GeoStudio Example File
Soil Vapor Intrusion

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Introduction

Vapor intrusion into inhabited buildings has been the focus of several studies over the years. Most of the early studies centered on radon and methane intrusion while more recent studies have shifted to concerns over vapor-forming chemicals that include volatile organic compounds (such as trichloroethylene), semi-volatile organic compounds (such as naphthalene), mercury, poly-chlorinated biphenyls and pesticides. As with radon and methane, the intrusion of vapor-forming chemicals raises concerns of health risk from exposure. Simulation of the migration of vapor-forming chemicals from subsurface sources into overlying buildings provides a better under-standing of the process, facilitates remediation, and guides field investigations.

The objective of this example is to simulate chemical volatilization of trichloroethylene from a shallow contaminated groundwater table into cracks in the basement of an overlying three-dimensional building. Migration of the volatile organic compound is mostly driven by diffusion in the ground and by advection at the ground/building interface. The exercise lends credibility to the use of the software in multi-dimensional problems involving vapor transport and diffusion.

Numerical Simulation

A three-dimensional analysis was conducted to model vapor transport and diffusion from a shallow, 8 meter-deep, groundwater table into a small 5 mm-wide, 152 mm-deep, crack on the perimeter of the floor of a 2 meter-deep, 10×10 meter-square, basement of an inhabited building. The building lies on a homogeneous sandy deposit with a porosity of 0.35 and an intrinsic permeability of 10^{-11} m². The hydraulic and pneumatic properties of the deposit are estimated using the sample sand material with conductivities computed as $K = k\rho g/\mu$ where k is the intrinsic permeability, ρ is the density of the fluid, g is the gravitational acceleration constant, and μ is the dynamic viscosity of the fluid. The bulk diffusion coefficient of trichloroethylene in the gas and aqueous (or dissolved gas) phases is computed using Millington and Quirk's (1961) equation with molecular diffusion coefficients of 7.40×10^{-6} and 8.16×10^{-10} m²/s, respectively. The domain includes one-eighth of the basement due to the laws of symmetry and the crack is represented by a characteristic entrance region that allows for a significant reduction in the number of elements without altering the solution. The relative air pressure is zero (or atmospheric) at the ground surface and -5 Pa on the characteristic entrance region. The relative pore-water pressure is zero at the groundwater surface. The concentration of trichloroethylene in the groundwater (or aqueous phase) is constant and equal to 729 mg/m³ while concentration in the vapor (or gas phase) immediately above the groundwater table is found to be equal to 357.21 mg/m³ using Henry's law ($C_g/C_a = 1/H$ where H = 2.04 is Henry's law solubility constant, C_g is the gas concentration, and C_a is the aqueous concentration). Concentration of trichloroethylene in the atmosphere is very low and assumed negligible. The finite element mesh was generated with predominantly hexahedral elements and finer-meshed bodies near the basement. A review of the mesh quality reveals that the elements are generally fair to good near the basement and excellent in the remainder of the domain.

Results and Discussion

Figure 1 shows the contour surfaces of air total head in the domain. As with any fluid, air flows from regions of larger total head to regions of lower total head. The air therefore enters the domain at the ground surface, where total head is largest, and leaves the domain at the crack (or characteristics entrance region), where total head is smallest. The air fluxes are largest as air funnels through the crack, where the average air rate is equal to 4.84×10^{-7} m³/s per meter of crack. The pressure drop across the basement slab can be computed using the equation for incompressible laminar flow between two parallel plates, $\Delta P = 12\mu_a d_c Q / w_c^{\,3}$ = 1.31×10^-4 Pa where μ_a is the dynamic viscosity of air, d_c is the crack depth (or slab thickness), and w_c is the crack width. Subtracting the pressure drop from the relative air pressure applied to the characteristic entrance region yields the relative air pressure in the basement, which is essentially the same as that applied to the characteristic entrance region. For remediation purposes, mechanical ventilation can be used to increase the relative air pressure in the basement, and thereby halt or reverse airflow. In this case, the relative air pressure applied to the characteristic entrance region would need to be equal to (or larger than) the relative air pressure at the crack under static conditions, which is equal to 23.62 Pa according to the barometric formula.

