Extinguishing Petroleum Vapor Intrusion and Methane Risks for Slab-on-ground Buildings: A Simple Guide

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Abstract
The occurrence of aerobic biodegradation in the vadose zone between a subsurface source and a building foundation can all-but eliminate the risks from methane and petroleum vapor intrusion (PVI). Understanding oxygen availability and the factors that affect it (e.g., building sizes and their distribution) are therefore critical. Uncovered ground surfaces allow oxygen access to the subsurface to actively biodegrade hydrocarbons (inclusive of methane). Buildings can reduce the net flux of oxygen into the subsurface and so reduce degradation rates. Here we determine when PVI and methane risk is negligible and/or extinguished; defined by when oxygen is present across the entire sub-slab region of existing or planned slab-on-ground buildings. We consider all building slab sizes, all depths to vapor sources and the effect of spacings between buildings on the availability of oxygen in the subsurface. The latter becomes critical where buildings are in close proximity or when increased building density is planned. Conservative assumptions enable simple, rapid and confident screening should sites and building designs comply to model assumptions. We do not model the aboveground “building” processes (e.g., air exchange), and assume the slab-on-ground seals the ground surface so that biodegradation of hydrocarbons is minimized under the built structure (i.e., the assessment remains conservative). Two graphs represent the entirety of the outcomes that allow simple screening of hydrocarbon vapors based only on the depth to the source of vapors below ground, the concentration of vapors within the source, the width of the slab-on-ground building, and the gap between buildings; all independent of soil type. Rectangular, square, and circular buildings are considered. Comparison with field sites and example applications are provided, along with a simple 8-step screening guide set in the context of existing guidance on PVI assessment.

Introduction
Background
Petroleum vapor intrusion (PVI) is a special case of broader vapor intrusion (VI) (Fitzpatrick and Fitzgerald 2002; Davis et al. 2009c; U.S. EPA 2012) because, compared to many chlorinated compounds, petroleum hydrocarbons, and methane readily degrade in the presence of oxygenated soil and groundwater conditions (Franzmann et al. 1999; Davis et al. 2005). Note that mono- and di-chlorinated hydrocarbons have also been shown to degrade aerobic ally (Davis et al. 2009a; Patterson et al. 2013). Johnson and Ettinger (1991) and a range of other efforts (Abreu and Johnson 2006; Yao et al. 2012, 2013) have parameterized VI models that are applicable to recalcitrant vapor compounds. While many have used the Johnson and Ettinger (1991) VI approach as a basis for PVI assessments, for aerobically degradable hydrocarbons where risks are more strongly mitigated, newer models and approaches have also been advanced (Lahvis and Baehr 1996; Trefy et al. 2001; Davis et al. 2005, 2009a, 2009b, 2009c; DeVaull 2007; Abreu et al. 2009; Lahvis et al. 2013; Verginelli et al. 2016b; Lahvis 2018; Ma et al. 2020).

For regulatory consideration, compilations of data have been used to identify vapor attenuation factors (Johnson and Ettinger 1991) based on the ratio of the vapor concentrations observed inside buildings to that measured in soil and close to the source of vapor threat to buildings (e.g., U.S. EPA 2014). Attenuation was observed to be more substantial for petroleum vapors compared to chlorinated vapors (U.S. EPA 2012, 2014; Lahvis 2018). Exclusion distances (vertically and laterally), being the distance between a vapor source and buildings (e.g., human receptors), have been utilized as part of screening criteria for VI (Lowell and Eklund 2004) and for PVI (CRC CARE 2013; Lahvis et al. 2013) assessments. Exclusion distances used for screening PVI sites have been developed for both groundwater plumes (dissolved) and nonaqueous phase liquid (NAPL) petroleum sources of vapors (e.g., CRC CARE 2013).

Specific national guidance on PVI (Friebel and Nadebaum 2011; CRC CARE 2013; Interstate Technology and Regulatory Council [ITRC] 2014; U.S. EPA 2015) has in
part included consideration of the aerobic biodegradation of petroleum vapors to mitigate risks. In particular, the PVI risk has largely been shown to be negligible provided sufficient oxygen is present for aerobic biodegradation to occur between a source of hydrocarbon vapor in the subsurface and a building foundation. Understanding oxygen transport in the vadose zone and the factors that affect it have thus become a strong recent focus (Patterson and Davis 2009; Abreu et al. 2013; Knight and Davis 2013; Verginelli et al. 2016b).

There is a need for screening models for PVI assessments, that are simple, conservative and have a minimal set of variable parameters but (1) are inclusive of the biodegradability of petroleum and hydrocarbon compounds, (2) consider the footprint of buildings at ground surface in altering oxygen availability in the subsurface, (3) consider the influence of multiple (adjacent) buildings, (4) have wide applicability across fuel types, and (5) consider methane as a source of risk. We bring these aspects together here.

Yao et al. (2013) provides a good summary of VI models incorporating biodegradation; applicable to petroleum hydrocarbons. A range of modified codes and approaches (e.g., Biovapor, PVIScreen, and PV12D) have been published (DeVaull 2007; American Petroleum Institute 2010; Weaver and Davis 2016; Verginelli et al. 2016a). While these and an increasing number of PVI models link oxygen transport and consumption to that of hydrocarbon vapors (e.g., Abreu et al. 2013), few have focused on oxygenation of the subsurface building foundation area as a primary means of screening PVI sites, apart from the efforts of Knight and Davis (2013) and Verginelli et al. (2016a, 2016b). Most modeling approaches continue to model aboveground building features and building imperfections (air circulation, stack and wind effects, cracks in foundations, and the like) which entails complexity and requires a large number of parameters to be estimated. All approaches other than those of Davis et al. (2009b) and Knight and Davis (2013) also utilize finite degradation rates and as such typically screen sites based on petroleum vapor concentration criteria. By applying an instantaneous degradation rate approach, and ensuring oxygen concentrations are reduced (consumed) during biodegradation by all sources of hydrocarbon vapors (inclusive or methane) the two-dimensional (2D) modeling approach of Knight and Davis (2013) allows screening to focus on the availability of oxygen in the subsurface beneath slab-on-ground buildings. This eliminates the biodegradation rate as a variable parameter. Verginelli et al. (2016a, 2016b) and Abreu et al. (2013) both indicate that the biodegradation rate plays a limited role in PVI risk variations.

