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Impacts of Changes of Indoor Air Pressure and Air Exchange Rate in Vapor Intrusion Scenarios

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Abstract

There has, in recent years, been increasing interest in understanding the transport processes of relevance in vapor intrusion of volatile organic compounds (VOCs) into buildings on contaminated sites. These studies have included fate and transport modeling. Most such models have simplified the prediction of indoor air contaminant vapor concentrations by employing a steady state assumption, which often results in difficulties in reconciling these results with field measurements. This paper focuses on two major factors that may be subject to significant transients in vapor intrusion situations, including the indoor air pressure and the air exchange rate in the subject building. A three-dimensional finite element model was employed with consideration of daily and seasonal variations in these factors. From the results, the variations of indoor air pressure and air exchange rate are seen to contribute to significant variations in indoor air contaminant vapor concentrations. Depending upon the assumptions regarding the variations in these parameters, the results are only sometimes consistent with the reports of several orders of magnitude in indoor air concentration variations from field studies. The results point to the need to examine more carefully the interplay of these factors in order to quantitatively understand the variations in potential indoor air exposures.

Keywords

Vapor intrusion; indoor air pressure; indoor air exchange rate; modeling

1. Introduction and review of transient indoor air contaminant vapor concentration field measurements

The migration of potentially harmful volatile organic compounds (VOCs) from subsurface soil contaminant sources into structures built atop or in proximity to the source (often present in groundwater) leads to vapor intrusion as defined by U.S. EPA 2002. Vapor intrusion involves complex, often difficult to predict, transport processes in the soil subsurface. It is associated with inhalation health risks for building occupants, which are

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themselves hard to predict. With the growing awareness of the problem, as evidenced by numerous studies of the problem in the past two years, e.g. (Beckley et al., 2014; Brusseau et al., 2013; Dawson, 2013; Goreham et al., 2014; Holton et al., 2015; Johnson et al., 2014; Johnston and Gibson, 2014; Jourabchi et al., 2013; Lowe et al., 2015; Marchant, 2014; Perron et al., 2013; Schumacher and Zimmerman, 2013; Verginelli and Baciocchi, 2014; Yao et al., 2013c; Yao et al., 2015), there remains a strong impetus to better quantitatively characterize vapor intrusion processes.

In 2015, the U.S. EPA (2015) issued its official guidance for vapor intrusion assessment. Prior to this, field data have also been collected into a U.S. EPA vapor intrusion database (EPA, 2012b), which complements the guidance documents. In analyzing nationwide vapor intrusion field data, the 2008 version of the U.S. EPA vapor intrusion database included about 3000 paired high quality measurements of subsurface and indoor air concentrations. The preliminary evaluation of this database (EPA, 2008) included mostly paired measurements of indoor air contaminant vapor concentration c_{in} along with the vapor concentration assumed to be in equilibrium with the groundwater near the structure, or subslab vapor concentration, mostly for chlorinated hydrocarbons. In 2012, the U.S. EPA (2012b) updated the 2008 database, and greater attention was drawn to the possible importance of sources other than vapor intrusion (so-called background indoor sources of contaminants).

There has been significant attention paid in the vapor intrusion literature to analyzing subsurface contaminant vapor concentrations profiles (Diallo et al., 2012; EPA, 2012a; Ferguson et al., 1995; Krylov and Ferguson, 1998; Shen et al., 2012; Shen et al., 2014; Shen and Suuberg, 2014; Shen et al., 2013c; Yao et al., 2013b). Previous studies (Suuberg et al., 2011; Yao et al., 2012) have indicated that reported indoor vapor concentrations can be considerably more variable than would be expected based upon the subslab vapor concentrations. Olson and Corsi (2002) concluded that the complexity in analyzing indoor air contaminant concentrations comes from variability of many factors including building ventilation, existence of background indoor sources, sorptive interactions and chemical reactions. The present study will focus on analyzing some of the factors affecting indoor air contaminant vapor concentrations. Not all factors are considered here — the above cited background sources and related sorption/desorption processes will be examined elsewhere. Likewise, chemical reactions, of critical important in petroleum vapor intrusion, are not considered.

For indoor air contaminant vapor concentration assessment, the U.S. EPA database contains few examples of multiple rounds of measurement at the same location. Thus despite the large number of data that have been gathered, these do not offer a large source of data that can be used for analyzing transient effects. Generally speaking, while there have been many vapor intrusion field investigations in the United States, there have been relatively few well-documented and publicly accessible studies of transient effects. This is easily understood, since obtaining even one single residential measurement of indoor air, using EPA method TO-15 (EPA, 1999, 2012c, d) is costly, not to mention highly inconvenient for the occupants of potentially impacted structures. Therefore, multiple measurements using TO-15 have not been widely practiced (Pennell et al., 2013). Recently, use of passive samplers (Johnston and

Gibson, 2014; Perron et al., 2013), which may be less costly, has drawn more attention, but still does not resolve the issues of inconveniencing occupants, nor of defining the true time scales of relevance.

There are increasing numbers of studies that have reported temporal indoor air contaminant vapor concentrations (EPA, 2012b; Holton et al., 2015; Johnston and Gibson, 2014; Johnston and Gibson, 2010; Pennell et al., 2009). Earlier, Nazaroff *et al.* (1987) studied the temporal effects of induced-pressure differences between indoor and ambient on radon intrusion. The results from two-monthly sampling rounds in a recent field study on a chlorinated solvent vapor intrusion site in the greater Boston, MA area showed two orders of magnitude variation between different rounds of measurements (Pennell et al., 2013). Meanwhile, EPA (EPA, 2012b) reported a variation of more than one order of magnitude in indoor Trichloroethylene (TCE) concentration for individual buildings at Lowry Air Force Base over one year, involving six rounds of measurements. McHugh and Brock (2007) conducted a three-year study on two vapor intrusion sites, and observed relatively small variability of short term (scale of days) subsurface and indoor vapor measurements, but relatively larger variability in longer term measurements. Folkes *et al.* (2009) summarized a large amount of field data at two sites and found considerable variation in both indoor and subsurface vapor concentrations from month to month and season to season. They also found that the indoor air contaminant vapor concentration tended to vary less across space but more with time.

