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# NUMERICAL ANALYSIS OF VAPOR INTRUSION FROM THE GROUND INTO BUILDINGS IN THE PRESENCE OF LATERAL SOURCES OF POLLUTION

Juan Sebastian Rios Mora (*juan-sebastian.rios-mora@cstb.fr*)<sup>1,2</sup>, Bernard Collignan (*bernard.collignan@cstb.fr*)<sup>1</sup>, Thierno Diallo (*thierno.diallo@cstb.fr*)<sup>1</sup>, Marc Abadie (*marc.abadie@univ-lr.fr*)<sup>2</sup>, Karim Limam (*karim.limam@univ-lr.fr*)<sup>2</sup>

<sup>1</sup>Centre Scientifique et Technique du Batiment, Health and Comfort Department, Saint-Martin-d'Hères, CO 38400 France

<sup>2</sup>University of La Rochelle, Laboratoire des Sciences de l'Ingénieur pour l'Environnement \_ LaSIE UMR CNRS 7356, La Rochelle, CO 17042 France

**Abstract.** Various screening-level and analytical models have been proposed in order to evaluate Vapor Intrusion (VI) and provide assessment tools for exposure risk in indoor environments. However, many in situ investigations show important differences between predicted and measured indoor concentrations generally associated with inappropriate conceptual modelling, incomplete VI process or by ignoring critical parameters in the evaluations. In this study, a numerical model is developed to better understand how polluted site characteristics as source position, soil properties, building pressure and type of construction may affect VI process from non-degrading chemicals. The results confirm that source location plays a critical role on VI compared to soil properties and building features. Increasing lateral distance from a building decreases indoor concentration about 5 orders of magnitude when the source is shallow and 2 to 3 orders of magnitude for deeper sources. However, despite the main influence of the position of the source, soil properties and building characteristics impacts are not insignificant: building pressure (-4 Pa) may increase VI by a factor of 2 compared to building at atmospheric pressure, slab on grade construction types

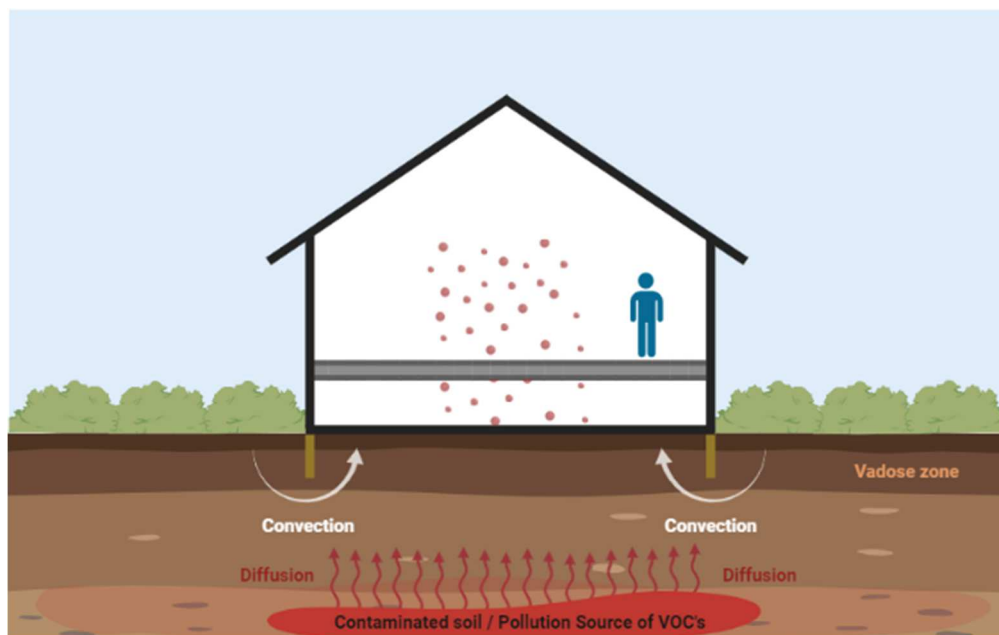
increase vapor attenuation of 80% compare to a bare ground configuration and permeable soils may allow vapors to migrate more easily to the building by generating an indoor concentration up to 10 times higher compared to impermeable soils. Current VI models including lateral separation, generally adopted in polluted site engineering, are unable to consider those influencing parameters, especially building features, and thus need to be extended to improve the management of contaminated land before building constructions.

**Highlights.** Lateral separation remains a key factor in VI attenuation; strong assumptions of VI models may restrain their use in particular situations; misrepresentation of the site of interest can lead to unrealistic VI modeling; finer characterization of VI can significantly improve modelling estimations.

**Keywords.** Gas soil transfer · indoor air quality · lateral source/building distance · numerical study · polluted soils · vapor intrusion

## 1. INTRODUCTION

Indoor Air Quality (IAQ) is related to the health and comfort of building occupants in terms of air quality. A poor IAQ, may negatively impact occupant's health, causing immediate and long-term health effects, extending from respiratory irritation to heart diseases and cancers (US EPA, 2015). In addition to the pollution sources from buildings (construction materials, furniture, carpets, paint, cleaning products, perfumes, humidity ...), Volatile Organic Compounds (VOCs) in the soil can migrate from the subsurface into buildings and get mixed with the indoor air (here after called Vapor Intrusion - VI). Many factors or activities may generate a vapor source in the ground (contaminated groundwater or soil), including gas leakage and historical subsurface disposal of industrial wastes and landfills (US EPA, 2015).



*Fig. 1 Schematic of VI mechanisms and pathways.*

The assessing health risks for the management of polluted sites is divided into 3 stages: characterization of pollution sources and transfer pathways, evaluation of indoor concentration and exposure levels and assessment of associated health risks. After the realization of the site characterization, indoor concentrations can be evaluated using in-situ screening-level instruments or by computational approach such as VI models. VI models

describe the VOCs transfer from the pollutant source, through the unsaturated soil and foundations, to the indoor environments (Fig. 1). Far from the building, VOCs mainly spread by diffusion through the vadose zone to the area close to the building foundation. In this zone, VI pathway through cracks, holes and seams existing in the building foundation and walls, is due to both diffusion and advection. Finally, once inside, VOCs are mixed with the indoor air.