Knight and Davis (2013) and Verginelli et al. (2016a, 2016b) depicted 2D depth cross sections and, as such, outcomes represent those for infinitely long buildings. Abreu and Johnson (2006) reported three-dimensional (3D) simulations and Abreu et al. (2013) evaluated the influence of different dimensions of the footprint of buildings in considering rectangular and square buildings (from 10 × 10 m slab size to 632 × 632 m as an extreme case). To date, no screening models consider the effects of adjacent buildings on PVI risks. Typical assessments (e.g., Abreu et al. 2013) assume that beyond the edge of the slab there is an infinitely wide ground surface domain that is open to the atmosphere as in Figure 1. No assessment has been undertaken to quantify the role of the size of gaps between buildings in sustaining or limiting oxygen transport beneath buildings.

Further Motivation for the Approach

Simple screening approaches have universal appeal, because of their ease of use and their potential for eliminating costly and unnecessary additional invasive PVI investigations. But such approaches need to be based on robust scientific evidence. Here we suggest such is possible for PVI screening based on a limited range of generally known site parameters.

VI models such as that of Johnson and Ettinger (1991) require greater than a dozen input parameters including air exchange rates, building air volumes, building foundation parameters (including crack dimensions and diffusion coefficients, soil and/or crack permeabilities), advective air inflow rates through the foundation and a range of soil parameters including diffusion coefficients. This extensive list of parameters has been further expanded in PVI assessments where biodegradation has been accommodated to include sorption, biodegradation rates and diffusion coefficients for not only petroleum vapors but also oxygen as they react and migrate in soils (Abreu et al. 2013). While thorough, the range of parameters challenges ease of use, costs, accuracy, and risk sensitivity undertakings, and even though the investigations are substantial, all simulations are done for individual soil types, for example, sandy and silty clay soils in Abreu et al. (2013).

Here we present a simple-to-apply, robust and conservative approach with minimal parameters that allow a screening assessment of most slab-on-ground PVI sites, regardless of soil type. Three key variable input parameters proposed here are the slab width, the depth to the source of petroleum vapors below ground surface and the concentration of vapors in that source, and a fourth parameter is the lateral separation distance between slab-on-ground buildings if they are

![Figure 1. Conceptualization of the slab-on-ground model scenario after Knight and Davis (2013); top right is a planar graphic depicting a square/circular slab foundation. Not shown is the additional scenario of another slab-on-ground building of size $2a$ with its closest edge at a distance $x = a + 2g$ away from the half slab-on-ground building depicted.](Image 307x117 to 541x274)
close to each other. The latter is to allow determination of the minimal separation distance between slab-on-ground buildings that ensure no change in the oxygen penetration (i.e., oxygen shadow) beneath individual buildings.

Our approach is not to attempt to predict indoor air concentrations or even connect the subsurface to indoor air. We simply estimate the region of the sub-slab of a slab-on-ground building that is entirely oxygenated, or has an oxygen shadow if oxygen is depleted by petroleum biodegradation processes. As such our model and approach does not need the soil porosity or soil moisture content, a finite degradation rate, an assumed air exchange rate in the building nor the building volume, a perimeter crack and its width in the concrete, a pressure differential between the under-slab and the building, a diffusion coefficient within the crack, a slab thickness, a soil permeability, nor other parameters.

The shortened list of parameters enjoins greater agreement between industry, regulators and other stakeholders as to what parameter ranges are valid and indeed allow more rapid screening of PVI sites. This also allows two simple graphs to be used to screen sites for potential vapor incursion into existing buildings, or those to be potentially built on a site; that is, no additional modeling is required to apply the outcomes.

In the second section, we outline the technical framework and assumptions and previously unpublished technical advances. The third section has the key results for different building shapes and gap widths between building slabs. The fourth section provides applications to screening sites and step by step guidance. The fifth section concludes with commentary around key assumptions and limitations.

Technical Overview, Assumptions, and Parameters

The basis of the approach is fundamental work undertaken and reported in Davis et al. (2009b) and Knight and Davis (2013) and complementary new work presented here to assess the entire effects of the finite dimensions of the slab-on-ground footprint, and also the effects on subsurface oxygen and vapors of the separation distance between buildings.

Technical Framework and Key Assumptions

Our argument based on Davis et al. (2009b) is that if oxygen is present at concentrations sufficient to support aerobic biodegradation under a building foundation, then the risk from hydrocarbons (including methane) is negligible and likely extinguished. This is because Davis et al. (2009b) showed that oxygen and hydrocarbon vapor data were consistent with a rapid biodegradation rate with minimal overlap of oxygen and vapor concentrations across a range of field sites — i.e., the degradation rate was limited by transport rates of oxygen and hydrocarbon vapors to the location of biodegradation (and mass consumption). They formalized it in an instantaneous modeling approach which approximates such conditions and dismisses the need for a choice of degradation rate or half-life.