Continuous daily measurements of indoor air contaminant vapor concentration (Beckley et al., 2014; Dawson, 2013) have now recently been obtained for houses in Utah (Holton et al., 2015; Holton et al., 2013) and Indianapolis (Schumacher and Zimmerman, 2013). The indoor air contaminant vapor concentrations were found to vary by over one order of magnitude between different measurements taken over the time scale of a week in both sites and in some cases up to three orders of magnitude variation was observed. Obvious seasonal effects of indoor contaminant vapor concentrations were observed by Schumacher and Zimmermann (2013) in the Indianapolis study and by Holton et al. (2013, 2015) in the Utah study. Moreover, in the former, the indoor contaminant vapor concentration was found to vary by two orders of magnitudes depending upon whether a subslab mitigation system was on or off, but of course this was expected, showing that changes in subslab conditions do influence indoor air contaminant concentrations. Folkes *et al.* (2010) compared the effects of long term and short term variation of groundwater concentration on indoor air concentrations. It was concluded that long term rising and falling trends in groundwater concentrations could affect the prediction of the indoor vapor attenuation factor, while short term fluctuation of groundwater concentrations might have limited effect on indoor vapor concentration.

It is therefore possible to conclude from the available published data that temporal variations in indoor air contaminant concentrations are common, if not the norm. There are unquestionably some factors related to building operation that can affect observed indoor contaminant vapor concentration levels, but there might also be some external environmental factors that can play a role.

The most recent US EPA vapor intrusion guidance (EPA, 2015) has noted the importance of the acute and short-term exposure, which may be considered to pose an unacceptable human health risk. This guidance also noted that EPA will work to develop expanded science policy direction to address the short-term exposures. Given the significance of understanding vapor intrusion related indoor air quality, the present study has focused on analyzing the short-term temporal factors and seasonal factors that might affect indoor air contaminant vapor concentrations, including soil gas entry rate and building air exchange rate.

2. Modeling Methodology

2.1 Subsurface Contaminant Vapor Transport Modeling

A typical three-dimensional vapor intrusion model solves the equations listed in Table 1, subject to the boundary conditions shown and relevant initial conditions (described below) (Abreu and Johnson, 2006; Bozkurt et al., 2009). For sample calculations, a residential building is assumed to have a footprint of 10 m × 10 m, and its foundation slab is taken to be located 1 m bgs. The effect of different geometry settings, including the size of the building, basement depth, source depth, were studied and presented in previous papers (Shen et al., 2014; Shen and Suuberg, 2014). The basement space, generally of greatest concern in vapor intrusion, is assumed to have a height of 2 m. A 0.01 m perimeter crack (Johnson and Ettinger, 1991), around the foundation slab, is assumed to be the entry point for contaminant vapor from the soil into the structure. An earlier study has shown that the location of a foundation breach is less important than its total area (Yao et al., 2013a). The groundwater table, which is assumed to be the contaminant vapor source, is assumed to be 4 m bgs. The finite element code, COMSOL, was used for solving the three-dimensional vapor transport problem in the subsurface and from soil through the foundation crack. The typical aspects of using this code to solve vapor intrusion problems have been described in several earlier publications (Shen et al., 2013a; Shen et al., 2013c).

2.2 Indoor Air Contaminant Vapor Transport Modeling

There exist various models that have been developed to simulate indoor air contaminant vapor concentrations. These have generally been developed independently of any consideration of vapor intrusion. One of the most widely used in indoor air quality modeling (EPA, 2000a) is the well-mixed building (or room) model. Such models normally involve assuming rapid mixing in some volume of indoor air; the indoor vapor concentration can then be calculated knowing the various source and sink terms relevant to the volume of concern (EPA, 2000b; Meininghaus et al., 2000; Sparks et al., 1999; Wolkoff and Nielsen, 2001; Zhang, 2001). However, this kind of sub-model has not generally been incorporated into vapor intrusion modeling, nor has this kind of model involved consideration of a vapor intrusion source. There have been examples of vapor intrusion analysis that have involved assumption of multiple, interconnected volumes in a single building, e.g. (Krylov and Ferguson, 1998; Olson and Corsi, 2001). Considering a multi-compartment building structure, Equation (3) in Table 1 can be used to calculate the vapor concentration in the building. The first term on the right hand side is the contaminant mass flow contributed by vapor intrusion. The second term accounts for all indoor source emissions. Again, in actual residential settings, it may not always be possible to remove all sources. The third and fourth

terms account the mass flow from the compartment k to the compartment of concern, or out of compartment of concern to compartment k . The fifth and sixth terms account for adsorption and desorption to surfaces in the compartment. The last term accounts for chemical reactions involving the contaminant within the building. Again, while this type of equation has been commonly used in analysis of indoor air concentrations, its use here involves explicit consideration of a vapor intrusion source which has normally not been done. The multi-compartment scenario is not explored here. Rather, it is the transient concentration variation in response to the first and third terms of Equation (3) that is initially considered.

