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Estimating the oxygenated zone beneath building foundations for petroleum vapor intrusion assessment

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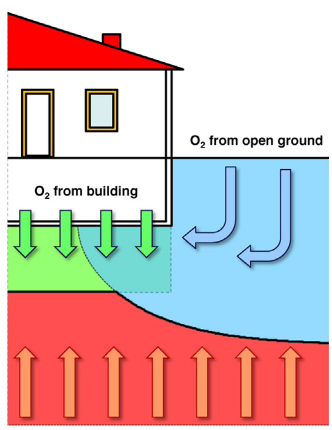
HIGHLIGHTS

- A 2-D analytical model for estimating subslab oxygen availability is presented.
- The analytical model replicates quite well 3-D numerical results.
- The role of pervious and impervious foundations slab is investigated.
- The site parameters affecting the development of subslab oxygen shadow are examined.

GRAPHICAL ABSTRACT



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ABSTRACT

Previous studies show that aerobic biodegradation can effectively reduce hydrocarbon soil gas concentrations by orders of magnitude. Increasingly, oxygen limited biodegradation is being included in petroleum vapor intrusion (PVI) guidance for risk assessment at leaking underground storage tank sites. The application of PVI risk screening tools is aided by the knowledge of subslab oxygen conditions, which, however, are not commonly measured during site investigations. Here we introduce an algebraically explicit analytical method that can estimate oxygen conditions beneath the building slab, for PVI scenarios with impervious or pervious building foundations. Simulation results by this new model are then used to illustrate the role of site-specific conditions in determining the oxygen replenishment below the building for both scenarios. Furthermore, critical slab-width-to-source-depth ratios and critical source depths for the establishment of a subslab "oxygen shadow" (i.e. anoxic zone below the building) are provided as a function of key parameters such as vapor source concentration, effective diffusion coefficients of concrete

Abbreviations: PVI, petroleum vapor intrusion; UST, underground storage tank; 3-D, three-dimensional; 2-D, two-dimensional 1-D; VI, vapor intrusion; US EPA, United States Environmental Protection Agency; ITRC, interstate technology & regulatory council; CO_2, carbon dioxide; O_2, oxygen; CSM, conceptual site model.

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and building depth. For impervious slab scenarios the obtained results are shown in good agreement with findings by previous studies and further support the recommendation by U.S. EPA about the inapplicability of vertical exclusion distances for scenarios involving large buildings and high source concentrations. For pervious slabs, results by this new model indicate that even relatively low effective diffusion coefficients of concrete can facilitate the oxygen transport into the subsurface below the building and create oxygenated conditions below the whole slab foundation favorable for petroleum vapor biodegradation.

Nomenclature

λ_b	Degradation rate of benzene in water phase h^{-1}
λ_i	Degradation rate of hydrocarbons in water phase h^{-1}
δ_b	Stoichiometric mass of oxygen consumed per mass of benzene g_{o_2}/g_{HC}
δ_i	Stoichiometric mass of oxygen consumed per mass of hydrocarbons g_{o_2}/g_{HC}
θ_t	Porosity of the soil –
θ_w	Water-filled porosity of the soil –
A_b	Foundations area m^2
c_b^s	Vapor source concentration of benzene g/m^3
c_i	Concentration of hydrocarbons in the soil-gas phase g/m^3
c_i^s	Vapor source concentration of hydrocarbons g/m^3
c_o	Concentration of oxygen in the soil-gas phase g/m^3
c_o^{atm}	Oxygen concentration in the atmosphere g/m^3
c_o^{min}	Minimum oxygen concentration to sustain biodegradation g/m^3
c_o^{ss}	Subslab concentration of oxygen g/m^3
d_f	Depth of the building foundation below ground surface m
d_s	Depth of contaminant source below ground surface m
D_b	Effective porous medium diffusion coefficient of benzene m^2/h
D_i	Effective porous medium diffusion coefficient of hydrocarbons m^2/h
D_o	Effective porous medium diffusion coefficient of oxygen m^2/h
D_o^{slab}	Overall diffusivity of oxygen through the foundations slab m^2/h
H_i	Henry's law constant of hydrocarbons –
k_i	First-order reaction rate constant for hydrocarbons h^{-1}
L	Source vertical distance from the bottom of the foundations m
L_a	Thickness of the aerobic zone in the subsurface m
L_b	Thickness of the anaerobic zone in the subsurface m
L_c	Critical source vertical distance from the bottom of the foundations m
L_{ck}	Thickness of the slab m
L_{slab}	Slab width of the building m
$L_{slab,c}$	Critical slab width of the building m
R_i	Loss rate of hydrocarbons due to biodegradation (first-order kinetic) $g/\left(m^3h\right)$
w	Constituent oxygen and hydrocarbons variable –
w_a	Constituent oxygen and hydrocarbons variable at the interface –
x	Coordinate in the horizontal direction m
z	Coordinate in the vertical direction m
z_a	Position of the aerobic to anaerobic interface m