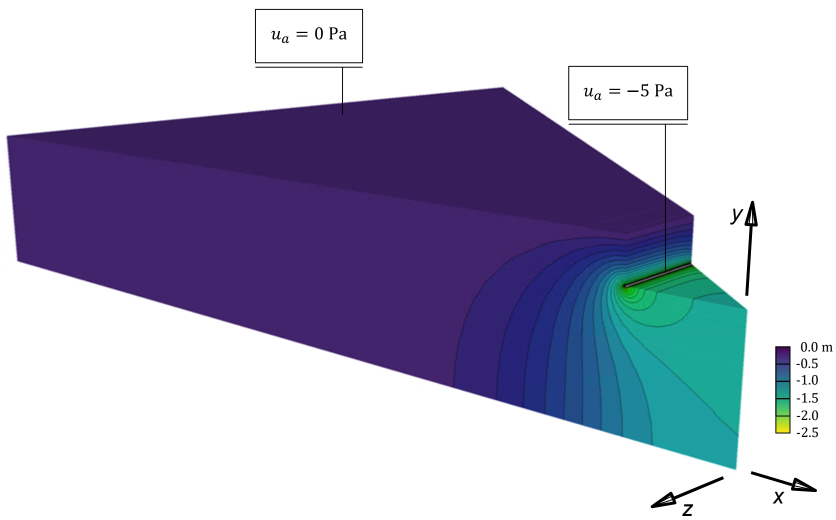


Figure 1. Contour surfaces of air total head and applied pneumatic boundary conditions.

Figure 2 shows the contour surfaces of gas (or trichloroethylene vapor) and dissolved gas concentrations in the entire domain. The gas concentration is highest at the groundwater surface and lowest at the ground surface. This difference in concentration results in an upward diffusion of gas. The dissolved gas concentrations in the aqueous phase are computed using Henry's law and are thus proportional to those found in the gas phase. This difference in concentration also results in an upward, but significantly smaller, diffusion of dissolved gas. It is important to recognize that the gas enters the basement by advection. Although not shown here, the gas mass flux across the basement slab is equal to the sum of advection and molecular diffusion through the crack (Pennell et al., 2009; Bozkurt et al., 2009).

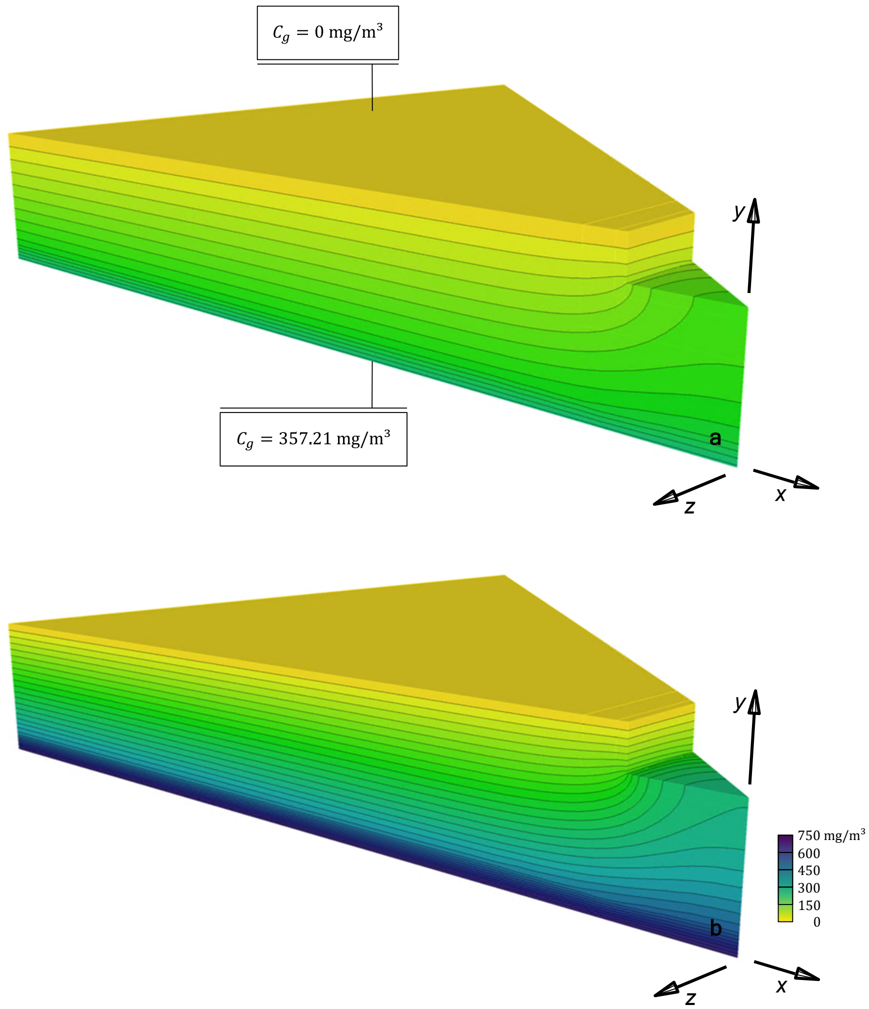
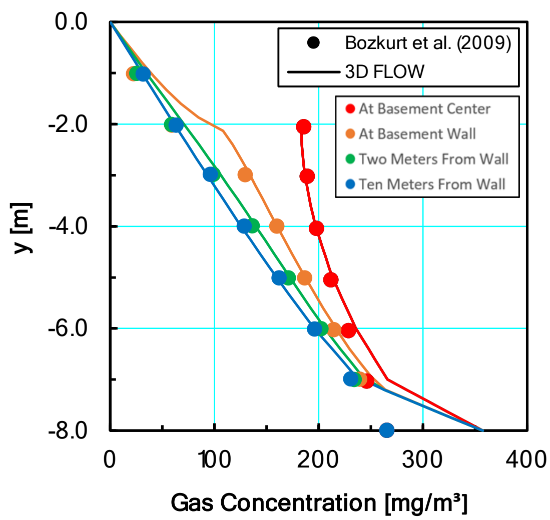