3. Results and Discussions

3.1 The Influence of Soil Gas Entry Rate at Steady State Conditions

One of the most widely discussed transient parameters characterizing the indoor environment is pressure change. Both indoor air pressure and open field pressure vary with weather conditions and building operations, and can lead to the changes of soil gas flow rate into the building. While this advective flow is generally not significant in determining the contaminant concentration profiles in the subsurface, in some cases, it may play a major role in bringing contaminant into the building from the immediate vicinity of the building (Yao *et al.*, 2013a). This, in turn, can have a major effect on indoor air contaminant concentrations.

Before conducting detailed transient modeling that involves significant computational effort, it is helpful to review some conclusion that may be drawn from already available steady state results. The typical numerical vapor intrusion model calculates the total soil gas flow rate through the crack into the building Q_{ck} (which is different from J_{ck} , which represents the contaminant vapor mass flow rate through the crack by both diffusion and advection) here assumed to be taking place through the modeled perimeter crack. The typical calculation of Q_{ck} involves using the steady state form of Darcy's law in the soil, in which the left hand side in Equation (2) is absent, as well as an expression for pressure driven flow in a channel (i.e., the crack). It is Darcy's law that actually relates soil gas flow and pressure gradient in the soil, near the building foundation. In steady state modeling, the value of Q_{ck} depends upon soil permeability, and on the boundary conditions applied at the crack, i.e. B.C.(2)a or B.C.(2)b. Around the building foundation, soil moisture tends to have a relatively low and constant value, since it may be less affected by rainfall water, and therefore, most vapor intrusion models have not considered the effects of soil moisture variation when calculating soil gas flow using Equation (2). If advection dominates contaminant entry then J_{ck} is calculated from the product of Q_{ck} and then relevant local contaminant concentration.

In Figure 1, simulated steady state indoor air contaminant vapor concentrations are plotted as a function of corresponding simulated soil gas entry flow rates Q_{ck} . In this figure, the data points were obtained from both a U.S. EPA vapor intrusion modeling document (EPA, 2012a) and the results obtained by Yao *et al.* (2011), all for steady state scenarios. These are the two most widely used 3D vapor intrusion numerical models. Both models assumed a perimeter crack as the only entry point for contaminant vapor. These data included results from models involving a range of values of soil permeability, vapor diffusivity in the soil and crack, indoor to ambient pressure differences, and source depth, and also considered

different building structures (basement or slab-on-grade). The predictions of indoor air contaminant concentrations are all normalized relative to a contaminant concentration at a groundwater vapor source. The results for $Q_{ck} > 0$ are seen to fall in a band that is around two orders of magnitude wide. This reflects the fact that this method of plotting combines the results from many very different conditions. Regardless of this fact, the plot helps illustrate some important points as discussed below.

From Figure 1, it is obvious that c_{in}/c_{gw} is very sensitive to the absolute value of the total volumetric soil gas entry rate Q_{ck} when the latter is either small or negative. The calculated values of c_{in}/c_{gw} were found to be much lower than 10^{-5} when the building was pressurized and thus Q_{ck} was negative; when the building was pressurized, this forced a flow of gas outward from the crack. Under these conditions, the only mechanism for contaminant entry into the building is diffusion, counter to an advective flux.

As expected, the indoor air contaminant vapor concentrations increased significantly when the building was under-pressurized. What might be unexpected is the fact that the values of c_{in}/c_{gw} were observed to approach a limiting value of 10^{-2} when the soil gas entry rate reached $2 \times 10^{-4} \text{ m}^3/\text{s}$. In this range, the ability of soil vapor diffusion to maintain subslab concentrations, is limiting. In other words, there is only a certain limit to which increasing soil gas entry into a structure via its depressurization will serve to increase contaminant vapor intrusion. It is important to note that the results here were obtained for the typical few Pa extents of depressurization that characterizes the operation of normal buildings (hence the low values of Q_{ck}) (Nazaroff et al., 1987).

It should be reiterated that results in Figure 1 were based on a steady state assumption, which means that both the soil gas flow and vapor transport have reached steady state values, and c_{in}/c_{gw} is calculated from

$$\frac{c_{in}}{c_{gw}} = \frac{(J_{ck}/c_{gw})}{A_E V_{bldg}} \quad \text{Eq.(5)}$$

where, as usual, the soil gas entry rate Q_{ck} is assumed to not significantly influence the building air exchange rate because of the low value of the former compared with the latter. In both cited studies, the building air exchange rate A_E , was kept constant for the calculations. It was set to 0.5 /h in Abreu's model, and 0.25 /h in Yao's model.

It is seen from Eq (5) that c_{in}/c_{gw} is linearly proportional to the contaminant mass entry rate J_{ck} . Again, Figure 1 shows that in steady state, J_{ck} is sensitive to Q_{ck} only at relatively low absolute values of Q_{ck} . Thus, the results of Figure 1 do suggest that variations in soil gas entry rate might serve to influence indoor air concentrations to a maximum extent of two orders of magnitude, in a typical underpressurized building scenario.

The conclusions from a steady state analysis may not, however, directly apply to short time scale transients, such as can be caused by a sudden indoor pressure change by turning on some HVAC system, or opening or closing doors and windows. The change of mass entry rate can be inferred from the steady state simulations over long timescales, which condition

is defined by the contaminant vapor concentration in the subsurface reaching quasi static state. This required long time scale depends on many conditions, such as the gas diffusion coefficients in soil. The point is, though, that to see the orders of magnitude variation in concentration implied by Figure 1 requires these long time scales, and that these may be much longer than the transients observed in the field studies cited above. This is discussed further below.

