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# Evaluation of site-specific lateral inclusion zone for vapor intrusion based on an analytical approach

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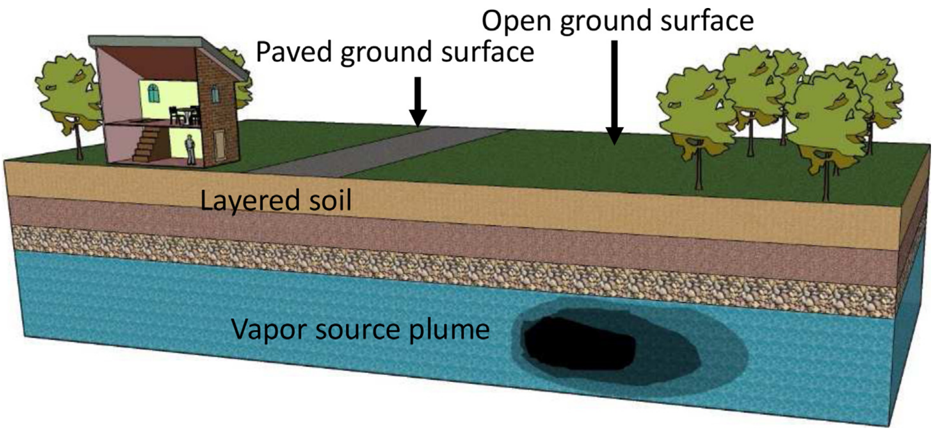
## HIGHLIGHTS

- A new vapor intrusion (VI) screening tool named "AAMLPH" is introduced.
- Lateral safe distance can be evaluated when involving layering and surface cover.
- A comparision between AAMLPH and 3-D numerical model is provided.
- Key factors determining lateral safe distance are source strength, depth and cover.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In 2002, U.S. EPA proposed a general buffer zone of approximately 100 feet (30 m) laterally to determine which buildings to include in vapor intrusion (VI) investigations. However, this screening distance can be threatened by factors such as extensive surface pavements. Under such circumstances, EPA recommended investigating soil vapor migration distance on a site-specific basis. To serve this purpose, we present an analytical model (AAMLPH) as an alternative to estimate lateral VI screening distances at chlorinated compound-contaminated sites. Based on a previously introduced model (AAML), AAMLPH is developed by considering the effects of impervious surface cover and soil geology heterogeneities, providing predictions consistent with the three-dimensional (3-D) numerical simulated results. By employing risk-based and contribution-based screening levels of subslab concentrations (50 and 500 $\mu g/m^3$, respectively) and source-to-subslab attenuation factor (0.001 and 0.01, respectively), AAMLPH suggests that buildings greater than 30 m from a plume boundary can still be affected by VI in the presence of any two of the three factors, which are high source vapor concentration, shallow source and significant surface cover. This finding justifies the concern that EPA has expressed about the application of the 30 m lateral separation distance in the presence of physical barriers (e.g., asphalt covers or ice) at the ground surface.

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## 1. Introduction

Vapor intrusion (VI) is a process by which chemical vapors originating from subsurface sources migrate into the enclosed space of the buildings above the contaminated soil or groundwater [1], and can induce negative effects on human health [2–4]. To identify a complete VI exposure pathway, U.S. EPA recommended screening evaluations by using sampling, mathematical models, empirical concentration attenuation factors and separation distances [5–15]. For example, 100 feet (30 m) laterally was considered as a reasonable criterion for diffusive transport in the absence of preferential pathway. Independent of site-specific characterizations, the judgment of 30 m laterally was summarized based on available information and practice experiences up to 2002. This recommended lateral separation distance is also supported by recent modelling studies [7,16–17], which reported that a 30 m lateral transport distance can induce at least 3 orders of magnitude attenuation in soil gas concentration, unless involving a very deep vapor source.

However, the scenarios simulated in above modelling work are limited to homogenous soil gas diffusivity and the absence of physical barrier at ground surface. In practice, especially in urban areas, the ground surface can be paved and become impervious or difficult for soil gas flow to go through. Previous studies showed that such capping effect can increase the contaminant subslab vapor concentration when source plume is beneath the building foundation [18–19]. On the other hand, the spatial variabilities of soil gas concentration identified in field studies implied a possibility that soil heterogeneities may also play a role [20–26]. In EPA's spreadsheet version of the Johnson–Ettinger (J–E) model, the van Genuchten parameters for 12 kinds of soil type (SCS soils) are provided so that they can be chosen to apply in a multilayer system [27]. Even in scenarios involving single type of soil, the spatial variability of moisture content due to capillary fringe and rainfall events could also affect the distribution of the effective diffusivity of soil gas [28–30].

Though these studies involving paved surface and soil heterogeneities focus on the influences of individual factor, and are limited to vertical soil gas transport, the results still hint at the need to examine the lateral separation needed to achieve a sufficient attenuation under the circumstances with joint influences of those factors. Moreover, EPA recommended investigating soil vapor migration distance on a site-specific basis in cases where the 30 m buffer is threatened by significant surface cover and become inappropriate to apply [5]. In this study, with the help of three-dimensional (3-D) numerical simulations and mathematical approximations, we introduce a VI screening tool (AAMLPH) as an alternative to evaluate lateral VI inclusion zones based on site-specific characterizations including surface cover and soil geology, by employing a critical subslab concentration $C_{ss}$ and source-to-subslab attenuation factor $\alpha_s^{ss}$ as the screening criteria. Similar to the Analytical Approximations Methods (AAMs) developed in previous studies [17,31–32], AAMLPH can be used independent of building operational conditions without computational efforts.