Models can provide not only theoretical understanding, but also quantitative estimations of VI process. In general, the interest in modelling VI is to predict indoor concentrations that agree with measured ones to provide a risk assessment. Thus, it helps to manage the pollution situation, optimizing the implementation of corrective and/or preventive measures to decrease VOCs indoor exposure.

Several screening-level instruments and analytical models have been proposed in order to estimate VI (Johnson and Ettinger, 1991; Little et al., 1992; MFW et al., 1996; Verginelli and Baciocchi, 2011; Yao et al., 2012; Diallo et al., 2015). However, some site investigations have shown that there are important differences between predicted and measured indoor concentrations (Provoost et al., 2009, 2010; Shirazi et al., 2020). By their assumptions, VI models present difficulties to accurately estimate indoor air concentrations. More precisely, the inaccuracy in VI modelling is generally related with (Ma et al., 2020):

- An inappropriate conceptual modelling: most VI models are based on a conventional VI pathway. For example, a contaminated groundwater is typically assumed as the main contaminant source in existing VI models. However, in fact, the contaminant-source repartition may not be uniform, thus limiting the use of classic VI models become unrealistic in many cases (Yao et al., 2013a).
- Incomplete VI process: many VI models account for vapor entry into buildings only through a crack in the perimeter of the slab, ignoring the soil vapor transfer through

the soil/structure interface (Abreu and Johnson, 2005a; Yao et al., 2011; Borgoni et al., 2014; Diallo et al., 2015). Even in some cases, the authors do not take into account advection generated by the pressure difference between indoor and outdoor playing an important or even essential role in VI process under certain conditions (Loureiro et al., 1990; Mendoza and Frind, 1990; Johnson and Ettinger, 1991; W. Nazaroff, 1992; Diallo et al., 2013).

- Ignoring critical parameters: prediction of VI is complex and depends on the variability of numerous factors, including vapor source type (Abreu and Johnson, 2005; Shen and Suuberg, 2014; Yao et al., 2013b); vapor source concentration and chemical reactions (Abreu and Johnson, 2005; E DeVauill, 2007; Verginelli and Baciocchi, 2011); vapor source location relative to the building (S. Lowell and Eklund, 2004; Abreu and Johnson, 2005a; Verginelli et al., 2016; Yao et al., 2013a); and soil physical properties (Bozkurt et al., 2009; Pennell et al., 2009; Diallo et al., 2015). Unreasonable input values may lead to an unreasonable VI process assessment and thus misleading estimations of indoor concentrations.

For example, a common assumption is to consider an infinite and homogeneous source as the main source of contaminant vapors and lateral sources, i.e. sources that are not located right below the building, are often neglected in VI modelling. There are only a few studies directed to lateral migrations (Little et al., 1992; S. Lowell and Eklund, 2004; Abreu and Johnson, 2005a; Yao et al., 2013a; Verginelli et al., 2016). The authors agree that lateral separation plays an important role in indoor gas concentration attenuation unlike homogenous source scenarios where the vapors attenuation is mostly associated with the source depth. In fact, when the source is located laterally away from the building, the vapors may migrate mostly upwards to the atmosphere and less into the building compared to a source underneath the building (Abreu and Johnson, 2005).

In view of the limitations of the analytical models, numerical models have been proposed in order to study more complex scenarios, i.e. lateral separation (Abreu and Johnson, 2005; Bozkurt et al., 2009; Pennell et al., 2009; US EPA, 2015; Yao et al., 2013c). These studies are instructive and provide further insight into real scenarios. However, there is still not simple answer regarding the impact of the lateral separation on the VI process and further analysis are required. In this context, a numerical model is developed to compute both advective and diffusive transfers in VI process for non-degrading chemicals. This model is used to realize a finer study of how factors such as source depth and distance from the building of interest, soil physical properties, building pressure and foundation construction type, may affect the resulting indoor concentration. Finally, a critical review of existing VI models that consider lateral separation is proposed to identify their difficulties to evaluate indoor air concentrations.

## **2. MODEL DEVELOPMENT**

OpenFOAM, used in the present analysis as the modelling tool, is a Computational Fluid Dynamics (CFD) open source software based on C++ programming language for the development of multi-physical simulation tools focused on fluid mechanics. A finite element method is used to solve the soil gas continuity and chemical transport equations in order to simulate VI process. Therefore, the proposed model in this work computes vapor migration through the soil (vadose zone) and their entry into the building via the VI pathways (foundation porosity and existing cracks). This model is based on the following assumptions:

- The pollutant transport is in steady-state.
- The soil is considered as a homogeneous and isotropic porous media.
- The vapor source is constant and infinite.
- There is no transfer through the groundwater and the effects of the capillary fringe are not considered.

- The pollutant entering the building mixes immediately and homogeneously (Johnson and Ettinger, 1991).
- The pollutant is completely diluted as soon as it reaches the soil surface (i.e. the atmosphere).
- Biodegradation and chemical interactions with the media are not considered.
- The transport of pollutants from the source of pollution to the building is governed by the continuity equation (1) and the general transport equation (2):

$$(P^0/\phi_g\mu_g)\nabla(k_gP) = 0 \quad (1)$$

$$\nabla F_i = 0 \quad (2)$$

where  $P$  is the pressure of the soil gas [kg/m/s<sup>2</sup>],  $P^0$  is the pressure to the relative atmospheric conditions [kg/m/s],  $\nabla$  is the vector operator [1/m],  $\phi_g$  is the gas-filled porosity [m<sup>3</sup>/m<sup>3</sup>],  $k_g$  is the soil gas permeability [m<sup>2</sup>],  $\mu$  is the soil gas dynamic viscosity [kg/m/s], and  $F_i$  is the mass flux vector ( $F_i = C_{ig}q_g - D_{ig}\nabla C_{ig}$ ) [kg/m<sup>2</sup>/s], with  $C_{ig}$  the total concentration of the pollutant  $i$  in the soil [kg/m<sup>3</sup>]. Finally, the soil gas specific discharge field is calculated from Eq. 1 and Darcy's law as  $q_g = (k_g/\mu_g)\nabla P$ .

VI process occurs under transient conditions and depend on several parameters (i.e. humidity, biodegradation, fluctuations in atmospheric pressure, ...). However, in this study steady-state conditions are considered which remain consistent with an evaluation of mean values of pollutant transfer over time. Under steady-state conditions, concentrations and pressures are constant with time, although they may vary spatially.

