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Role of the source to building lateral separation distance in petroleum vapor intrusion

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ABSTRACT

The adoption of source to building separation distances to screen sites that need further field investigation is becoming a common practice for the evaluation of the vapor intrusion pathway at sites contaminated by petroleum hydrocarbons. Namely, for the source to building vertical distance, the screening criteria for petroleum vapor intrusion have been deeply investigated in the recent literature and fully addressed in the recent guidelines issued by ITRC and U.S.EPA. Conversely, due to the lack of field and modeling studies, the source to building lateral distance received relatively low attention. To address this issue, in this work we present a steady-state vapor intrusion analytical model incorporating a piecewise first-order aerobic biodegradation limited by oxygen availability that accounts for lateral source to building separation. The developed model can be used to evaluate the role and relevance of lateral vapor attenuation as well as to provide a site-specific assessment of the lateral screening distances needed to attenuate vapor concentrations to risk-based values. The simulation outcomes showed to be consistent with field data and 3-D numerical modeling results reported in previous studies and, for shallow sources, with the screening criteria recommended by U.S.EPA for the vertical separation distance. Indeed, although petroleum vapors can cover maximum lateral distances up to 25–30 m, as highlighted by the comparison of model outputs with field evidences of vapor migration in the subsurface, simulation results by this new model indicated that, regardless of the source concentration and depth, 6 m and 7 m lateral distances are sufficient to attenuate petroleum vapors below risk-based values for groundwater and soil sources, respectively. However, for deep sources (>5 m) and for low to moderate source concentrations (benzene concentrations lower than 5 mg/L in groundwater and 0.5 mg/kg in soil) the above criteria were found extremely conservative as the model results indicated that for such scenarios the lateral screening distance may be set equal to zero.

1. Introduction

Petroleum vapors can be considerably attenuated in the subsurface due to the occurrence of aerobic biodegradation (Hers et al., 2000; McHugh et al., 2010). The significance of biodegradation in reducing vapor concentrations towards potential receptors has been deeply documented in the recent guidelines released by U.S.EPA (2015a); ITRC (2014) and CRC care (2013) where it was clearly highlighted that biodegradation by ubiquitous soil microbes can attenuate petroleum vapors of several orders of magnitude within few meters of clean soil, provided that sufficient oxygen is available to sustain the aerobic reaction. Namely, based on a statistical analysis of large empirical soil vapor data sets, different works (Davis, 2009; Peargin and Kolhatkar, 2011; Wright, 2011; Lahvis et al., 2013) have recently estimated the vertical separation screening distances (i.e. the thickness of clean biologically active soil between the source and the overlying receptor) beyond which

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the potential for petroleum vapor intrusion can be considered negligible. Although these studies were based on different empirical data sets or different methods for the data interpretation (e.g. vertical distance method or clean soil method), a high degree of consistency among them was observed (U.S.EPA, 2015a). Based on the evidences provided by the above-mentioned empirical studies, U.S.EPA (2015a) suggested that additional investigation may be not necessary when the source to building vertical separation distance is greater than 1.8 m (6 ft) for dissolved contamination or 4.6 m (15 ft) for light non-aqueous phase liquid (LNAPL). Furthermore, results from numerical (Hers et al., 2000; Abreu and Johnson, 2006; Abreu et al., 2009; Knight and Davis, 2013; Hers et al., 2014) and analytical models (DeVaull, 2007; Yao et al., 2014; Verginelli and Baciocchi, 2014; Yao et al., 2016) were consistent with the empirical exclusion distance values reported above, showing that, in nearly all cases, a source to building vertical separation distance greater than 2 m or 5 m is sufficient to attenuate to acceptable risk-based levels petroleum hydrocarbon vapors from dissolved-phase or LNAPL sources, respectively.