## 2. Methods

### 2.1. 3-D numerical model

The development, validation and applications of the 3-D finite element model examined here were already presented in former studies [18–20,28–33]. In the present study, the model is applied only in a steady-state mode for non-degradable contaminants. The scenarios studied consist of a single square 10 m × 10 m footprint structure built on a field of 100 m × 50 m, with a vapor source plume (10 m × 10 m). Since all scenarios studied here are symmetrical, only a half domain is actually simulated. Impervious boundary conditions are employed at parts of ground surface between the building and the vapor source to simulate the physical barrier such as asphalt, concrete, or frozen soil, though in some studies the concrete slab was considered permeable to soil gas flow but of higher resistance compared to soil [34–35]. For readers who are interested in the differences between impervious and low-permeability slabs, a comparison is provided in the discussion section below. In the present study, the thickness of the pavements and the base course layer are not considered here, either. The non-flux boundary conditions are also applied at planes of symmetry, the groundwater surface and the foundation (except for the crack). The open ground surface is taken to be at atmospheric reference pressure and is a sink of zero contaminant concentration. A negative pressure of −5 Pa and a contaminant flux equation is assigned at the crack, the same as in the former studies [28–33]. The detailed parameters are shown in Table 1. Though permeability and diffusivity are both related to the porosity of the soil, permeability is assumed to be constant here because advection does not have a significant impact on soil gas transport [36].

**Table 1**
Input parameters used in 3-D simulations.

| Building/ Foundation parameters | Heterogeneous soil cases: |
|---|---|
| Foundation footprint length : 10 m | (1) Three-layer |
| Foundation footprint width : 10 m | Thickness of layered soil ($L_i$): |
| Depth of foundation($d_f$): 0.2 and 2 m | Top layer ($L_3$): 3 m |
| Crack width ($W_{ck}$): 0.005 m | Medium layer ($L_2$): 3 m |
| Thickness of crack ($d_{ck}$):0.152 m | Bottom layer ($L_1$): 2 m |
| Crack location : perimeter | High effective diffusivity: $1.05 \times 10^{-6}$ m$^2$/s |
| Crack area ($A_{ck}$):0.199 m$^2$ | Total porosity ($\eta_T$) : 0.3 |
| Disturbance pressure ($\triangle P$):−5 Pa | Moisture porosity ($\eta_w$): 0.03 |
| Depth to source ($d_s$): 3,5,8,11,14 m | Medium effective diffusivity : $8.68 \times 10^{-7}$ m$^2$/s |
| **Contaminant vapor source properties** | Total porosity ($\eta_{T)}$: 0.35 |
| Source plume size: 10 m × 10 m | Moisture porosity ($\eta_w$): 0.07 |
| Lateral source-building Separation ($d_\eta$):0 ~ 60 m | Low effective diffusivity : $4.37 \times 10^{-7}$ m$^2$/s |
| **Contaminant properties:** | Total porosity ($\eta_{T):}$ 0.45 |
| Source vapor concentration ($c_s$) : 1 mol/m$^3$ | Moisture porosity ($\eta_w$): 0.19 |
| Diffusivity in crack ($D_{ck}$) : $8.81 \times 10^{-6}$ m$^2$/s | (2) Two-layer |
| Diffusivity in air ($D_g$) : $8.81 \times 10^{-6}$ m$^2$/s | Sand: |
| Effective diffusivity($D_{eff}$) : $1.04 \times 10^{-6}$ m$^2$/s | Effective diffusivity in upper soil: $1.42 \times 10^{-6}$ m$^2$/s |
| **Paved ground surface parameters** | Thickness of capillary fringe : 0.1705 m |
| Width of paved ground size ($L_p$) : 10 ~ 60 m | Effective diffusivity in capillary fringe : $5.70 \times 10^{-8}$ m$^2$/s |
| Paved ground-building separation ($L_0$):0–50m | Sandy loam: |
| **Soil properties** | Effective diffusivity in upper soil: $8.88 \times 10^{-7}$ m$^2$/s |
| Soil permeability (k):10–11 m$^2$ | Thickness of capillary fringe: 0.25 m |
| Viscosity of soil gas ($\mu_g$):$1.8 \times 10^{-6}$ kg/m/s | Effective diffusivity in capillary fringe: 8.61 × 10 |
| Soil bulk density ($\rho_b$):1700 kg/m3 | Clay: |
| **Homogeneous soil cases:** | Effective diffusivity in upper soil: $3.81 \times 10^{-7}$ m$^2$/s |
| Effective diffusivity : $1.04 \times 10^{-6}$ m$^2$/s | Thickness of capillary fringe: 0.8152 m |
| Total porosity ($\eta_T$) : 0.35 | Effective diffusivity in capillary fringe:$3.70 \times 10^{-9}$ m$^2$/s |
| Moisture porosity ($\eta_w$): 0.07 | |