### 2.1. Model Domain and Boundary Conditions

A schematic of the modelling domain is shown in Fig. 2.





No vapor flux boundary conditions are assigned at the lateral and at the lower horizontal boundaries (Eq. 4).

$$\nabla C_{ig} \cdot n = 0 \quad (4)$$

The vapor concentration at the ground surface (soil/atmosphere interface) is prescribed to be the atmospheric concentration (generally approached to be zero) (Eq.5).

$$C_{ig} = C_{ig}^{atm} \quad (5)$$

## 2.2. Vapor Source Concentration

A volume of constant vapor concentration is located in the domain in order to simulate the corresponding vapor source zone (Eq. 6).

$$C_{ig} = C_{ig}^{source} \quad (6)$$

## 2.3. Indoor concentration

The indoor concentration is determined from a steady-state mass balance in the enclosed space (Eq. 7).

$$C_{ig}^{indoor} = J/A_{ex}V_b \quad (7)$$

Where  $J$  is the total flux across the building foundation [kg/m<sup>2</sup>/s],  $V_b$  is the enclosed space volume [m<sup>3</sup>], and  $A_{ex}$  is the air change rate of the building [1/s]. The values of  $C_{ig}^{indoor}$  and  $J$  are obtained iteratively. The iterations stop when the convergence criteria ( $10^{-6}$ ) is reached.

The attenuation factor is frequently used to express the normalize indoor concentration (Johnson and Ettinger, 1991). This factor is defined as the ratio between the indoor pollutant concentration and the source concentration (Eq. 8):

$$\alpha = C_{ig}^{indoor}/C_{ig}^{source} \quad (8)$$

## 2.4. Mesh Generation

In order to solve the governing equations by a finite element method over the domain, the geometry is divided into small volume elements. A variable mesh size is used to provide more details in areas of most interest, i.e. underneath the building. Therefore, a finer mesh was used in the immediate vicinity of the foundation as shown in Fig. 3.

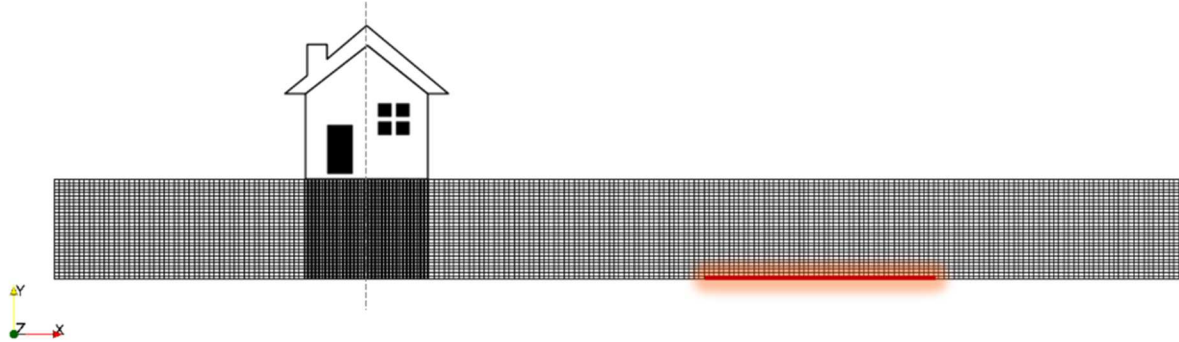


Fig. 3 Vertical cross section – Mesh of the modelling scenario.

The mesh was improved by increasing its density until the overcoming flux obtained became constant and thus the resulting airflow and indoor concentration were too (Table 1).

Table 1 Mesh dependency results.

Number of cells	Airflow (m <sup>3</sup> /s)	Indoor concentration (mol/ m <sup>3</sup> )
2 500 000	0.000226	0.006864
4 900 000	0.000231	0.008476
8 100 000	0.000234	0.011338
14 400 000	0.000234	0.011339

The 8.1 million-cell mesh was chosen as it gave sufficiently accurate results, converging in around 3 minutes. The use of a finer mesh showed slightly improvements in the result but it was about 3 times more of time-consuming. For the scenarios presented herein, a machine of 64 CPU 256 GB of RAM was used.

## 3. RESULTS AND DISCUSSIONS

### 3.1. Numerical Model Validation

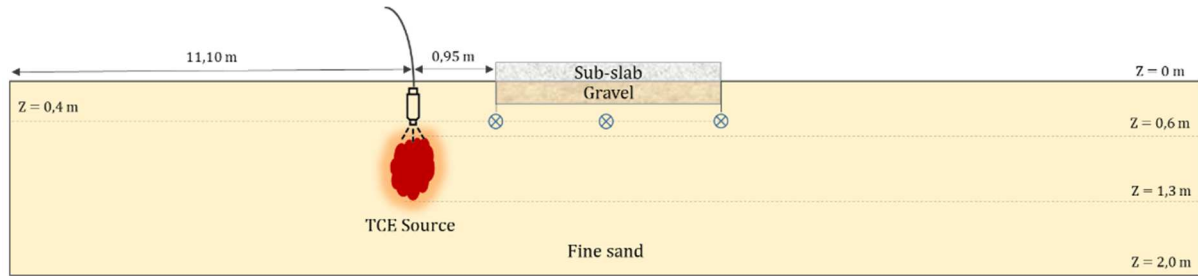
The proposed model is compared to the experimental and existing VI model in order to validate its accuracy to compute VI process.

