Chemosphere 95 (2014) 140–149

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Analytical modeling of the subsurface volatile organic vapor concentration in vapor intrusion

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HIGHLIGHTS

- A 2D implicit analytical solution is offered describing subsurface vapor concentration.
- Building geometrical factors affecting subslab vapor concentration are evaluated.
- The analytical solution is compared with numerical modeling results.

ARTICLE INFO

Article history:
Received 21 May 2013
Received in revised form 7 August 2013
Accepted 15 August 2013
Available online 10 September 2013

Keywords:
Volatile organic compounds
Modeling
Chemical fate and transport
Vapor intrusion

ABSTRACT

The inhalation of volatile and semi-volatile organic compounds that intrude from a subsurface contaminant source into indoor air has become the subject of health and safety concerns over the last twenty years. Building subslab and soil gas contaminant vapor concentration sampling have become integral parts of vapor intrusion field investigations. While numerical models can be of use in analyzing field data and in helping understand the subslab and soil gas vapor concentrations, they are not widely used due to the perceived effort in setting them up. In this manuscript, we present a new closed-form analytical expression describing subsurface contaminant vapor concentrations, including subslab vapor concentrations. The expression was derived using Schwarz-Christoffel mapping. Results from this analytical model match well the numerical modeling results. This manuscript also explores the relationship between subslab and exterior soil gas vapor concentrations, and offers insights on what parameters need to receive greater focus in field studies.

1. Introduction and review of the field data

Vapor intrusion involves complex transport processes and is associated with inhalation health risks. With the growing awareness of the problem as evidenced by numerous various studies of the problem in recent years (e.g. Johnson, 2002; Hers et al., 2003; Karapanagioti et al., 2003; Sanders and Hers, 2006; Brand et al., 2007; Mills et al., 2007; McAlary et al., 2009; Eklund et al., 2012; McHugh et al., 2012), there is a strong impetus to better quantitatively characterize vapor intrusion processes.

While the value of actually sampling subsurface volatile organic contaminant vapors has been realized in relation to fully understanding the problem, e.g. Suuberg et al. (2011), Eklund et al. (2012), and Yao et al. (2013a,b,c), rationalizing measured concentrations often presents difficulties e.g. Shen et al. (2013a,b). Vapor intrusion models (Turczynowicz and Robinson, 2007; Provoost et al., 2009) have been widely used in examining subsurface vapor concentrations. For example, some factors that have been hypothesized to influence subslab and soil gas vapor concentrations include those of spatial and temporal nature, such as the complexity of soil properties (Abreu and Johnson, 2005; Luo et al., 2009; Pennell et al., 2009), contaminant concentration gradients in groundwater (Little et al., 1992; Abreu and Johnson, 2005; Luo et al., 2009; Yu et al., 2009; Picone et al., 2012), contaminant source to building distance (Abreu and Johnson, 2005; EPA, 2012a; Yao et al., 2012a), temporal environmental changes (Little et al., 1992; DeVaull, 2007; Tillman and Weaver, 2007; Shen et al., 2012b).

When access is denied for subslab sampling, exterior soil gas sampling has also been suggested to be a useful part of the field investigations (ASTM, 1992; API, 2005; Pacific, 2009; EPA, 2012c). (a) In 2012, the U.S. Environmental Protection Agency (EPA) published a series of numerical simulation results, including some examples of the relations between soil gas and subslab vapor concentrations (EPA, 2012a,b) (this will be discussed in Section 3.2). It is generally believed that in the absence of reliable indoor air measurements, the subslab values might offer the best perspective on potential hazard from vapor intrusion. Unfortunately, there also remains considerable uncertainty in relating exterior soil gas

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0045-6535/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.chemosphere.2013.08.051

Nomenclature

c	contaminant vapor concentration (μg m^{-3})
c_0	open field ambient vapor concentration (μg m^{-3})
c_1	source vapor concentration in equilibrium with the groundwater (μg m^{-3})
c_{sg}	soil gas concentration away from the building (μg m^{-3})
c_{sg_B}	soil gas concentration at Point B (μg m^{-3})
c_{ss}	vapor concentration at the center of the subslab (μg m^{-3})
D^{eff}	the effective molecular diffusivity of contaminant in the water and gas phase (m^2 s^{-1})
D^{air}	diffusivity of contaminant in the air (m^2 s^{-1})
g	the acceleration due to gravity (m s^{-2}) acting in the vertical direction $\boldsymbol{z}$
k^{eff}	the effective soil gas permeability (m^2)
l	the vertical distance from the building slab to source (m)
l_0	source depth below ground surface (m)
$l_{basement}$	basement depth from the open ground (m)
l_{sg}	vertical distance from soil gas sampling point to source (m)
l_{slab}	thickness of the building slab (m)
p_g	the soil gas pressure (Pa)
q	the contaminant mass flux (μg m^{-2} s^{-1})
q_{crack}	the contaminant mass flux through crack (μg m^{-2} s^{-1})
u_g	the superficial velocity of soil gas (m s^{-1})
β	characteristic building footprint length (m), including any outdoor pavement
μ_g	the soil gas viscosity (kg m^{-1} s^{-1})
ρ_g	the soil gas density (kg m^{-3})
Ω	a function of β/l, defined in Eq. (8) (–)

contaminant concentration measurements to subslab contaminant concentration measurements.