Transport in Davis et al. (2009b) was only via diffusion. There is much debate and investigation as to the importance of methanogenesis related to anaerobic biodegradation of petroleum hydrocarbons, because (1) methane biodegradation is a sink for oxygen in the vadose zone, and (2) methanogenesis is a potential mechanism for inducing pressure differentials in the vadose zone and hence advective movement of gases and vapors. Methanogenesis may be more dominant for large volume spills (Molins et al. 2010), for ethanol rich spills (Ma et al. 2014) or where anaerobic groundwater and soils already exist (Barber et al. 1990). Molins et al. (2010) indicated that methanogenesis at their crude oil site can induce advection close to the source zones, but also showed that oxygen flux exceeded net oxygen demand due to methane biodegradation at the site. Sihota et al. (2013) also noted the extended circumstances required for methane hazards to eventuate that is, that “the development of such hazards is locally constrained, will require a high degree of soil moisture, close proximity to the source zone, a good connection between the soil and the confined space, and poorly aerated conditions.”

Here we assume advective influences are limited, but that oxygen demand is the total biodegradation demand for all vapors emanating from the petroleum source either as volatile organic components of the petroleum source but also inclusive of all degradation and mineralization products (including methane). Included in Table 1 are field sites where methane was the dominant risk and sink for oxygen (e.g., Lundegard et al. 2008).

Knight and Davis (2013) extended the approach of Davis et al. (2009b) to specifically consider the effects of a slab-on-ground building construction in reducing the overall flux of oxygen into the subsurface (Figure 1) whereby oxygen ingress to the subsurface was only assumed to occur beyond the edges of the slab and effectively the slab was assumed to be impervious (cf. Patterson and Davis 2009). This is in contrast to open ground conditions whereby oxygen ingress would be assumed to enter freely through the ground surface as in Davis et al. (2005, 2009b) or where diffusion of oxygen through the slab is allowed (Verginelli et al. 2016b). The model of Knight and Davis (2013) allowed assessment of the slab-on-ground width that may have generated conditions for vapor (or methane) accumulation beneath the slab, and hence generate a nonzero risk of vapor migration to the interior of a slab-on-ground building. Conversely, the model provided estimates of when oxygen would be everywhere beneath a slab of certain width (or less) and hence when risk would be negligible. The results were depicted as a function of the half slab width (1), the depth to the source of vapors (2) and the maximum hydrocarbon vapor concentration in the source (h_r) (Figure 1).

The model of Knight and Davis (2013) is considered conservative for four main reasons:
1. The model assumed an infinitely extensive and constant subsurface vapor source over all time and sought a steady state solution.
2. The instantaneous rate approach consumes oxygen at a maximum rate and hence predicts least oxygen under a slab.
3. The slab was assumed impervious and hence did not allow oxygen diffusion through the slab itself (cf. Patterson and Davis 2009; Verginelli et al. 2016b), and did not allow advection migration of oxygen through cracks or via pressure gradients across the foundations of the slab.
### Table 1

Petroleum Vapor/Methane Studies Under Buildings or Covered Ground Conditions (modified after Knight and Davis 2013)

| Study            | Slab Size (m × m)   | Half Width of Slab (a) (m) | Depth to Vapor Source (b) (m) | Maximum Vapor Concentration (h_s) in Source (μg/L) | a/b | Vapor Immediately Under Slab |
|------------------|---------------------|----------------------------|-----------------------------|-----------------------------------------------|-----|-----------------------------|
| Hers et al. (2000) | 6.1 × 9.3           | 3.05                       | 1.5                         | 11,000                                        | 2.0 | No                          |
| Davis et al. (2001) | 13.3 × 15.2 (ground cover) | 6.65                        | 2.25                        | 50,000-70,000                                | 3.0 | Yes                         |
| Ririe et al. (2002) | 49 × 98 (asphalt cover)    | 24.5                       | 3.05                        | ≥40,000                                      | 8.0 | Not at 13.2 m in from an edge |
| Sanders and Hers (2006) | 6.9 × 10.3, 8.3 × 6.6, 15.2 × 8.3, 9.7 × 8.6, 13.8 × 9.7 | 3.45                      | 1.6 (basement) to 3.3 (slabs) | 12,000 (basement)                            | 2.2 | Maybe                       |
| Lundegard et al. (2008) | U shaped building with minimal width of 6.8 m | 3.4                              | 1.8                        | 66,000-85,000 (10-13%, v/v methane)          | 1.9 | No                          |
| Patterson and Davis (2009) | 13.5 × 18            | 6.75                       | 2.25                       | 47,000                                       | 3.0 | Yes                         |
| Luo et al. (2009) | 14 × 15              | 7                           | 0.15-1.37                  | 110,000                                      | 5.1-47 | Yes                        |
| DeHate et al. (2011) | 36 different types of buildings | Variable                     | 0-7.5 m                    | Not determined                               | —   | Yes                         |
| Jayasinghe and Heggie (2012) | 15 × 20 to 43 × 53 (8 sites) | 7.5-21.5                   | 2.5-8.0                    | Not available                                | 2-8.6 | No (yes for one site)        |

1. Most estimated as half of the narrowest slab dimension.
2. “Vapor” here means all hydrocarbons inclusive of methane.
3. Observed in the study immediately beneath the underside of the slab or covered region.
4. No source concentration data are available.

Building (e.g., Fischer et al. 1996; McHugh et al. 2006; DeVaull 2007). This assumption provided a minimum oxygen flux that would be consumed per mass of hydrocarbon consumed during aerobic biodegradation of vapors.