### 3.1.1. Validation against experimental data

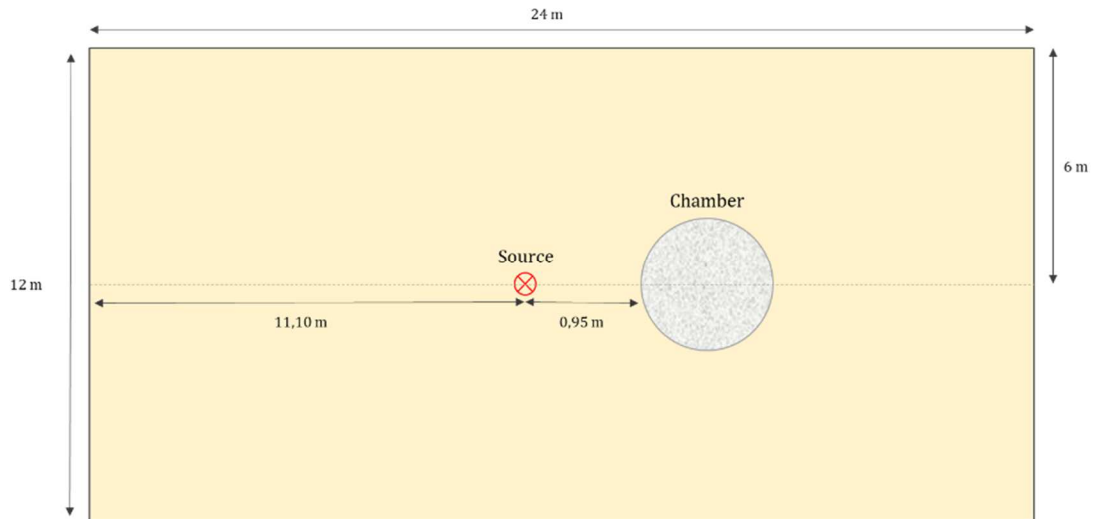
The model has been adapted in order to represent the experimental work done by Marzougui (Marzougui S., 2013) at the Controlled Experimental Research Site for Water and Soil rehabilitation (SCERES), and thus to verify the accuracy of the code to compute VI process.

The SCERES experimental site represents a model of an unconfined aquifer with groundwater table, built in a waterproof basin of reinforced concrete.

The porous aquifer is 24 m long, 12 m wide and 2 m deep (Fig. 4).



(a) Vertical cross section.



(b) Horizontal cross section.

Fig. 4 Experimental set up of SCERES experimental site.

⊗ Measured points of TCE in the vadose zone.

The experiment consists of injecting Trichloroethylene (TCE) into the soil to study the transfer of contaminated vapors through the soil to indoor environments. The source zone is created by injecting 3.5 L of TCE (~ 5.1 kg) for one hour in the vadose zone. The center of the source zone is located on the axis of symmetry of SCERES at a distance of 11.10 m from the horizontal boundaries of the basin, 0.95 m from the upstream edge of the slab, and 6 m from the vertical sidewalls.

The contaminant is injected at 0.60 m of depth from the ground surface and 1.4 m from the top of the groundwater table, extending itself about 0.70 m in the sand from 0.25 m<sup>2</sup> to 0.30 m<sup>2</sup>.

To represent the building environment, a stainless steel chamber is installed on a concrete slab on grade. All physical parameters including effective permeability and diffusion coefficient of soil, gravel and slab were determined on the grade. Installation properties are as follows:

- Soil permeability is  $6 \times 10^{-12}$  m<sup>2</sup>.
- A chamber with a diameter of 1.6 m and a height of 0.5 m.
- Slab on grade permeability of  $4.8 \times 10^{-12}$  m<sup>2</sup>.
- A gravel bed under permeability of  $10^{-9}$  m<sup>2</sup>.

The chamber is exposed to various negative pressures to represent different indoor environment scenarios with a constant air exchange of 1 m<sup>3</sup>/h. In order to monitor TCE vapor concentrations in the vadose zone, three measurement points were determined at 0.4 m below the chamber (Fig. 4a). In addition, the pollutant flux entering the chamber is evaluated for three different indoor negative pressure values (Table 2).

*Table 2 Measured values (Marzougui S., 2013).*

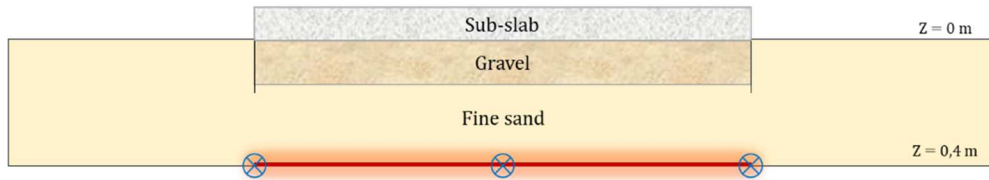
	<b>Measured parameter</b>			
Indoor pressure ( $p_{\text{indoor}}$ )	-5.9	-10.9	-21.4	Pa
Incoming airflow ( $Q_{\text{air}}$ )	0.038	0.064	0.093	m <sup>3</sup> /h
Measured concentration ( $C_{ig}^{\text{slab}}$ )	1684	1903	1715	mg/m <sup>3</sup>

Indoor concentration ( $C_{ig}^{indoor}$ )	64	123.3	160	mg/m <sup>3</sup>
Total pollutant flux ( $J$ )	64	123.3	160	mg/h

From the experience, two modeling configurations are proposed to simulate the pollutant vapors entry into the chamber (Fig. 5).



(a) Lateral source.

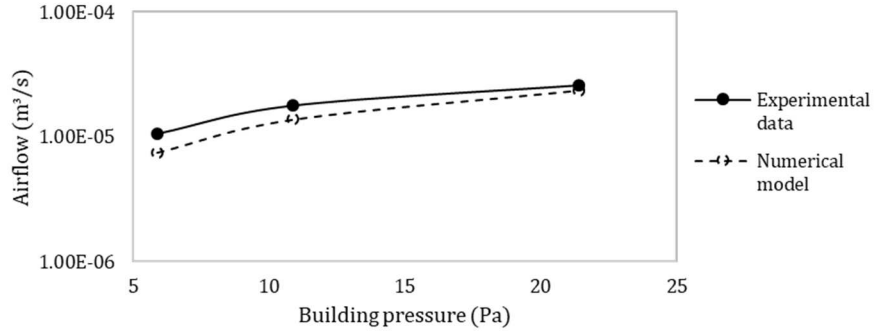


(b) Continuous source.