1. Introduction

The accidental release of petroleum hydrocarbons into the subsurface may cause petroleum vapor intrusion (PVI), a process by which vapors of petroleum chemicals migrate from subsurface to overlying buildings [1]. The resulting indoor air quality problem from these vapors can pose potential threats to human health [2–4]. The difference between PVI and vapor intrusion (VI) involving other volatile contaminants (typically chlorinated compounds), is the potential of petroleum hydrocarbons to biodegrade in the presence of oxygen [5]. As described in the recent guidance on petroleum vapor intrusion issued by the United States Environmental Protection Agency (U.S. EPA) [6] and Interstate Technology & Regulatory Council (ITRC) [7] **t**he potential threats of PVI to residents' health can be indeed significantly reduced or eliminated in oxygen-rich soils due to the occurrence of aerobic biodegradation by soil microbes. It is well known that microorganisms can oxidize petroleum hydrocarbons to carbon dioxide while utilizing electron acceptors such as molecular oxygen [8,9]. Unlike recalcitrant compounds such as chlorinated solvents, a large number of petroleum hydrocarbon are susceptible to aerobic biodegradation at rates that are quite rapid with respect to rates of physical transport by diffusion and advection [21,22], leading to vapors attenuation by several orders of magnitude within a few meters [2,10–18]. Based on this, U.S. EPA and ITRC guidances [6,7] proposed vertical screening distances (i.e. the thickness of clean biologically active soil between the source and the overlying receptor) beyond which the potential for PVI can be considered negligible. In these guidance documents no particular concerns are addressed to sources underlying an open ground surface. In such scenarios, indeed, oxygen can readily penetrate into the subsurface and create oxygenated conditions favorable for petroleum vapor biodegradation [19]. Conversely, both U.S.EPA and ITRC guidances highlight that a key aspect to be evaluated is the establishment of oxygenated soil zones beneath large buildings [1]. An impervious slab can potentially act as a surface cap reducing the migration of oxygen into the soil beneath the slab, and consequently, limiting the attenuation of vapor concentrations due to aerobic biodegradation [20]. In most PVI conceptual site models (CSMs), atmospheric oxygen at ground surface beyond the building perimeter is considered as the primary source of oxygen in the subsurface [1,30,31]. For instance, in different analytical PVI models [20,21,23–29] and in a series of numerical modeling studies conducted by Abreu and Johnson [30] and Abreu et al. [31], this migration pathway was considered the only mechanism of oxygen replenishment in the subsurface below the building. However, U.S. EPA [6] suggests that diffusive transport through permeable concrete slabs can also enhance the oxygen availability in the subsurface and reports values for the effective diffusion coefficient for oxygen through permeable concrete slabs in the range of 1.08–15.6 cm^2/h. Although these effective diffusion coefficients of concrete are significantly lower than the ones typical of soils [32–34], the net flux of oxygen through the slab might be significant if the building size is large enough to make the diffusive oxygen flux from open ground surface beyond foundation edge, negligible towards the middle of the subslab zone. Further-