4. The slab was assumed to be one dimensional, that is, it was assumed infinitely long in one dimension and a finite width in the other. As such, no oxygen diffusion through the ground surface along the longitudinal dimension of the building edge was accounted for, leading to reduced oxygen flux beneath the slab compared to realistic building configurations with a finite length.

As such the model was devised to correspond to the minimum oxygen penetration beneath the slab foundation and as such the minimum petroleum vapor (and methane) biodegradation that is likely to occur, or the maximum potential for petroleum vapors to migrate from a subsurface source to close to the base of the building slab while still allowing oxygen-limited aerobic biodegradation of the petroleum vapors to occur (i.e., to provide conservative outcomes).

### Consideration of Finite Length and Width Slab-on-Ground Buildings

There are a myriad of building shapes and dimensions, with most (see Table 1) approximating a rectangle in shape. The infinitely long rectangular slab of Knight and Davis (2013) equates to the minimum flux of oxygen to the sub-slab region for a rectangular shape. For a “rectangular shape,” with the same model assumptions, collapsing the length scale, 2L, to be equal to its width 2a, creating a square slab-on-ground building provides the case for the maximum oxygen flux beneath a “rectangular” slab. This is because a square has the maximum perimeter length per area of slab for any rectangular shape.

Theoretically, the geometric configuration that would allow maximum oxygen diffusion flux beneath the edge of a slab-on-ground slab would be circular. A square and circle, as per the depiction in Figure 1, have the same perimeter length to surface area ratio of 2a, but a circular slab is the shape with the minimal distance from any part of the edge of the slab to the center point of the slab.

In this paper, we extend the 2D (depth and width) model of Knight and Davis (2013) to account for the 3D behavior of vapor and oxygen due to accommodating not only the finite width but also the longitudinal dimension of slabs. This relaxes the otherwise conservative condition described earlier (infinitely long slabs) and yet still preserves the other conservative elements of the model.

As in Knight and Davis (2013), we modeled the diffusion of vapors from an infinitely extensive and constant vapor source below ground (Figure 1). Oxygen is assumed to diffuse downward from the ground surface where the oxygen concentration is held at atmospheric oxygen concentration wherever the surface is not covered by the building slab. The building slab is considered impervious, to minimize oxygen ingress and thus establish conservative criteria for vapor biodegradation relative to the size of a building footprint.

The governing equations and dimensionless parameters for the 3D and radially symmetric cases are given in the Appendix and follow the framework of Knight and
Davis (2013). The equations were approximated by the method of finite differences. The resultant difference equations were solved iteratively using the successive over relaxation computational method.

To validate the computational method, the results of the finite difference approximation were compared to their analytical solutions for the value of \( \psi(x, y) \) at the surface under the slab. Grid sizes were also refined to ensure no changes in estimates. At a grid size of \( \Delta x = \Delta y = \Delta z = 0.02 \) and a solution region with a maximum value of \( x \) and \( y \) of 6.0, results were largely indistinguishable for estimates of values at field scale.

The Effect of Adjacent Slab–on–Ground Buildings

An additional key consideration is the separation distance between buildings and if slab-on-ground buildings that are in close proximity to each other may reduce the potential for oxygen to be transported beneath the buildings. We sought to determine the minimal lateral separation distance between slab-on-ground buildings that would ensure no change in the oxygen penetration (i.e., oxygen shadow) beneath individual buildings. This is particularly relevant where cities are driving infill programs with smaller blocks of land and sizable dwellings adjacent to one another, or for sizable commercial premises that are adjoining.

A gap of width \( 2g \) was simulated between two slabs of equal slab width \( 2a \) with repeated gaps beyond the edge of those slabs. In essence it depicts a periodic slab-gap-slab-gap feature across the ground surface. The slabs and gaps are all infinitely long. The only access for oxygen to the subsurface under the two slabs was then via the gaps of width \( 2g \). All other aspects of the conceptualization as depicted in Figure 1 are assumed the same (i.e., infinitely extensive and constant source of vapors at depth \( b \), instantaneous reaction of oxygen with vapors at the aerobic/anaerobic interface, etc.). Details of the mathematical approach can be found in Knight et al. (2021).

After formulating the equations in a similar way to that described in the Appendix, we were able to generate an analytical solution to this problem in terms of Complete Elliptical Integrals \( K(m) \) (for details see Knight et al. 2021). Complete Elliptical Integrals can be found in Abramowitz and Stegun (1972). In particular, for example, the total nondimensional flux through a gap of width \( 2g/b \) becomes \( 2K[\tanh(\pi g/2b)]/K[\text{sech}(\pi g/2b)] \); where \( \tanh \) and \( \text{sech} \) are Hyperbolic Functions.

Key Parameters

As mentioned previously, only four variable parameters are needed to undertake the modeling and screening assessment proposed here—

1. the slab width \( 2a \),
2. the depth to the source of vapors/methane below ground surface \( b \),
3. the hydrocarbon vapor/methane concentration within the vapor/methane source \( h_0 \), and
4. the lateral distance (or gap) between adjacent slab-on-ground buildings \( 2g \).

The slab dimensions are assumed known from measurement or intended plans for buildings (see later discussion), as is the actual or intended gap between buildings \( 2g \). As with any typical PVI assessment, estimation of the depth of the source \( b \) and the peak concentration \( h_0 \) coming from that source is needed. The peak concentration \( h_0 \) can be estimated from groundwater concentrations, from petroleum NAPL partitioning calculations, or via direct measurement of vapor and methane concentrations near to the source zone in the field.

Using the instantaneous rate approach allows us to neglect the need for a choice of degradation rate or half-life. The stoichiometry coefficient \( \gamma \) for mass consumption of oxygen relative to typical hydrocarbons is taken as 3.1 (DeVaul 2007). The concentration of oxygen in the atmosphere \( (c_\infty) \) is also fixed and taken as 2.79E+5 μg/L (Davis et al. 2009b).