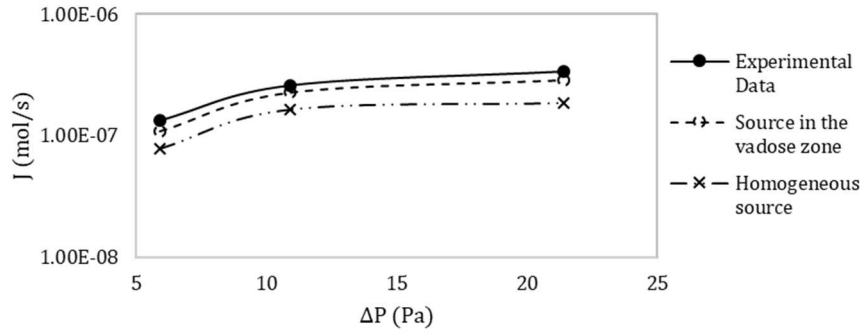
Fig. 5 Schematic of the modelling scenarios.

- Modelling scenario 1 - Lateral source: a source zone of 0.30 m<sup>2</sup> is created in the vadose zone, where the pollutant is injected (Fig. 5a).
- Modelling scenario 2 – Continuous source: an average value is calculated from the three measured concentrations and used to define an equivalent continuous source located below the chamber (Fig. 5b).

According to the assumptions previously described, both pollution scenarios were simulated and numerical results and experimental values are compared in Fig. 6.



(a) Airflow entering into the building.



(b) Total flux entering into the building.

Fig. 6 Comparison between numerical estimations and experimental data - Total flux entering into the building.

Predicted entering airflow estimations are similar to experimental measures. However, numerical model may underestimate the airflow by approximately 29% when the depressurization is 5.9 Pa. These deviations can be explained by the assumptions made for the development of the analytical model and the uncertainties in the measurements to deduce incoming air flow through the slab.

Concentration profile of the numerical model may vary depending on the modeling of the source (Fig. 7).

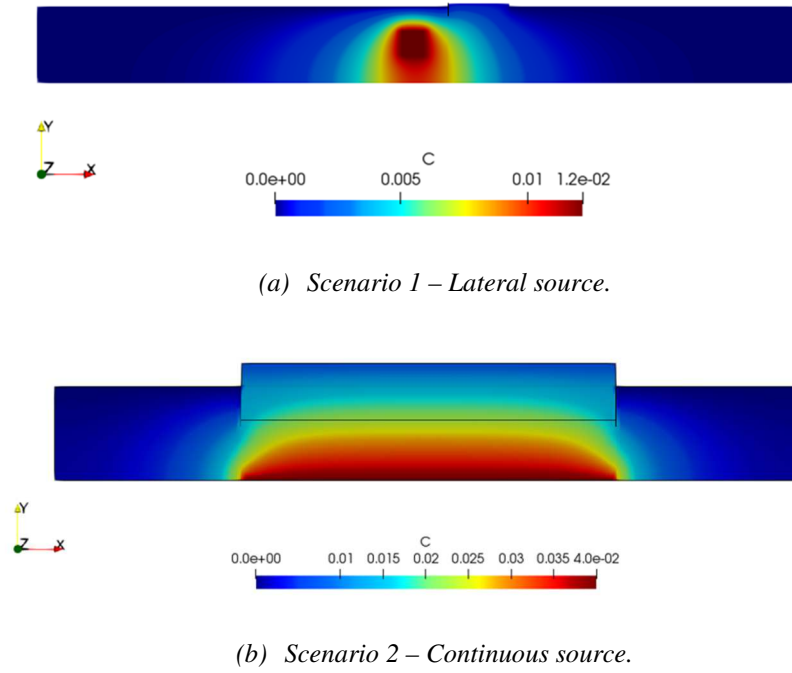


Fig. 7 Vertical cross section – Soil gas concentration profile of continuous source modelling.

However, both modelling scenarios show a close agreement with the measurements (Fig. 6b). The results show that detailed description of the source features increases the accuracy of the estimations. More precisely, the difference with the experimental data when a lateral source is considered, it is only 19%, while modelling a continuous source generates a higher difference of 45%. These differences can be explained on one hand by the uncertainty in the various measurements and on the other hand by numerical modelling assumptions such as the source modelling (i.e. source distribution in the soil).

### 3.1.2. Comparisons with existing VI models

The proposed model was also compared to Abreu et Johnson (Abreu and Johnson, 2005) and Yao et al.'s work (Yao et al., 2013a) to verify its accuracy.

Abreu et Johnson (Abreu and Johnson, 2005) proposed a numerical study in order to study the effect of the lateral source/building separation on VI process.



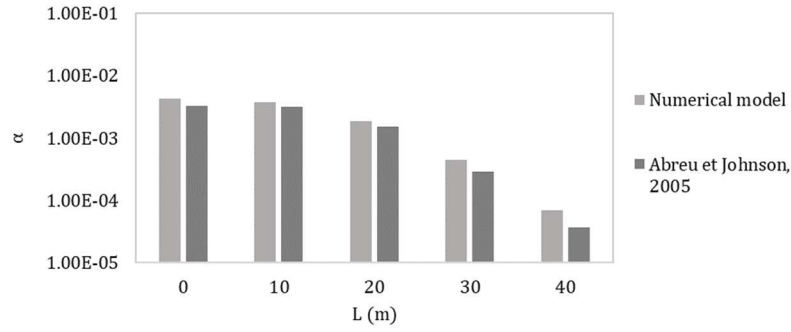


Fig. 8 Comparison between the proposed numerical model and Abreu et Johnson's results (Abreu and Johnson,

2005) -  $H = 8m$  ;  $k_g^{soil} = 10^{-11} m^2$  and  $P_{indoor} = -5 Pa$ .

The comparison between the proposed model and Abreu et Johnson's work show similar results (Fig. 8). Both approaches are in good agreement, even if the proposed numerical model presents higher values of the indoor concentration (average relative error of 42%). These differences can be associated with the differences between both algorithms (finite-difference method is used to solve partial differential equations and boundary conditions in Abreu et Johnson's study) and the assumptions made by the authors.

Yao et al.'s approach allows computing the slab on grade concentration as a function of the source position in the soil including lateral source/building distance. Assuming a homogeneous soil and neglecting advection flow, an analytical solution of the 2D steady state diffusion equation is proposed to describe gas diffusion in the soil (Eq. 9) based on a Schwarz-Christoffel mapping (Schwarz-Christoffel, 1959).

$$\frac{C_c}{C_{source}} = \sqrt{\frac{d_f}{H}} e^{-(L/2H)\pi} \quad (9)$$

The concentration is calculated at the point C (existing crack in the foundations) considered to be the main cause of vapors leakage into the building (Fig. 9).