Figure 2. Contour surfaces of concentration and applied boundary conditions. (a) Gas. (b) Aqueous (or dissolved gas).

Figure 3 shows the gas concentration profile at the basement center, the basement wall, two meters from the basement wall, and ten meters from the basement wall. As expected, the concentration profile furthest from the basement wall decreases linearly from the groundwater



surface to the ground surface. The other concentration profiles depart from linearity as the basement impedes diffusion and forces the gas to diffuse laterally. The concentration is highest below the basement irrespective of the presence or absence of advection. The results are generally in very close agreement with those found in Bozkurt et al. (2009). The discrepancy near the groundwater surface is due to the different source concentrations used to compensate for the differences in volumetric water and air content (and thus bulk diffusion) in the capillary-saturated vadose zone. This diffusion dominated response dictates the concentration around the basement, and most importantly, near the crack. The air that flows across this region carries the gas into the basement. Stated otherwise, diffusion governs gas concentration around the basement whereas advection governs gas concentration in the basement.

Figure 3. Concentration profiles along the axis of symmetry of the domain.

It is important to recognize that the diffusion and advection processes are highly dependent on the hydraulic conditions that prevail in the vadose zone. As shown in Figure 4, the volumetric air content increases as volumetric water content decreases with elevation. This change in volumetric air content results in a significant increase in the bulk diffusion coefficient of trichloroethylene in the gas phase, which remains near constant in the upper portion of the vadose zone. The change in volumetric air content also results in a significant change in air conductivity near the foundation, which is of utmost importance to gas inflow rates.

Although the current example focuses on a non-biodegradable volatile organic compound, the software can also be used to model biodegradable volatile organic compounds (such as benzene) assuming first-order bio-kinetics.