In order to better understand the subslab contaminant vapor concentration c_{ss} in relation to other soil gas contaminant vapor concentration c_{sg} measurements, a short review of actual site data is useful. The U.S. EPA has assembled a database of field monitoring results. The paired subslab and exterior (meaning not subslab) soil gas concentrations, which have information regarding the soil gas sampling depths, are plotted in Fig. 1. Only chlorinated organic solvent data are considered here, in order to avoid complications due to possible biodegradation processes, which can affect hydrocarbon data. Most of the soil gas sampling points were located near the surface of the groundwater table. Also, all of the soil gas data were located at least 8 m horizontally displaced from the buildings that they were assigned to. These paired subslab and soil gas vapor concentrations are plotted as a function of the vertical distance of the sampling point to the groundwater surface (l and l_{sg} for subslab and other soil gas, respectively). As most of the points fall on the right side of this figure ($l/l_{sg} > 1$) this indicates that the subslab sampling probes were located at higher elevations than the corresponding soil gas sampling points. It is obvious that there is no simple relationship between the exterior and subslab values.

While all of the various environmental factors mentioned above may affect the subsurface vapor concentration, one of the most obvious factors that contributes to the differences between subslab and soil gas concentrations is the blockage or capping effect of the building foundation (or surrounding pavement, if any) on vapor diffusion to the atmosphere. This effect would generally push the subslab values to be higher than those at corresponding elevation not under a diffusional cap. But it is seen that there is no simple rule that governs these results. This points to the need to more formally analyze such results, taking into account the influence of several factors at a time. This is where numerical models are of great value. Unfortunately, they do not lend themselves well to simple screening of field data.

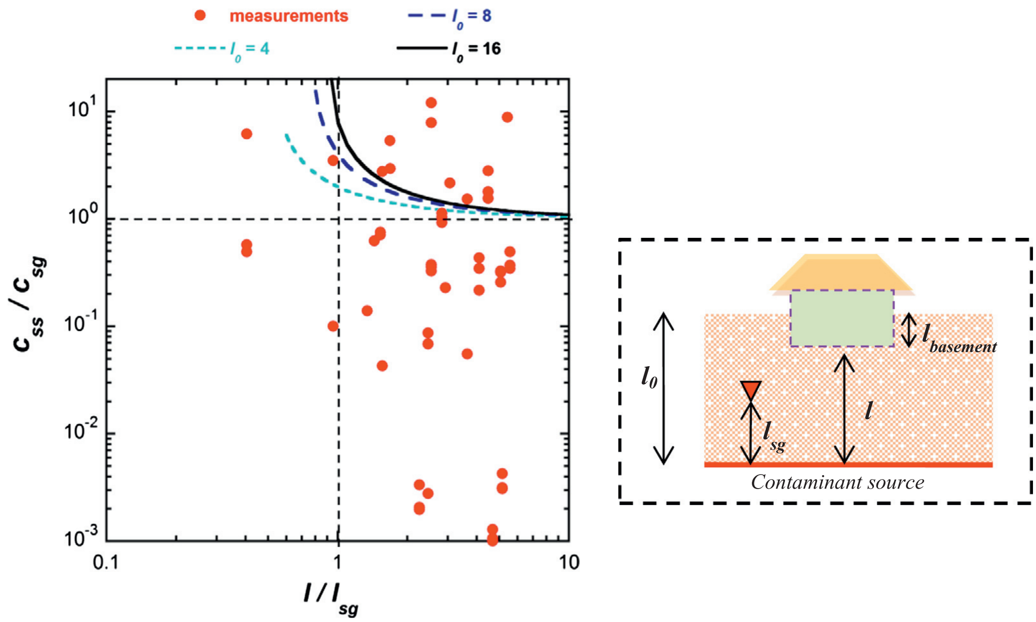

Fig. 1. Field data from the U.S. EPA database. Subslab vapor concentrations divided by the paired exterior soil gas vapor concentration, plotted as a function of the ratio of the vertical distances to source of subslab and paired soil gas sampling points. l represents the vertical distance from subslab to vapor source, while l_{sg} represents the vertical distance from soil gas sampling point to source. All plotted concentrations are above the reporting limits. A vapor intrusion schematic with parameters are shown.