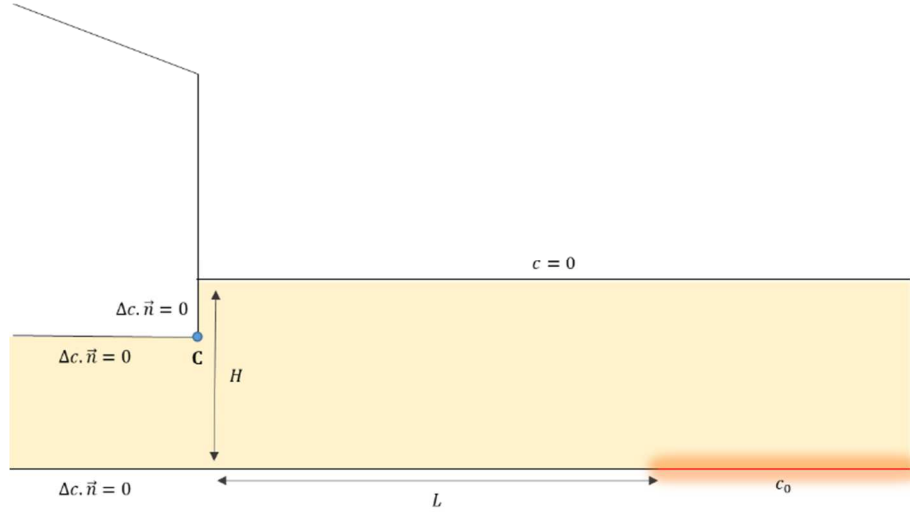


Fig. 9 Schematic of the modelling scenario including lateral source/building distance (Yao et al., 2013a).

An empirical factor is then introduced to the analytical expression (diffusion only), in order to compute the physical characteristics of the pollution scenario, including building depressurization, foundation construction, and soil properties (Eq. 10).

$$\frac{C_c}{C_{\text{source}}} = 0.5 \sqrt{\frac{d_f}{H}} e^{-(L/2H)\pi} \quad (10)$$

This factor has been determined by a numerical study using CFD calculations (Pennell et al., 2009), based on a similar configuration as presented in this study (Fig. 2). Therefore, this solution is independent of soil and building characteristics and depends only on the source location in the soil.

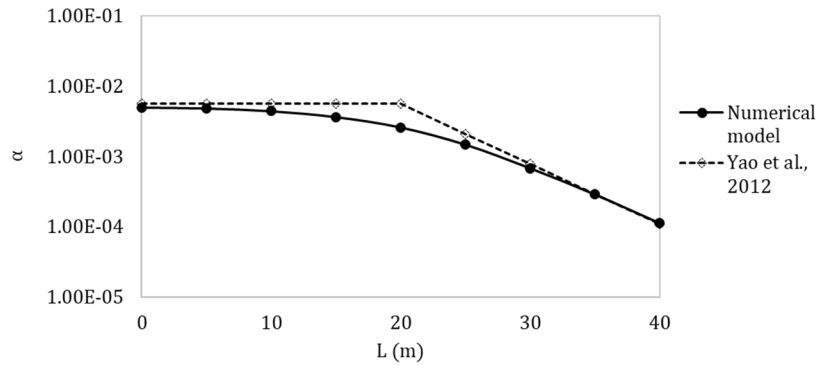


Fig. 10 Comparison between the proposed numerical model and the existing Yao et al. model (Yao et al., 2013c)

$$- H = 8\text{m} ; k_g^{\text{soil}} = 10^{-11} \text{ m}^2 \text{ and } P_{\text{indoor}} = -5 \text{ Pa.}$$

Considering that the source is similar to a contaminated groundwater under the building (Yao et al., 2012), the results show a close agreement between the two approaches (Fig. 10). At  $L = 0$  m, when the source center is aligned with the building center, the attenuation factor is similar with a relative error of 11%. However, even though the variation of the resulting indoor concentration is low under the building, this difference is higher when the source and foundation edges are coincident as Yao et al.'s criteria (Yao et al., 2013a). Their model overestimates the indoor concentration of about 54% compared to the proposed model. In fact, the semi-empirical model only considers an attenuation of the contaminant vapors from  $L = 20$  m, when the edge of the building and the edge of the source are aligned, and a constant concentration is considered under the building. However, even in this zone ( $L < 20$  m), vapors can migrate to the atmosphere when the lateral separation increases generating a higher attenuation of the indoor concentration. Thus, a constant concentration, associated with a homogenous source, cannot be considered anymore. On the other hand, increasing the source/building lateral distance leads to an increase in the attenuation of vapors as previously described. Both models agree with a slight difference when the lateral separation reaches 40 m (8%).

### *3.2. Numerical evaluation of the main drivers of VI in buildings*

In the previous section, the proposed model has been compared to both an experimental data and existing models. In both cases the model has shown its capacity to compute VI process with good accuracy as the differences are discrete and can be explained on one hand by the uncertainty in the various measurements and on the other hand by the modelling assumptions. Therefore, based on the proposed numerical model, the aim of the present section is to analyze the main drivers of VI in buildings. The scenarios studied in this work are limited to homogeneous soil properties, idealized foundations constructions, and recalcitrant chemicals

where degrading chemicals are not considered. Unless otherwise specified in the text and figure, the model inputs are summarized in Table 3.

Table 3 Input parameters of the model.