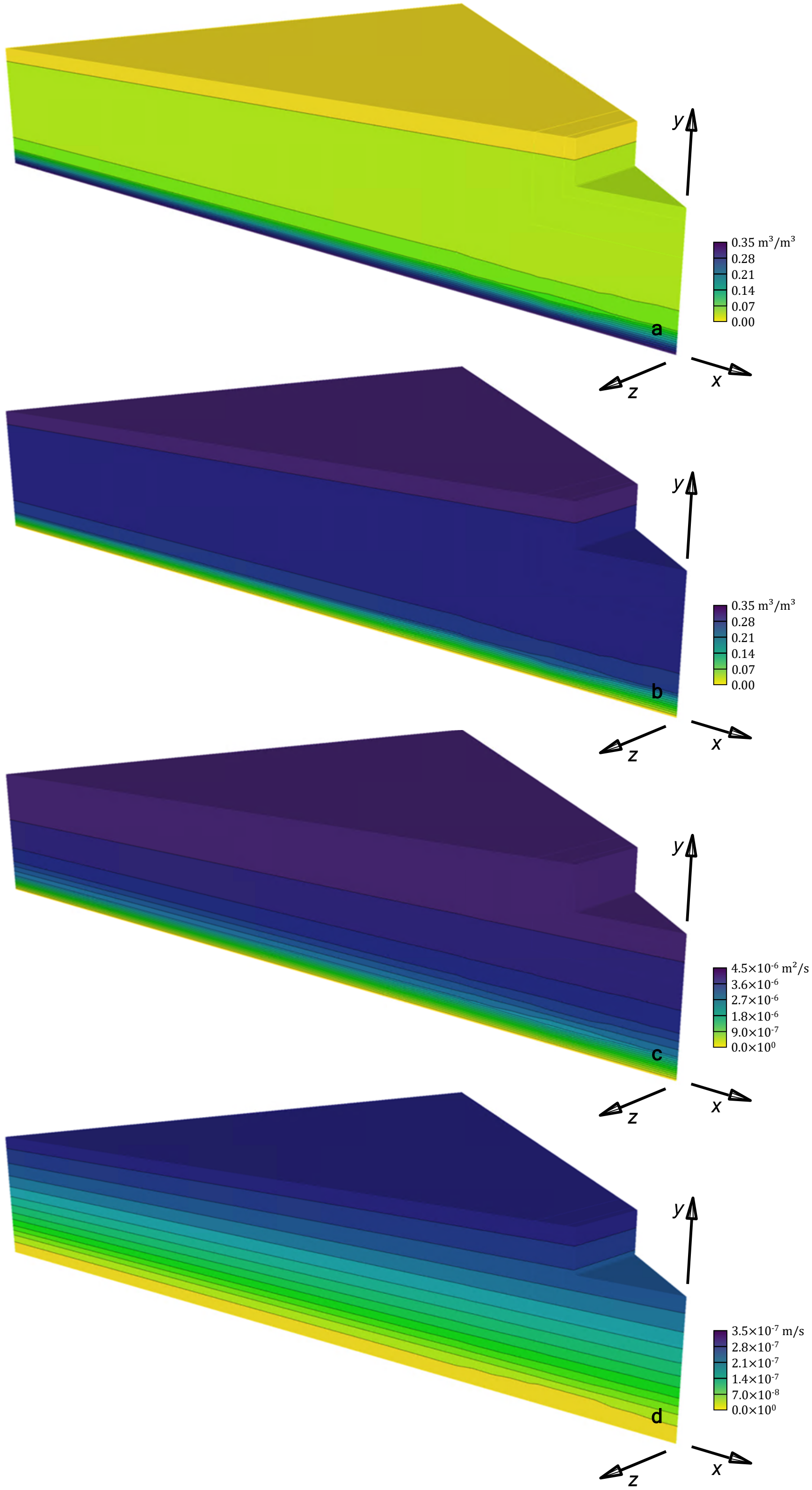


Figure 4. Contour surfaces. (a) Volumetric water content. (b) Volumetric air content. (c) Bulk diffusion coefficient of trichloroethylene in the gas phase. (d) Air conductivity.

Summary and Conclusions

The objective of this example was to demonstrate the ability of the 3D FLOW modeling package to solve multi-dimensional problems involving vapor transport and diffusion. The capabilities of the software were assessed using a well-documented vapor intrusion problem in which trichloro-ethylene migrates from a subsurface source into the basement of an overlying building. The analysis captured the basic nature of the phenomenon in which diffusion governs the gas concentration around the basement while advection governs gas concentration in the basement. In doing so, the results were shown to be in very close agreement with those of a reference numerical analysis.

References

Pennell, K.G., Bozkurt, O., and Suuberg, E.M. 2009. Development and application of a three-dimensional finite element vapor intrusion model. Journal of the Air & Waste Management Association, 59(4), 447-460.

Bozkurt, O., Pennell, K.G., and Suuberg, E.M. 2009. Simulation of the vapor intrusion process for nonhomogeneous soils using a three-dimensional numerical model. Groundwater Monitoring & Remediation, 29(1), 92-104.