3.2 The Influence of Short Time Transients on Soil Gas Entry

It should be noted that a negative indoor air pressure in a vapor intrusion impacted structure has usually been attributed to the “chimney” or “stack” effect (Nazaroff et al., 1987). The chimney effect, or other indoor variations such as temperature change, can lead to small indoor pressure changes on short timescales. The typical values of the indoor and subsurface pressure difference have been observed to be -10 Pa to 10 Pa (Nazaroff et al., 1985; Nazaroff et al., 1987). Based on the reported data, two hypothetical scenarios have been modeled to study these transients, and the results are shown in Figures 2(a) and 2(b). Our previous study has shown the effect of soil permeability (Shen et al., 2013b; Shen et al., 2013c; Yao et al., 2011). To address this factor in the current scenarios, different values of soil permeability were used and compared. The amplitude of indoor pressure change in transient scenario (a) is 5 Pa, and the soil permeability is assumed to have a typical value of 10^{-12} m². Transient scenario (b) involves a relatively larger indoor pressure change between -10 Pa to $+10$ Pa, while the soil permeability remained the same. Transient scenario (c) involved the same larger indoor pressure amplitude and a relatively more permeable soil ($k = 10^{-11}$ m²). In all scenarios, the indoor air pressure starts to decrease at $t = 0$, and varies as a sine function as shown in Table 2 (with a period of 12 hours). The amplitudes of the pressure variations are typical of those used in vapor intrusion modeling (Abreu, 2005; Bozkurt et al., 2009) and observed in field studies (Garbesi and Sextro, 1989; Nazaroff et al., 1987). Figure 4 shows the calculated Q_{ck} plotted versus time, for scenario (a) as an example.

It was also assumed that initially the indoor air contaminant concentration c_{in}/c_{gw} was at steady state as a result of pure diffusion through the foundation breach ($Q_{ck} = 0$), i.e., in this case indoor pressure initially equaled the outdoor pressure. Using the 3D model described above and the parameters in Table 1, the calculated contaminant mass entry rate J_{ck} , normalized by the groundwater vapor concentration c_{gw} , varied as shown in Figures 2 and 3.

Shown along with the transient results in Figures 2 and 3, there are three solid horizontal lines. The middle lines represent the initial values of the normalized vapor mass entry rates, which are all the same value in scenarios (a), (b) and (c). The uppermost horizontal lines represent the steady state normalized vapor mass entry rate with a -5 Pa or -10 Pa indoor air pressure, i.e., constant depressurization of the structure. Comparing scenarios (a) and (b), the variation in contaminant entry rate (and thus indoor concentration) doubled, when the air pressure change doubled. J_{ck} is higher in scenario (c) than that in scenario (b), as the soil gas entry rate is higher in the former scenario. The lower horizontal lines represent the steady state solution, with a $+5$ Pa or $+10$ Pa constant pressurized indoor conditions. In these scenarios, J_{ck} is still larger than zero, which means that the indoor air concentration is determined by diffusion from subsurface to indoor, rather than convection from indoor to

subsurface. With positive indoor pressure, Q_{ck} can reverse, as shown in Figure 4. Note the significance of this reversal, as in scenario (c), J_{ck} is 1000 times less than that in scenario (b) due to the higher Q_{ck} variation made possible by the higher soil permeability.

For transient cases, in Figures 2 and 3, the air entry rate Q_{ck} changed from positive values to negative when the indoor is pressurized. The minimum of J_{ck} is bounded by the lower horizontal line corresponding to the steady-state solution. This means that in the transient scenarios, the minimum J_{ck} is mostly limited by counter-diffusion of contaminant against the flow from the crack.

It can be seen that the fluctuation of J_{ck} has a very small time lag relative to pressure change. In other words, the vapor intrusion from the immediate subslab region responded quickly to the indoor pressure change.

In scenario (c), the variation of the contaminant mass entry rate is large, because it is very sensitive to the total soil gas entry rate into the building Q_{ck} . It is not usual to have as low as 10^{-11} m² permeability in undisturbed soils, but it may be possible in sands or gravels, particularly as might underlie a building (having been placed there during construction).

3.3 Effect of Transient Air Exchange Rate

For the modeled indoor environment, here assumed to be a single well-mixed compartment, the air exchange rate A_E plays a crucial role in determining indoor air concentration. This parameter was treated as a constant in Equation (3), but obviously may vary with time in practice. The distribution of A_E has been studied by researchers interested in the indoor air environment, in studies that were not directly related to vapor intrusion. Murray and Burmaster (1995) provided a comprehensive summary of the air exchange rate in different regions in the United States and at different seasons. They found that the natural logarithm value of the air exchange rate were characterized by normal distributions, i.e. $\ln A_E \sim N(\mu, \sigma^2)$ with mean μ and standard deviation σ . They found that in different seasons different geographical regions had different mean values and standard deviation values. These results showed that the air exchange rate generally has a larger mean value and variation in summer than in the other three seasons.

Another field study of a specific house by Holton et al. (2013), however, showed smaller air exchange rate in summer than other seasons, and the average daily variation of the air exchange rate was less than one order of magnitude.

The statistical distributions of the air exchange rate, such as that determined in (Murray and Burmaster, 1995) does not, however, provide an indication of what the real air exchange rate is in any one specific building or how fast that air exchange rate varies at any particular time. Considering this, fall (with $A_E = 0.3/h$) and summer (with $A_E = 1/h$) were selected as two hypothetical scenarios using deterministic method for simulating seasonal indoor air contaminant vapor concentration variations.