<b>Building/foundation properties</b>		
Length	10	m
Width	10	m
Foundation type	Bare ground	
Slab on grade/crack thickness ( $d_{slab}$ )	0.20	m
Slab permeability ( $k_g^{slab}$ )	$10^{-13}$	$m^2$
Crack width ( $w_{crack}$ )	0.001	m
Enclosed space volume ( $V_b$ )	250	$m^3$
Air exchange rate ( $A_{ex}$ )	0.5	$h^{-1}$
Indoor pressure ( $p_{indoor}$ )	-4	Pa
<b>Contaminant vapor source properties</b>		
Source size ( $L_s$ )	30 x 30	m
Source depth ( $H$ )	8	m
Source lateral separation ( $L$ )	30	m
Source vapor concentration ( $C_{ig}^{source}$ )	1	$mol/m^3$
Diffusivity in the air ( $D_{ig}^{air}$ )	$7.4 \times 10^{-6}$	$m^2/s$
Overall effective diffusivity in the soil ( $D_{ig}^{soil}$ )	$8.68 \times 10^{-7}$	$m^2/s$
Overall effective diffusivity in the slab ( $D_{ig}^{slab}$ )	$1.20 \times 10^{-8}$	$m^2/s$
<b>Soil properties</b>		
Soil permeability ( $k_g^{soil}$ )	$10^{-11}$	$m^2$
<b>Other properties</b>		
Soil domain in (x, y, z) dimensions	90 x H x 90	m
Dynamic viscosity ( $\mu_g$ )	$10^{-5}$	Pa.s

These inputs (dimension, air exchange rate, pressure, foundation features) are based on the values reported in the literature (Abreu and Johnson, 2005a; Bozkurt et al., 2009; Pennell et al., 2009; Yao et al., 2011; Diallo et al., 2015).

### 3.2.1. Airflow entering into the building

Diffusion is generally the main transfer to determine the concentration profile in the subsurface, but in some cases advection may play an important or even primary role in the contaminant vapors entry in the building (Mendoza and Frind, 1990). Fig. 11 compares the gas concentration in the soil and the attenuation factor for a building at atmospheric pressure, thus without induced advective flow, and a building at -4 Pa.

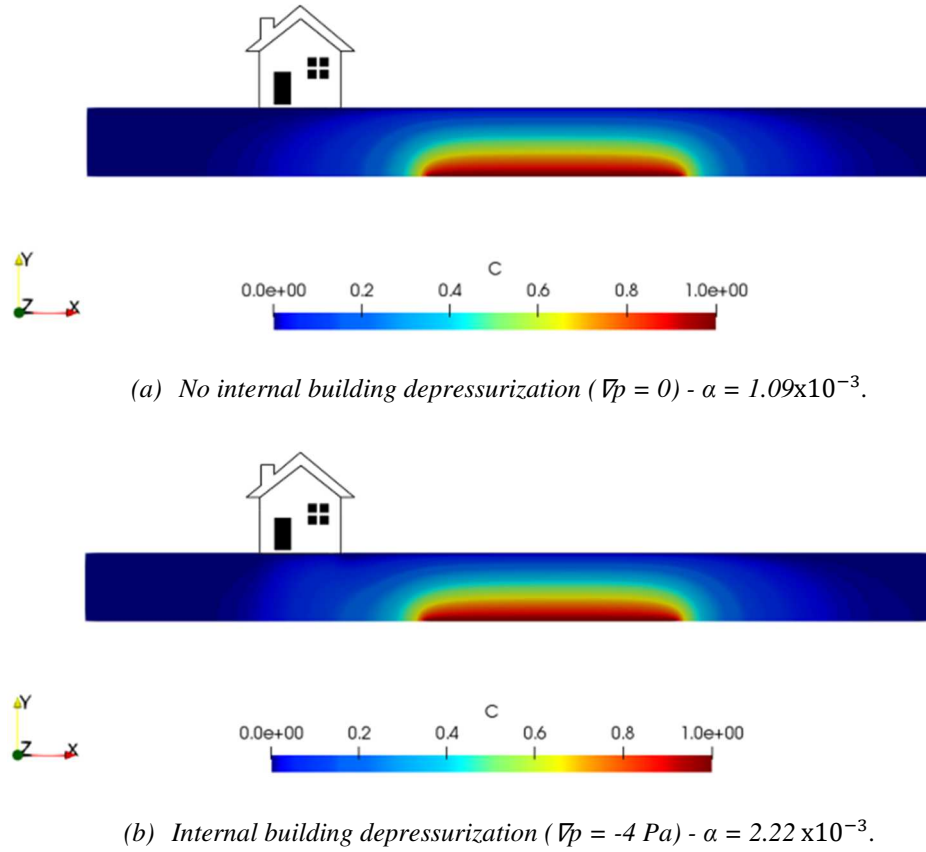


Fig. 11 Vertical cross section (building center) – Soil gas concentration profile.

In this case, iso-concentration lines are not significantly affected by the airflow entering the building. Vapors upward diffusion from the subsurface source towards the ground surface and the building is mainly due to the concentration gradients between the source and both the atmosphere and the indoor space. However, internal building negative pressure may significantly increase the resulting indoor concentration. Indeed, the pressure gradient generates an airflow that is drawn into the soil capturing the contaminant vapors in his pathway in and carries them into the indoor environment, increasing its indoor concentration. The consequence is an attenuation factor twice higher for the building at -4 Pa.

### 3.2.2. Source location in the soil

In classic VI models a homogeneous source in the soil (i.e. polluted groundwater) is commonly considered as the main contaminant source. Therefore, the source location is often described only by the depth between the source and the building. However, the pollution

source distribution in the soil is generally non-uniform and ignoring the lateral source/building distance, when the source is not underneath the building, may generate great mistaken estimation of VI. As mentioned before, the attenuation of the indoor concentration is more important with the lateral source/building separation. The numerical study conducted by Abreu et al. (US EPA, 2015) showed that the attenuation variation is more important for a shallow ( $H = 3$  m) than a deeper one ( $H = 8$  m), accentuating the lateral separation. Therefore, a study of the influence of the source position in the soil on the resulting indoor concentration is proposed for a source depth ( $H$ ) extending from 4 m to 20 m and a lateral separation ( $L$ ) between 0 m and 40 m.

Fig. 12 shows the evolution of attenuation factor ( $\alpha$ ) with the lateral source/building distance for different source depths.

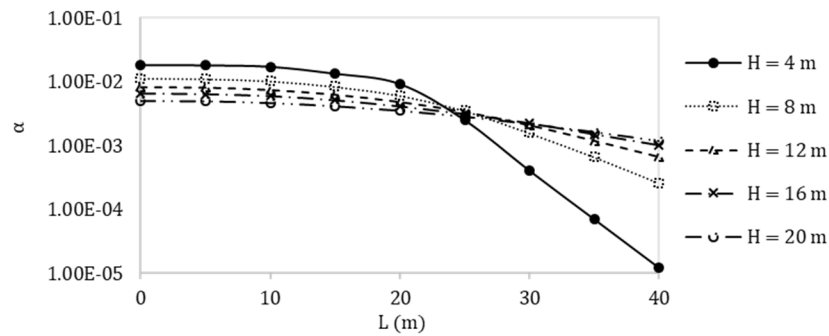


Fig. 12 Attenuation factor evolution as a function of the source/building lateral and vertical distance at different depths.