Conversely, the concept of source to building lateral exclusion distance has certainly received less attention, presumably due to the lack of empirical literature data that may help in the assessment of the vapor attenuation in the lateral direction. Besides, in cases of groundwater contamination, the lateral edge of the contaminant plume is generally not known with the same precision, as the uncertainty on the plume delimitation is over a scale of tens of feet horizontally, compared to a range of only few feet vertically (ITRC, 2014). Hence, the lateral exclusion distance is usually set equal to a conservative value of 30 ft (10 m) (ITRC, 2014) or assumed to be equal to the derived site-specific vertical screening distance (U.S.EPA, 2013). However, a greater attenuation of petroleum vapors is expected when hydrocarbon sources are offset laterally from buildings compared with sources directly below buildings (U.S.EPA, 2013). Indeed, moving laterally from the vapor source, the oxygen demand is likely to progressively decrease with a resulting enhancement of vapor attenuation due to aerobic biodegradation. Numerical simulations carried out by Abreu (2005) and Abreu and Johnson (2006) supported this assumption, showing that, for a vapor source of 200 mg/L, relatively short source-building lateral separation distances (e.g. 5–10 m) may lead to a vapor attenuation of several orders of magnitude higher than the ones achieved for a source located directly below the building. Although these results highlighted the potential key role of the lateral source-building separation in attenuating petroleum vapors, no systematic approaches are currently available to support this evidence on a site-specific basis. Indeed, the recent screening models available in the literature accounting for the lateral source-building separation (Lowell and Eklund, 2004; Yao et al., 2013, 2015) were developed by neglecting the occurrence of biodegradation, which is instead expected to be a key factor for a fair evaluation of the lateral screening distance at petroleum contaminated sites. Hence, in this work we introduce a simple analytical model that may be employed by practitioners to address this need. The developed steady-state model incorporates a piecewise first-order aerobic biodegradation limited by oxygen availability that accounts for lateral source to building separation. Namely, the lateral source-building separation is incorporated in the model by introducing an equivalent diffusive length for oxygen and vapors, estimated using a simple geometric approach. The results obtained by applying the proposed model are first compared with the evidences observed by Broholm et al. (2005); Christophersen et al. (2005) and Höhener et al. (2006) during a series of field experiments in order to assess the accuracy of the developed model. Furthermore, simulation results by this new models are compared with those obtained using a more rigorous 3-D numerical model. Finally, the model predictions are used to evaluate the role and relevance of the lateral source-building separation for petroleum vapor intrusion as well as to provide a site-specific assessment of the lateral screening distance needed to attenuate vapor concentrations to risk-based values.

2. Model development

2.1. Vapor transport and biodegradation

The first-order steady-state reactive transport of petroleum vapor hydrocarbons can be described by a one-dimensional (1-D) diffusion differential equation with reaction terms (DeVaull, 2007; Verginelli and Baciocchi, 2014):

$$\begin{cases} D_v \dfrac{\partial^2 C_v}{\partial z^2} - \dfrac{\lambda \cdot \theta_w}{H} \cdot C_v = 0 & \text{for} \quad 0 < z < L_a \quad \left(O_2 > O_2^{min}\right) \\ D_v \dfrac{\partial^2 C_v}{\partial z^2} = 0 & \text{for} \quad L_a \le z < L \quad \left(O_2 \le O_2^{min}\right) \end{cases} \tag{1a, 1b}$$

where C_v is the concentration of hydrocarbons in the soil-gas phase, λ the first-order biodegradation rate constant in the water phase, θ_w the water-filled porosity of the soil, H the dimensionless Henry's law constant and D_v the effective vapor diffusion coefficient in the porous medium, which can be estimated by applying a simplified form of Millington and Quirk (1961) expression, i.e. assuming a negligible diffusion in the water phase:

$$D_v = D_a \cdot \frac{\theta_a^{10/3}}{\theta_e^2} \tag{2}$$

with D_a the diffusion coefficients of vapors in air, θ_e the porosity of the soil and θ_a the air-filled porosity of the soil.

Note that in Eq. (1a,1b) the reaction is assumed to occur only in the aerobic zone, i.e. when the oxygen concentration (O_2) in the subsurface is higher than a specific threshold level (e.g. $O_2^{min} = 1\%$ v/v) below which aerobic biodegradation of hydrocarbons stops, or slows down to negligibly low rates (Hers et al., 2000).

An analytical solution of Eq. (1a,1b) can be derived assuming as boundary conditions a constant vapor source concentration C_{source} at a depth $z = L$, a vapor concentration C_a at the aerobic to anaerobic interface ($z = L_a$) and a negligible vapor flux at the ground surface ($\partial C/\partial z = 0$ at $z = 0$) (see Fig. 1). Under these assumptions, the following solutions that