Assuming all the VOCs in a building compartment result from vapor intrusion, the dynamic indoor air concentration can be calculated by:

$$V_{\text{bldg}} \frac{dc_{\text{in}}/c_{\text{gw}}}{dt} = -V_{\text{bldg}} A_E c_{\text{in}}/c_{\text{gw}} + J_{\text{ck}}/c_{\text{gw}} \quad \text{Eq.(6)}$$

Other indoor sources or sorption interactions of VOCs with building materials are ignored here. Equation (6) becomes Equation (5) at steady state.

Assuming the initial condition is the steady state given by Equation (5), Equation (6) has an analytical solution for $c_{\text{in}}/c_{\text{gw}}$:

$$c_{\text{in}}/c_{\text{gw}} = \frac{J_{\text{ck}}/c_{\text{gw}}}{A_E V_{\text{bldg}}} \bigg|_{t=0} + \frac{\int_0^t \exp\left(\int_0^\tau A_E d\gamma\right) \times J_{\text{ck}}/c_{\text{gw}} d\tau}{V_{\text{bldg}} \exp\left(\int_0^t A_E d\tau\right)} \quad \text{Eq.(7)}$$

And the solution of $c_{\text{in}}/c_{\text{gw}}$ can be obtained by solving Equation (7) numerically, given knowledge of J_{ck} and the temporal variation of A_E . It should be noted that the change of indoor contaminant vapor concentration, or the indoor contaminant vapor concentration itself, is not proportional to $1/A_E$, as in Equation (5).

In the following simulation, again, we assume for the initial condition, that the indoor gauge pressure is zero. Assume initially then, that A_E is 0.3/h, and J_{ck} is a constant, obtained from the steady state scenario in Figure 2(a) for 0 Pa pressure difference, i.e., J_{ck} , was here assumed to be that for entry by steady state diffusion only. The first scenario modeled is that for the fall season with A_E varying as:

$$A_E = [0.3 + 0.3 \sin\left(\frac{2\pi}{12[h]} t\right)] [1/h] \quad \text{Eq.(8)}$$

the calculation results of which are shown in Figure 5(a).

The second scenario modeled is that for a summer scenario. The air exchange rate is assumed to follow the variation:

$$A_E = [1 + \sin\left(\frac{2\pi}{12[h]} t\right)] [1/h] \quad \text{Eq.(9)}$$

The calculation results for this case are as shown in Figure 5(b).

Along with the transient simulation result, two limiting scenarios are added in Figure 5. The first limiting scenario is a scenario in which vapor intrusion mass flow rate stops at $t = 0$. It should be noted that if vapor intrusion is suddenly stopped at $t = 0$, i.e. $J_{\text{ck}} = 0$ when $t > 0$, the analytical solution of Equation (7) is:

$$c_{in}/c_{gw} = \frac{J_{ck}/c_{gw}}{A_E V_{bldg}} \bigg|_{t=0} \times e^{-A_E t} \quad \text{Eq.(10)}$$

which shows that the indoor vapor concentration decays exponentially with time, with a characteristic time, or mean lifetime $1/A_E$. The calculated c_{in}/c_{gw} for this case decreases quickly in both fall and summer. In the fall, the indoor air concentration decrease to 2% of its initial value at 12 h. In summer, the indoor air concentration decrease to 1% of its initial value within 6.8 h. This indicates that in a common residence scenario, the indoor air tends to clean itself within a time scale of hours, in the absence of a vapor intrusion source.

The other limiting scenario is a scenario in which the air exchange rate decreases to zero at $t = 0$. In this case, Equation (10) also has an analytical solution,

$$c_{in}/c_{gw} = \frac{J_{ck}/c_{gw}}{A_E V_{bldg}} \bigg|_{t=0} + \frac{J_{ck}/c_{gw}}{V_{bldg}} t \quad \text{Eq.(11)}$$

which shows a linear relation between c_{in}/c_{gw} and time. As seen from Figures 5 (a) and (b), the indoor air concentrations increases 2 ~ 4 times within 3 h, or 10 ~ 12 times within half a day. In examining buildings at very low air exchange rates (such as in sampling events involving closing all doors and windows of the building so as to prevent air exchange), this may lead to order of magnitude differences in the measured indoor air contaminant vapor concentrations, compared to normal air exchange conditions. This case is represented as the “sealed basement” scenario in Figure 5.

The indoor air contaminant vapor concentrations are observed to vary with time in response to sinusoidal time variation of A_E as seen in Figure 5. c_{in}/c_{gw} has a lag of about 2 h relative to the air exchange in fall, and 1 h in summer, as seen in Figures 5 (a) and (b). The magnitude of these fluctuations may be compared to the variation that resulted from indoor air pressure variation in Figure 2, and are seen to be comparable in magnitude.

The above scenarios in Figure 5 show the effects of transient air exchange rate on indoor contaminant vapor concentration in relatively simple vapor intrusion settings. In other words, the contaminant vapor entry from the crack was chosen to be either constant or zero. In the following discussion, a transient J_{ck} scenario is considered, calculated using the parameters in Table 2 (based upon scenario (a) of Figure 2). The results of J_{ck} from that 3D model may be fitted to a sinusoidal function as:

$$J_{ck}/c_{gw} = [4.7 \times 10^{-6} + 8.6 \times 10^{-7} \sin(\frac{2\pi}{12[h]} t - 0.015)] \times 3600(m^2/h) \quad \text{Eq.(12)}$$

Equation (12) for J_{ck}/c_{gw} from the 3D model was input into Equation (6). Combining with air exchange variations shown in Equation (8) and (9), the results in Figure 6 are obtained.