The outcomes are valid for all types of soils. This is shown to be true in the Appendix (Equation A3), which shows that the solution to the equations is a ratio of the diffusion coefficient for petroleum hydrocarbon vapors in the soil gas phase to the diffusion coefficient for oxygen. Thus, all aspects of soil porosity and soil moisture cancel each other out and we are left with the ratio of the diffusion coefficients for petroleum hydrocarbon vapors and oxygen in free air (i.e., free of soil properties). The diffusion coefficients in air for oxygen \((2.01E^-5 \text{ m}^2/\text{s})\) and hydrocarbon vapors \((8.0E^-6 \text{ m}^2/\text{s})\) are based on Gliński and Stepniewski (1985) and Grathwohl (1998) respectively.

Results and Discussion

A key determinant for screening of a site is if vapors are present and in immediate contact with the sub-slab region of a building or conversely if oxygen is available over the entire subsurface of the slab structure. If oxygen is present at the center point of the building slab (as in Figure 1), then oxygen will be present at even higher concentrations across the sub-slab region. These conditions can be used as a basis to develop exclusion criteria. Another determinant is that nearby buildings are not so close as to impinge on net oxygen flux through the ground surface and as such alter “single” building considerations.

Results for Finite Length (and Width) Buildings

Here we include calculations for both the infinite rectangular slab of Knight and Davis (2013) and the square slab — these two bound all possible rectangular building slab geometries. For completeness, a rectangular slab-on-ground building with a length twice its width was also simulated, but it showed little difference to the infinite long slab case of Knight and Davis (2013).

Figure 2 shows results from Knight and Davis (2013) and for the square and circular slab footprint. For these configurations, because the parameter \( 2a \) encompasses both the width and length scales, it is possible to depict all three configurations in the one graphic. Below and to the left of all lines in Figure 2 oxygen is predicted to be present everywhere beneath the slab, that is, vapors are predicted to be excluded from contact with the under surface of the slab by the boundary between the oxygen and vapors (as in Figure 1) being at the center point of the slab. As such, with this
combination of parameters, vapor inhalation and methane risks would be deemed to be negligible and the site screened out from further investigation. Contrariwise, sites that lie to the right of the lines would be screened in for possible further investigation. As expected, the square and circular slab predictions are further to the right and, for all values of \( a/b \), source vapor or methane concentrations that can be biodegraded by the available oxygen are higher.

Abreu et al. (2013) considered a range of slab sizes and source concentrations for three depths to the vapor source (1.6, 4.6, and 9 m). They found for a vapor source of 10,000 \( \mu \text{g/L} \) an oxygen shadow (depleted oxygen zone) was formed for slabs \( \geq 10 \times 10 \text{ m} \) for a source at 1.6 m deep (\( a/b \geq 3.1 \)) and for slabs \( \geq 30 \times 30 \text{ m} \) for a source at 4.6 m deep (\( a/b \geq 3.3 \)) — this is comparable to that shown in Figure 2, although Figure 2 might suggest no oxygen shadow at \( a/b \leq 2.8 \) (i.e., a slightly smaller slab size or a deeper vapor source). In contrast, for a vapor source of 100 \( \mu \text{g/L} \) at 1.6 m depth no oxygen shadow was estimated by Abreu et al. (2013) for any slab size up to \( 632 \times 632 \text{ m} \) (\( a/b = 198 \)), whereas in Figure 2 an oxygen shadow would still be expected for any \( a/b \) greater than approximately 7 for a vapor source concentration greater than 10 \( \mu \text{g/L} \). Abreu et al. (2013) assessments are also somewhat time-dependent with oxygen (depletion) shadows not apparent at earlier times for some values of \( a/b \) but transitioning to being depleted and creating an oxygen shadow at later times. For example, for a source of 1000 \( \mu \text{g/L} \) at a depth of 4.6 m no oxygen shadow is calculated up to 20 years of simulation for slabs sizes of \( 120 \times 120 \text{ m}, 200 \times 200 \text{ m}, 240 \times 240 \text{ m}, \) or even \( 632 \times 632 \text{ m} \), but continuing the simulation to 50 years shows an oxygen shadow for a slab \( 120 \times 120 \text{ m} \). This would imply that indeed an oxygen shadow would eventuate at all slab sizes greater than \( 120 \times 120 \text{ m} \) at later times and indicate that the assessment at earlier times (or at least up to 20 years) is not a conservative approximation of risk. Here our results are at steady state and determine long term risk and oxygenation of the subsurface.

**Results for Gap Sizes Between Buildings**

Figure 3 shows results for the gap calculations for three primary \( g/b \) values, compared to the infinite rectangle case (Model line) which in essence has infinite gaps on either side of its slab. Somewhat counter intuitively the effect of even a small gap between buildings does not seem to have a significant effect on the potential for oxygenation of the sub-slab region. For \( g/b = 0.1 \) (i.e., the half gap width is 10% of the depth to the source of vapors) for all \( a/b \), there is little variation from the “Model” line which assumed an infinitely wide gap at the edge of its slab. As \( a/b \) increases to say 5, the \( g/b = 0.1 \) line all but coincides with the “Model” line. This can be explained by considering that for larger slab sizes oxygen is only everywhere under such slabs if vapor concentrations are lower. In essence, reducing the gap size has little effect as oxygen is already significantly restricted from accessing the entire width of the sub-slab due to the large slab size itself. For smaller slab sizes, oxygen ingress is greater across the entire width of the sub-slab even for higher vapor source concentrations. As such, reducing the gap width generates a slightly greater influence on the oxygen ingress at low \( a/b \) ratios (see, e.g., \( a/b = 1 \) or 2 in Figure 3).

