concentration at the crack is twice as high for a building with 2m deep foundation, and five times as high for a building with 0.1m deep foundation, as compared to a building without surrounding cap. Soil gas flow and the crack location do not significantly affect subsurface concentration profiles, but do affect contaminant mass flow rate into the building. Capping surrounding a structure has a more significant impact on contaminant entry rates for slab on grade than for cases with 2m deep foundation. Crack location can impact contaminant entry rate significantly—the wall crack results show entry rates half those for a perimeter floor crack.

References:

1. Nazaroff, W. W.; Lewis, S. R.; Doyle, S. M.; Moed, B. S.; Nero, A. V. Experiments on pollutant transport from soil into residential basements by pressure-driven airflow. *Environ. Sci. Technol.* **1987,** *21,* 459-466.

2. Nazaroff, W.W. Predicting the rate of ^{222}Rn Entry from soil into basement of a dwelling due to pressure-driven air flow. *Radiation Protection Dosimetry,* **1988,** *22,* 199-202
3. Johnson, P.C.; Ettinger, E.A. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. *Environ. Sci. Technol.*, **1991,** *25,* 1445–1452
4. Johnson, P. C. “Identification of Critical Parameters for the Johnson and Ettinger (**1991**) Vapor Intrusion Model.” American Petroleum Institute Publication, API #17, **2002**.
5. US EPA “Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils”, **2002**
6. Hers, I., Zapf-Gilje, R., Johnson, P.C., Li, L. “Evaluation of the Johnson and Ettinger Model for the Prediction of Indoor Air Quality”, *Ground Water Monitoring and Remediation*, **2003**, *23*, 62-76
7. Abreu, L.D.; Johnson, P.C. Effect of Vapor Source-building Separation and Building Construction on Soil Vapor Intrusion as Studied With a Three-dimensional Numerical Model. *Environ. Sci. Technol.* **2005,** 39, 4550-4561
8. Johnson, P. C. “Identification of Application-Specific Critical Inputs for the 1991 Johnson and Ettinger Vapor Intrusion Algorithm.” *Ground Water Monitoring and Remediation.* **2005**, *25*(1): 63-78
9. Abreu, L.D.; Johnson, P.C. Simulating the effect of aerobic biodegradation on soil vapor intrusion into buildings: influence of degradation rate, source concentration, and depth. *Environ. Sci. Technol.* **2006,** *40,* 2304-2315
10. Tillman, F. D. and Weaver, J. W. Uncertainty from synergistic effects of multiple parameters in the Johnson and Ettinger (1991) vapor intrusion model, *Atmospheric Environment* **2006**, *40* (22): 4098–4112
11. Schuver, H. “Rold of Modeling & General Status of Revisions to EPA’s 2002 Vapor Intrusion Guidance” Updated J&E Model Spreadsheets Workshop AEHS Spring 2006 Meeting March 16, **2006**
12. Devall. G.E. Indoor vapor intrusion with oxygen-limited biodegradation for a subsurface gasoline source. *Environ. Sci. Technol.* **2007,** *41,* 3241-3248
13. Mills, W.B.; Liu, S.; Rigby, M.C.; Brenner, D. Time-variable simulation of soil vapor intrusion into a building with a combined crawl space and basement. *Environ. Sci. Technol.* **2007**, *41,* 4993-5001
14. Patterson, B.M.; Davis, G.B. Quantification of vapor intrusion pathways into a slab-on-ground building under varying Environmental Conditions. *Environ. Sci. Technol.* **2009,** *43,* 650–656
15. Pennell, K.G.; Bozkurt, O.; Suuberg,E. Development and application of a three-dimensional finite element vapor intrusion model. *J. Air & Waste Manage. Assoc.* **2009**, *59,* 447-460
16. Bozkurt, O.;l Pennell, K.G.; Suuberg,E. Simulation of the vapor intrusion process for nonhomogenous soils using a three-dimensional numerical model. *Ground Water Monitoring & Remediation* **2009,** *29,* 92-104
17. Bozkurt, O. Investigation of Vapor Intrusion Scenarios using a 3D numerical model. Ph.D. Dissertation, Brown University, Providence, RI, **2009**
18. Provoost, J.; Reijnders, L.; Swartjes, F.; Bronders, J.; Seuntjens, P.; Lijzen, J. “Accuracy of seven vapour intrusion algorithms for VOC in groundwater”, *J Soils Sediments* **2010**, *9*(1):62–743
19. Provoost, J.; Bosman, A.; Reijinder, L.; Bronders, J.; Touchant, K. and Swartjes, F. “Vapour intrusion from the vadose zone—seven algorithms compared”, *J Soils Sediments* **2010**, *10*,473–483