In this case, the indoor air depressurization is assumed to drive a variation in J_{ck} , with the same periodicity as A_E , here assumed to be either in phase (Figure 6(a)) or out of phase (Figure 6(b)). The results for time varying A_E may be compared with those for steady values of air exchange rate. The simulation results with constant A_E and varying J_{ck} show a relatively smaller amplitude than the results involving variation of A_E (see Figure 6). Thus the main driver for the indoor air contaminant concentration variations in Figure 6 is the variation in air exchange rate, rather than contaminant entry rate. The scenarios in which both A_E and J_{ck} varied with time showed that the amplitude decreased when these two factors varied in sync, as in Figure 6(a). If the air exchange rate decreased as vapor entry rate increased, the amplitude of c_{in}/c_{gw} decreased, as in Figure 6(b).

Regardless of whether the building is operated such that the period of air exchange rate is associated with depressurization (and thus increasing J_{ck}) or pressurization (and thus small J_{ck}), the results look quite similar. This is because in these hypothetical scenarios, the influence of the transient in J_{ck} is small relative to the influence of the transient in A_E . The process timescale is dictated by the purging time of the structure in this case.

The same scenarios as in Figure 6 were modeled with summer air exchange rates, as shown in Figure 7.

The initial indoor vapor concentration in summer is three times lower than that in fall. Lower indoor vapor concentration in summer than other seasons have also been observed in the field measurements by Holton et al. (Holton et al., 2015). The variation of indoor vapor concentration is predicted to be relatively larger in summer than fall because of the larger variation of air exchange rate, which can be seen by comparing Figures 6 and 7. Almost one order of magnitude change of c_{in}/c_{gw} is seen in Figure 7, achieved by varying A_E alone, but in the fall, the average indoor air contaminant vapor concentration is less variable and is on average two to three times that in the summer. For the case in which variations in A_E and J_{ck} are in phase, in both seasons, predicted variations of the indoor air contaminant vapor concentration of an order of magnitude can be expected from such variation in A_E alone. In none of these cases are the variations observed in field studies of several orders of magnitude indoor air contaminant concentration predicted. It is only when there are precipitous cutoffs of contaminant entry, such as in Figure 3, or the case of $J_{ck} = 0$ in Figure 5, that very low concentration are achieved. Alternatively, if there is a very strong source associated with a time-varying preferential pathway, this could result in driving concentrations to high values. Typical 3D steady steady models do not appear to predict the observed large temporal variations in indoor air concentration values from simple variation in a single parameter alone.

Holton et al. (2013) continuously measured indoor contaminant vapor concentration and the air exchange rate in a single house. Two hypothetical scenarios were considered here to represent for spring and summer in the Holton's scenarios, using the above calculation method. In their field study, the air exchange rate values were measured instantaneously at 30 min intervals and averaged daily, from day 120 to day 720. Also, in the model here, the initial indoor contaminant vapor (TCE) concentration c_{in} was assumed to be the values in Table 3.

While the parametric distribution of the air exchange rate is unknown from Holton's paper, a parametric distribution is assumed here. The A_E used in the model was assumed to be the following function for the spring scenario:

$$A_E = [0.8 + 0.7 \sin(\frac{2\pi}{12[h]}t)] [1/h] \quad \text{Eq.(8)}$$

And for the summer scenario:

$$A_E = [0.3 + 0.2 \sin(\frac{2\pi}{12[h]}t)] [1/h] \quad \text{Eq.(8)}$$

Using equation (6) to obtain c_{in} , the calculated results are shown in Figure 8.

From Figure 8, the predicted TCE concentration in indoor air varied less in summer than in spring which is crudely consistent with the field data. In both summer and spring scenarios, the predicted TCE concentration in indoor air changed less than an order of magnitude, thus failing to capture this important aspect of results. The measured TCE concentration in indoor air in spring, fall and winter mostly varied from 0.01 to 1 ppb, while in summer varied from 0.01 to 0.5. However, the calculated TCE concentration in air varied much less, as shown in the shaded boxes. Thus the variation of air exchange rate was not necessarily the single factor that determined the indoor contaminant vapor concentrations.

The variation of the indoor air exchange rates were observed to be much faster than the ones assumed in the cases above. A preliminary statistical analysis was conducted using Holton's published data. The daily averaged air exchange rate data points were obtained from their paper: 147 data points for spring and 47 data points for summer. The 30 min measurements had relatively larger variation, however, and they were difficult to obtain as the data were on top of one another. The density histograms of the spring and summer air exchange rates were plotted, and the maximum likelihood method was used to obtain the lognormal fit of the data. Probability plots were used as a simple visual way to understand the goodness of the lognormal fit. The distributions of the two data sets were observed to be generally fit by the lognormal distributions, while relatively larger tails were observed for the measurements. It can be seen that the real scenario can be much more complicated than that assumed in the above simulations.

Several vapor intrusion studies have reported sensitivity analyses on various parameters for different scenarios (Johnson, 2002; Mills et al., 2007). It has been noted in various settings (Johnson, 2002), that the indoor air exchange rate can be important in certain circumstances, but not in others. In another study (Schreuder, 2006), the indoor to subsurface pressure difference has been noted to be a variable to which there is high sensitivity. Other factors, such as variations in J_{ck} due to a preferential pathway, or complicated indoor air flow patterns and the effective building volume, or some combination of them, may help explain the observed two to three orders of magnitude TCE concentration variation. The existence of such a preferential pathway has been discussed relative to the structure that provided the

field data in Figure 8 (Holton et al., 2015), and the newly issued EPA vapor intrusion guidance warns of the need to be on the lookout for such pathways as might involve sewer connections (e.g., Pennell et al., 2013). To the extent that such preferential pathways are subject to transients beyond those that have been considered in this study, they can contribute additional complexity to the site.