Very small gap widths were simulated for \( a/b = 2 \) (see inset in Figure 3). For an infinitely wide gap oxygen is everywhere under the slab if the source concentration is maybe 15,000 \( \mu \text{g/L} \) or less, whereas for \( g/b = 0.1 \), oxygen is everywhere under the slab if the source concentration is approximately 10,000 \( \mu \text{g/L} \), or less, and for \( g/b = 0.01 \), oxygen is everywhere under the slab if the source concentration is 7260 \( \mu \text{g/L} \) or less. So, for a very small gap (i.e., \( g/b = 0.01 \)) at \( a/b = 2 \) the source vapor or methane concentration able to...
be fully consumed by oxygen biodegradation decreased by approximately 50% (i.e., 15,000 compared to 7260 μg/L). For a source at 2 m depth, to create this reduction of 50% the gap width would be 4 cm for a slab 8 m wide. For a one-third reduction (from 15,000 to 10,000 μg/L for g/b = 0.1) the gap width would be 40 cm for a slab 8 m wide.

Application to Screening PVI Sites

Comparison to Field Data

Data from several field sites are depicted in Figure 2. The sites are biased to published data and as such are sites with greater probability of showing impact from vapor (including methane). The Hers et al. (2000) site would be screened as having oxygen everywhere beneath it (its data point is below the lines), and indeed showed no vapor accumulating under the slab. Despite the shallow source (1.5 m) and modest peak concentration, it had the smallest slab half width.

For the Lundegard et al. (2008) house even though it also has a narrow half width, its data point lies above all lines in Figure 2. This house would then be screened as potentially not having oxygen everywhere under the house and hence having PVI potential (in this case methane). Despite this Lundegard et al. (2008) report no methane under the house. Even the “Square” slab line in Figure 2, remains below the location of the Lundegard et al. (2008) house data point. This may be for several reasons, including the U shape of the house which provides a mixture of access points and edges that may deliver more oxygen under the house; or oxygen may be exchanged through the slab via advection of diffusion. Measurement points are reasonably extensive but even so, methane may have been present where measurements were not possible to take. From a conservative point of view, that it would be screened in for further investigation (rather than screened out as of no risk) may be reasonable given that 10-13% (v/v) methane is the vapor source concentration at a depth of only 1.8 m below the house slab.

The other field sites have reasonably large slab dimensions and relatively high source concentrations at a maximum of 2.25 m below ground, and as such their data points lie above the lines in Figure 2. This concurs with the observations of vapor being observed under the slabs at all these three sites. Interestingly, the Ririe et al. (2002) site has an a/b of about 8 and a considerable vapor source concentration (Table 1), so lies above all lines in Figure 2 (and off the scale depicted). Despite this they showed oxygen present immediately below the asphalt covered surface at a monitoring point 13 m away from the edge, but oxygen was depleted relative to atmospheric at about 8% (v/v) at 0.15 m below ground surface. In this case oxygen was continuing to migrate via access pathways to beneath the asphalt covered area.

Some Explicit Examples and Comparison to Screening Distances

Figure 4 annotates Figure 2 including some typical slab dimensions and depths and some typical maximum vapor concentrations that may be associated with fresh gasoline, diesel and mineral oil (e.g., heavy fuel oils, automotive and lubricating oils) (CRC CARE 2013). As indicated for a fresh gasoline (approximate maximum vapor concentration of 100,000 μg/L), for oxygen to be everywhere beneath a slab typically a/b is approximately 1, which means for shallow sources oxygen is unlikely to be everywhere under a slab unless it is a very small slab size. However, for deeper sources at 5 m or greater, a slab size of 10 m would still show oxygen everywhere beneath the slab. For a fresh diesel (approximate vapor concentration of 8000 μg/L), a slab size of 10 m is screened out from further investigation as having oxygen everywhere under the slab as long as the source is 2 m or greater below ground. A 20 m slab would also be acceptable if the source was 4 m or greater below the base of the slab. A mineral oil source (approximate vapor concentration of 700 μg/L) might pose little risk for large slab-on-ground buildings with quite shallow sources. Despite being able to screen out a 10 m slab with a source at 1 m, having a source of vapors at 1 m below a building may be unacceptable for other reasons such as being in the shallow zone of potential preferential pathways such as utility (water, gas, electrical, sewerage) conduits.

We briefly compare the separation distances estimated here against those developed by others or those in guidance. Modelling undertaken by Abreu et al. (2009) showed that oxygen concentrations in the unsaturated zone were relatively unaffected by benzene vapor sources of less than 10 mg/L (10,000 μg/L) located 3 m or more distant (i.e., depth) from building foundations. This concurs with results in Figure 4 but only for rectangular slabs with half-widths of 6.75 m or smaller (i.e., ≤13.5 m wide slabs), or ≤16.5 m along each edge if a square slab building. This is calculated by moving across from the 10 mg/L concentration on the y axis of Figure 4 until intersecting the line for the rectangular or square building and dropping down to the x axis to find a/b ≈ 2.25 (rectangle) and 2.75 (square). Multiplying these values by the depth of 3 m gives these slab sizes.