4. Conclusion

This manuscript presents an analysis of vapor intrusion, accounting the dynamic effect of soil gas entry rate and the air exchange rate.

The modeling of transient indoor air pressure variation indicated that the soil gas entry rate variation quickly responded to the pressure change for the given scenarios. The resulting variation of the indoor air contaminant vapor concentration greatly depends on the soil permeability. For a relatively less permeable soil, the predicted indoor air contaminant vapor concentration variation was within one order of magnitude, as vapor diffusion controls the vapor transport process, while for a relatively permeable soil near the subslab, the predicted indoor air contaminant vapor concentration was shown to vary up to three orders of magnitude, as advective contaminant entry plays a much larger role.

In a typical residence in the United State, the air exchange rate variation can also lead to temporal indoor air contaminant vapor concentration changes. The indoor air contaminant vapor concentration can be calculated using a simple well-mixed room model. The modeling results showed that air exchange rate variation, within the typical range, can lead to an order of magnitude indoor air contaminant vapor concentration variation for a typical scenario. When the vapor intrusion pathway is closed off, the indoor air contaminant vapor concentration can decrease one order of magnitude within half a day, for typical room volumes and air exchange rates. Previous study (Pennell et al., 2013) has shown that the close-off of the preferential pathway (sewer gas), led to a decrease of measured indoor air vapor concentrations using active sampling.

Further work must be done to account for variation in other parameters, such as indoor contaminant vapor sorption, effects of changes in other metrological conditions and changes in source strength. These will be presented in future publications.

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Abbreviations

A_E	indoor air exchange rate [1/h]
A_m	Indoor sorbent material effective area [m^2]
c	contaminant vapor concentration [$\mu g/m^3$]
c_{amb}	ambient (outdoor) vapor concentration [$\mu g/m^3$]
c_{gw}	vapor concentration in equilibrium with groundwater concentration [$\mu g/m^3$]
c_{in}	indoor air contaminant vapor concentration [$\mu g/m^3$]

c_k	indoor air contaminant vapor concentration of compartment k [ug/m ³]
c_m	sorbed on-material contaminant concentration [ug/m ²]
c_s	sorbed vapor concentration in the material [ug/kg]
D^{eff}	the effect diffusivity in the water and gas phase [m ² /s]
D_g	the molecular diffusivity of contaminant in the soil gas phase [m ² /s].
D_w	the molecular diffusivity of contaminant in the water phase [m ² /s].
f_{oc}	organic carbon partition content, assumed to be 0.1%
E_{emis}	indoor source vapor emission rate [ug/s]
g	the acceleration due to gravity [m/s ²] acting in the vertical direction z
K_H	the Henry's law constant [dimensionless]
k^{eff}	the effective permeability [m ²]
k_a	linear adsorption rate constant [m/s]
k_d	linear desorption rate constant [/s]
k_{oc}	organic carbon partition coefficient [m ³ /kg]
l_{slab}	the thickness of the basement slab [m]
p	the gas pressure [Pa]
p_{indoor}	indoor air depressuration [Pa]
Q_{ck}	the air flow rate from subsurface through the building crack
$Q_{from,k}$	the air flow rate from compartment k to the compartment of concern
$Q_{to,k}$	the air flow rate from compartment of concern to compartment k
R_{rxn}	Reaction rate [ug/m ³ /s]
u_g	the soil gas velocity [m/s]
V_{bldg}	the building compartment volume [m ³]
z	the vertical height above the groundwater table [m]
η	air viscosity [kg/m/s]
ρ_b	soil bulk density [kg/m ³]
ρ_g	air density [kg/m ³]

Highlights

- The dynamics of vapor intrusion-induced indoor air contaminant concentrations to indoor air pressure and air exchange rate variations are modeled
- Predicted indoor air contaminant vapor concentration variations, in typical vapour intrusion scenarios, are about an order of magnitude
- Field reports of several order of magnitude variations in indoor air concentrations require special combinations of circumstances.
- Both daily and seasonal scenarios have been simulated.

Figure 1.
 Normalized indoor air contaminant vapor concentration as a function of calculated soil gas flow rate in (positive) or out (negative, shaded area) of the building through the simulated crack

Scenario (a)

Scenario (b)

Figure 2.

Transient vapor mass entry rate through the crack into the building, normalized by the groundwater vapor concentration, as a function of time. (a) indoor pressure varied between - 5 Pa to + 5 Pa, with soil permeability 10^{-12} m^2 . (b) indoor pressure varied between - 10 Pa to + 10 Pa, with soil permeability 10^{-12} m^2 . s-s stands for steady state

Scenario (c)

Figure 3.

Scenario (c): Transient vapor mass entry rate through the crack into the building, normalized by the groundwater vapor concentration, as a function of time, with indoor pressure varied between -10 Pa to +10 Pa, with soil permeability 10^{-11} m^2

Scenario (a)

Figure 4.
Calculated transient soil gas entry rate into (positive) or out of (negative) the building through crack, for scenario (a) of Figure 2

Figure 5.

Simulated transient indoor air contaminant vapor concentration with varying building air exchange rate (A_E) during (a) fall season, and (b) summer

Figure 6.

Fall season: simulated temporal indoor air contaminant vapor concentration with varying building air exchange rate (A_E) or the indoor gauge pressure (± 5 Pa), or both. A_E is assumed to have the seasonal mean as in fall. In scenario (a) A_E increase at $t = 0$. In scenario (b) A_E decrease at $t = 0$. In both scenarios, J_{ck} varied as in that in Figure 2(a), or Equation (12)

Figure 7.

Summer season: simulated temporal indoor air contaminant vapor concentration with varying building air exchange rate (A_E) or the indoor gauge pressure (± 5 Pa), or both. A_E is assumed to have the seasonal mean as in fall. In scenario (a) A_E increase at $t = 0$. In scenario (b) A_E decrease at $t = 0$. In both scenarios, J_{ck} varied as in that in Figure 2(a), or Equation (12)

Figure 8.

Upper panel: the calculated TCE concentrations in indoor air for hypothetical spring and summer scenarios. Lower panel: the calculated TCE concentrations (in boxes) compared to the field data from Holton *et al.* (2013). The green boxes represent spring, and orange boxes represent summer condition.

Table 1

Equations, boundary and initial conditions used in the numerical model

Governing equations	
Contaminant species conservation in subsurface soil	Eq.(1)
$(\theta_g + \frac{\theta_w}{K_H} + \frac{\rho_b k_{oc} f_{oc}}{K_H}) \frac{\partial c}{\partial t} = \nabla \cdot (D^{\text{eff}} \nabla c) - \nabla \cdot \mathbf{u}_g c - R_{\text{rxn}}$	
Subsurface gas flow	Eq.(2)
$[\chi_g \theta_g + \chi_{\text{soil}} (1 - \theta_g)] \frac{\partial p}{\partial t} = \nabla \cdot \left[\frac{k^{\text{eff}}}{\eta} (\nabla p + \rho_g g \mathbf{z}) \right]$ $\mathbf{u}_g = - \frac{k^{\text{eff}}}{\eta} (\nabla p + \rho_g g \mathbf{z})$	
in which the Darcy's law is	
Indoor air concentration variation, multi-compartment scenario	Eq.(3)
$V_{\text{bldg}} \frac{\partial c_{\text{in}}}{\partial t} = J_{\text{ck}} + \sum E_{\text{emis}} + A_E V_{\text{bldg}} c_{\text{amb}} + \sum Q_{\text{from},k} c_k - \sum Q_{\text{to},k} c_{\text{in}} - \sum A_m k_a c_{\text{in}} - \sum A_m k_d c_m - R_{\text{rxn}}$	
Constitutive equation	
$D^{\text{eff}} = D_g \frac{\theta_g^{10/3}}{\theta_t^2} + \frac{D_w}{K_H} \frac{\theta_w^{10/3}}{\theta_t^2}$	Eq.(4)
Boundary conditions	
Contaminant transport through the crack without advection	B.C.(1)a
$J_{\text{ck}} = D_g \frac{c}{l_{\text{slab}}}, \text{ when } \mathbf{u}_g = 0$	
Contaminant transport through the crack with advection	B.C.(1)b
$J_{\text{ck}} = \frac{\mathbf{u}_g c \exp(\frac{ \mathbf{u}_g }{D_{\text{air}}} l_{\text{slab}})}{1 - \exp(\frac{ \mathbf{u}_g }{D_{\text{air}}} l_{\text{slab}})}, \text{ when } \mathbf{u}_g \neq 0$	
Contaminant concentration at open field surface	B.C.(1)c
$c = 0$	
Contaminant concentration at groundwater level	B.C.(1)d
$c = 1$	
Contaminant transport all other boundaries:	B.C.(1)e
$\mathbf{q} = 0$	
Pressure at the crack without pressure difference:	B.C.(2)a
$u_g = 0$	
Pressure at the crack with pressure difference:	B.C.(2)b
$p = -\rho_g g z + p_{\text{indoor}}$	
Pressure at open field surface:	B.C.(2)c
$p = -\rho_g g z$	
Soil gas flow at all other boundaries:	B.C.(2)d
$\mathbf{u}_g = 0$	
Initial conditions	
At $t = 0$, for soil vapor concentration, use the steady state concentration profile	I.C.(1)
At $t = 0$, for soil gas pressure, no pressure difference between indoor and soil gas: $p_{\text{indoor}} = 0$, and therefore $p = -\rho_g g z$ everywhere	I.C.(2)

Governing equations

At $t = 0$, for indoor vapor concentration, use the steady state concentration

I.C.(3)

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Table 2

Parameters used in the modeling transient effects of indoor pressure changes

Modeling parameters	Hypothetical values
Building footprint size	10 m × 10 m
Basement depth	1 m bgs
Perimeter crack width	0.01 m
Basement inner size	9.7 m × 9.7 m × 1.85 m
Groundwater source depth	4 m
Effective vapor diffusivity in soil D^{eff}	$10^{-6} \text{ m}^2/\text{s}$
Effective soil gas permeability k^{eff}	Transient scenarios (a) and (b): 10^{-12} m^2 Transient scenario (c): 10^{-11} m^2
Indoor gauge pressure applied at the crack boundary	$-5\sin\left(\frac{2\pi}{12[h]}t\right)\text{Pa}$ Transient scenario (a): Transient scenarios (b) and (c): $-10\sin\left(\frac{2\pi}{12[h]}t\right)\text{Pa}$

Table 3

Cited data and assumed input data for transient scenarios with typical varying air exchange rate in spring and summer

Season	Parameter	Value	Unit	Reference
Spring	Daily average A_E	15~25	/d	Holton et al. (2013)
	Instantaneous excursion of A_E	10~35	/d	Holton et al. (2013)
	Steady state c_{in}	0.1	ppb	Assumed
Summer	Daily average A_E	5~10	/d	Holton et al. (2013)
	Instantaneous excursion of A_E	4~12	/d	Holton et al. (2013)
	Steady state c_{in}	0.02	ppb	Assumed