Lahvis et al. (2013) indicated that “Aerobic conditions are generally observed at distances more than 13 ft (4 m) above LNAPL sources.”. Davis et al. (2009b) supports this...
for open ground conditions, but where a slab is present the current analysis (Figure 4) only supports this for slab widths of less than 8 m if the NAPL is gasoline, 20 m if a diesel NAPL and between 30 and 40 m for mineral oil NAPL. As pointed out by Verginelli et al. (2016b), where oxygen diffusion through the concrete slab is ignored then simple exclusion distances devoid of consideration of building footprint (slab) sizes do not universally account for oxygen availability nor hydrocarbon biodegradation. However, where there is confidence that diffusion through a concrete slab is occurring, then exclusion distances devoid of consideration of building footprint (slab) sizes may be applicable.

CRC CARE (2013) cautions, for NAPL sources and for large slab buildings with greater than or equal to 7.5 m half width, that the screening distance (i.e., depth to vapor source) of 8 m should not be used. This paper extends the range of slab sizes and screening distances that may be considered. As shown in Figure 4, for an 8 m depth to the vapor source a slab width of greater than or equal to 16 m would still have oxygen everywhere beneath it even if sited above a fresh gasoline NAPL release (see \(a/b\) = 1 in Figure 4).

### Screening Steps

Figures 2 and 3 provide the primary information to undertake a PVI/methane screening process at petroleum impacted sites. Based on these outcomes and the results described, we outline a series of steps for undertaking a screening assessment of PVI sites (i.e., when PVI and methane risks would be negligible):

1. As with all such assessments, determine whether the presence of certain conditions preclude site screening (e.g., an intensity of shallow preferential gas transport pathways such as utility conduit or trenches; highly heterogenous soil/rock formations; extremely shallow or highly variable water tables). If so, do not use this or other screening techniques, as further investigation may be required, especially if source zones are shallow. See CRC CARE (2013), ITRC (2014) or other guidance for typical exemptions.

2. From preliminary site investigations and/or prior knowledge determine or estimate the depth to the vapor/methane source \(b\), and the likely maximum hydrocarbon gas-phase concentration (including vapors and methane) at that depth \(h_0\).

3. Determine from your current or future building plans the dimensions of typical buildings to determine the slab width \(a\) and the likely spacing \(g\) between building slabs.

4. Calculate \(a/b\) and \(g/b\), then determine using \(h_0\) from Figure 3 if the oxygen distribution is affected by the proximity of an adjacent slab-on-ground building.

5. From the values of \(a/b\) calculated in Step 4 and using \(h_0\), place the data point in Figure 2 to see if oxygen would be everywhere beneath the slab-on-ground building (i.e., the data point lies below the lines on the graph). If the building is approximately square the assessment could be made against the “Model-square” line.

6. If adjacent buildings have no effect at Step 4 (which is likely), and the data point lies below the line at Step 5 then the site could be screened out for risk and not require further investigation.

7. If adjacent buildings have some effect at Step 4, and the data point lies below the line at Step 5 further consideration of the size of the effect at Step 4 may be warranted using Figure 3.

8. Regardless, if the data point lies above the line at Step 5, further consideration of PVI/methane risk at the site may be warranted and further consideration of screening via the CRC CARE (2013) decision pathway or other guidance may be the next step.
Note that if the slab size is of potential importance, this does not automatically mean there is a risk to occupants in buildings, only that there is potential for biodegradation of vapors and methane to be limited beneath some parts of the building and further investigation may be warranted. As in Patterson and Davis (2009), despite oxygen not being everywhere beneath the building they studied, oxygen was apparent across more than 80% of the under-slab area, with vapors only in contact with the sub-slab toward the middle of the building. This, in itself, mitigates a significant amount of the PVI risk. Additionally, Verginelli et al. (2016b) and Patterson and Davis (2009) noted the likelihood of additional oxygen diffusion through concrete slabs, further mitigating vapor risks.

Conclusions

A simple conservative PVI/methane screening approach, for application across broad field conditions where either buildings are present or are planned, has been made possible by combining previous and newly presented outcomes. The premise is that wherever oxygen is present beneath slab-on-ground buildings the risk from petroleum vapors and methane is negligible (and perhaps extinguished) due to their aerobic biodegradability (Davis et al. 2009b; Knight and Davis 2013). Based on field data and analytical and numerical solutions to one-, two- and three-dimensional models, we provide two simple graphical representations to assess if oxygen is present everywhere beneath slab-on-ground foundation buildings, and also consider any limiting effects on oxygen movement into the subsurface due to the proximity of adjacent slab-on-ground buildings. The applicability of the approach is outlined, and a simple eight step guide is provided on the screening of PVI/methane risks at sites.

For the assumptions inherent in the model no rerunning of the model is required. Because the model excludes consideration of the built structure aboveground (inclusive of air exchange rates, cracks in foundations, pressure differentials etc.), apart from the dimensions of the slab footprint and the gap between slab-on-ground buildings, all results depend simply on the depth below ground surface to the source of vapors/methane, and the maximum vapor/methane concentration in the source. As such the outcomes effectively span all slab dimensions and depths to sources across the range from low vapor/methane source concentrations to those found in contact with fresh gasoline. Similarly, the outcomes are valid for all soil types not just a few. As such all results are depicted as a simple set of graphics for all circumstances (except where soil heterogeneity and subsurface structures would obviate such a screening approach). Note that the outcomes are not valid for buildings with basements or crawl spaces.

All results assume homogeneous soils and soil moisture and that steady state conditions apply. This is common across most screening models, although Abreu et al. (2013) use a transient model approach which is less conservative where oxygen consumption via biodegradation has not stabilized. Where variations from such conditions occur then further investigation may be warranted. Additionally, the model assumes that oxygen consumption is only driven by the presence of degradable vapors (including methane), not other sinks for oxygen such as organic carbon or sulfide minerals (Davis and Ritchie 1986; DeVaull 2007).

To maintain a conservative approach, we assume the building footprint is an impervious slab (cf. Verginelli et al. 2016b). Simplistically, this could be viewed as posing no risk since vapors cannot move through an impervious surface. The intent is not to avoid risk in this way, but to establish the conditions for minimal oxygen availability while accounting for building footprint size — to ensure conservative regulation and simple screening of sites is possible. For larger slab sizes, there may be more potential for oxygen to diffuse or be advected through the slab itself, as cracks and defects may arise.

Note too that assuming a depleting (transient) NAPL or groundwater vapor source, or a finite length source, or a source laterally offset from the building would yield lower potential vapor risks, and hence a less conservative outcome. These variants could also be accommodated in a Tier 2 assessment rather than the screening assessment proposed here. The longevity of NAPL or groundwater as a source of vapors and/or methane is being tackled via natural source zone depletion (NSZD) studies (e.g., Sookhak Lari et al. 2019).

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Appendix: Mathematical Formulation and Approach to the Finite Length and Width Slab Effects

Conceptualization and Model Set-up

As in Knight and Davis (2013), we modeled the diffusion of vapors from an infinitely extensive and constant vapor source at depth \( b \) below ground surface (Figure 1). Oxygen was assumed to diffuse from the ground surface where the oxygen concentration is held at atmospheric oxygen concentration wherever the surface is not covered by the building slab. The building slab was considered imperious, to minimize oxygen ingress and so establish conservative criteria for vapor biodegradation relative to the size of a building footprint. Here, additionally, we considered the lateral length dimension of buildings giving rise to the need to consider three dimensional gas and vapor transport in the soil profile above the vapor source. Square and circular plan building footprints are also depicted in Figure 1.

Model Equations

We considered the three dimensional diffusion and reaction problem with the upper surface partly covered by an impervious slab. In general the slab has dimensions \( 2a \times 2L \).
(half width \(a\), as shown in Figure 1 with a half slab length \(L\)). For consistency, the axes have been retained as in Knight and Davis (2013) with \(y\) being depth, \(x\) the short (width) dimension of the building slab. Here \(z\) is used to denote the axis in the direction of the lateral (length of) slab dimension.

At a depth \(b\) below the surface (at the depth of the vapor source) we take the vertical coordinate \(y\) to be zero, with a fixed concentration \(h_0\) of hydrocarbon vapor, and a hydrocarbon concentration \(h(x, z, y)\) at a height \(y\) above the depth \(b\). \(c(x, z, y)\) is the oxygen concentration in the aerobic region. \(c_0\) is the fixed concentration at the surface \(y = b\) where the ground surface is open to the atmosphere (i.e., no slab structure is present). Where the slab is present, \(\frac{dh}{dy} = 0\) is assumed to indicate that the slab is impervious to gas diffusion or transport.

The interface is at an unknown height \(y = b - L(x, z)\), with \(h(b-L) = c(b-L) = 0\).

The hydrocarbon and oxygen concentration profiles satisfy the steady state diffusion equation in three dimensions

\[
\frac{d^2c}{dx^2} + \frac{d^2c}{dz^2} + \frac{d^2c}{dy^2} = 0 \tag{A1}
\]

for \(b - L < y < b, \) and

\[
\frac{d^2h}{dx^2} + \frac{d^2h}{dz^2} + \frac{d^2h}{dy^2} = 0 \tag{A2}
\]

for \(0 < y < b - L\).

The fluxes of oxygen and hydrocarbon are equated at the interface including the inclusion of \(\gamma\) which is the stoichiometric mass of oxygen consumed per mass of hydrocarbon consumed. The depth of the interface is \(a\) priori unknown, but the conditions at the interface give a well posed problem for its position.

Below we transform Equations (A1) and (A2) into those solved via a variation on the Shvab-Zel’dovich formulation. The dimensionless quantity \(\eta\) is

\[
\eta = \frac{D_c c_0}{\gamma D_h h_0} \tag{A3}
\]

with \(D_c\) and \(D_h\) being the diffusion coefficients for oxygen and hydrocarbon vapor, respectively. As in the one and two dimensional problems considered in Knight and Davis (2013), the equations can be reformulated as a conventional boundary value problem on a fixed three dimensional region by the choice of a new dependent variable \(w(x, y, z)\), with

\[
w(x, y, z) = \frac{D_c c_0(x, y, z) + \gamma D_h h_0}{D_c c_0 + \gamma D_h h_0} \tag{A4}
\]

in the aerobic region \(b - L < y < b, \) and

\[
w(x, y, z) = \frac{\gamma D_h [h_0 - h(x, y, z)]}{D_c c_0 + \gamma D_h h_0} \tag{A5}
\]

in the anaerobic region \(0 < y < b - L\). Then \(w(x, y, z)\) is a dimensionless concentration and satisfies Laplace’s equation

\[
\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} = 0 \tag{A6}
\]

everywhere, and \(w\) and the partial derivatives \(\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y},\) and \(\frac{\partial w}{\partial z}\) are continuous everywhere, including at the interface which is the height \(y_0(x, z)\) at which

\[
w(x, y_0, z) = \frac{\gamma D_h h_0}{D_c c_0 + \gamma D_h h_0} = 1/(1 + \eta) \tag{A7}
\]

The boundary conditions are that \(w = 0\) at \(y = 0\), and at the soil surface \(y = b\) \(\frac{\partial w}{\partial y} = 0\) under the slab and \(w = 1\) everywhere else.

For flow with a circular slab on the surface we use the cylindrical coordinates \((r, y)\) with \(r^2 = x^2 + z^2\), and the equation

\[
\frac{\partial^2 w}{\partial y^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) = 0. \tag{A8}
\]

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