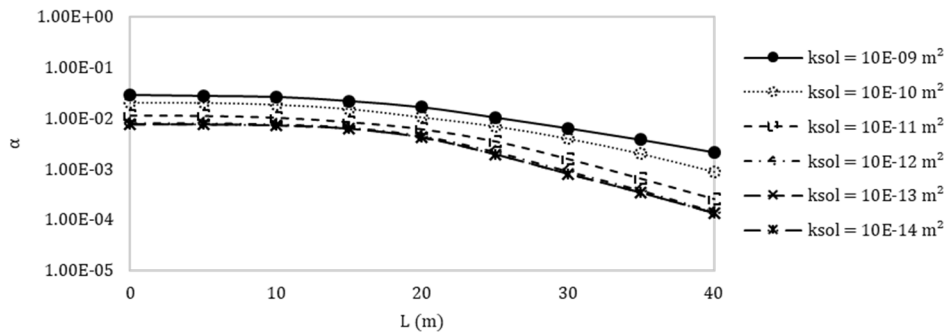
Under the building ( $L < 20$  m), the indoor concentration decreases mostly with the source depth than with the lateral distance. As explained earlier, the vapors migrate vertically straight into the building when the source is positioned under the building. However, when the source is no longer below the building ( $L > 20$  m), the attenuation factor quickly decreases when the lateral separation increases. In particular, comparing a source below the building with another one laterally separated 40 m from the building, both sources being at 4 m depth, the difference is about three orders of magnitude.

As expected, it is shown that the attenuation is more important for shallow sources than for deeper ones (i.e.  $H = 4$  m). Considering a source located at 40 m laterally offset from the building, the attenuation factor is about five orders of magnitude when the source is 4 m deep and only about three orders of magnitude when the source is at 8 m or deeper. Indeed, shallow sources may promote VI when the source is under or near the building. Nevertheless, if the source is close to the ground surface and laterally displaced from the building, the vapors migrate directly to the atmosphere, generating a higher attenuation. On the other hand, increasing the source depth allows the vapors to migrate laterally, and not just preferentially vertically, diminishing the impact of the lateral separation.

### 3.2.3. Air permeability of the soil

In the literature, different studies have shown the influence of different soil configurations, i.e. subsurface heterogeneity barriers, layered soils and covered surfaces (Bozkurt et al., 2009; Pennell et al., 2009; US EPA, 2015). However, in all proposed cases soil permeability values remained constant for given cases. According to the permeability value, soils may vary from a fine to a coarse grained type (W. Nazaroff, 1992; Abdelouhab, 2011). Therefore, a study on the impact of the soil permeability variation on the VI process is proposed.

Fig. 13 shows the evolution of the attenuation factor ( $\alpha$ ) as a function of the lateral source/building distance for different soil permeability values under homogeneous soil conditions.



*Fig. 13 Attenuation factor evolution as a function of the source/building lateral and vertical distance for different soil permeability values –  $H = 8$  m.*

All curves show a similar trend regardless of the soil permeability, i.e. a vapor attenuation with increased lateral source/building distance as shown before. As expected, higher values of soil permeability (coarser soils) generate higher indoor concentrations compared to less permeable (finer) soils. In fact, coarser soils induce indoor concentration of about 10 times higher than finer ones. As explained before, the airflow entering the building carries with it contaminant vapors. Thus, higher soil permeability values result in relatively higher air and contaminant rates into the building.

The variation of the soil permeability value may determine the different weight of both transfer mechanisms, i.e. advection and diffusion, on the VI process (Diallo, 2013). More precisely, for low permeability values ( $k_g^{\text{soil}} < 10^{-12} \text{ m}^2$ ), vapors are mainly transported by diffusion and VI is slightly influenced by advection close to the building. For higher soil permeability values ( $k_g^{\text{soil}} > 10^{-12} \text{ m}^2$ ), the influence of the airflow becomes more important and vapors migrate by both advective and diffusive effects. The combined effects of soil gas concentration and flow rate result in a higher mass contaminant flow rate and thus higher indoor concentration levels.

#### *3.2.4. Building foundation type*

Different building foundation characteristics may have different response against VI (Provoost et al., 2009; Diallo et al., 2015). For example, a building on a bare ground may be more exposed to VI than one on sub-slab on grade (US EPA, 2015). In addition to the former configurations, a supported sub-slab on grade (no peripheral crack), commonly used in France, was considered in order to study the influence of the building foundation characteristics on VI.



Fig. 14 compares the dimensionless indoor concentration ( $\alpha$ ) with the increasing lateral source/building distance for three different construction type: bare ground, slab-on-grade (supported sub-slab), and slab-on-grade including a peripheral crack in the slab (floating sub-slab). Bare ground constructions are not often found in reality but this type of construction is representative of a crawl space on the ground surface (representation of VI into the crawl space).

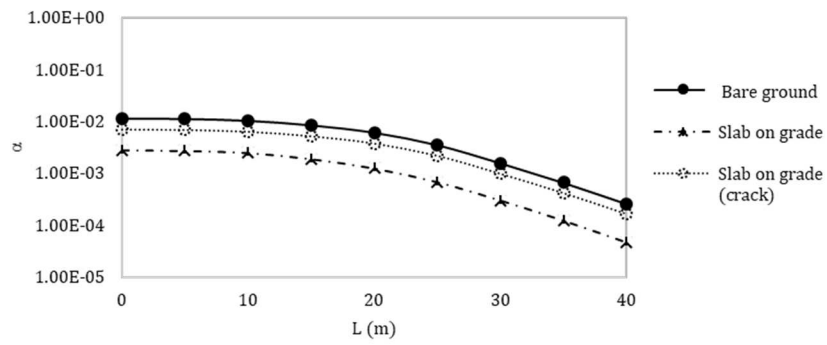


Fig. 14 Attenuation factor evolution as a function of the source/building lateral and vertical distance for different building foundation characteristics -  $H = 8$  m.

The three studied configurations present the same trend: the vapor concentration is reduced with the increase of the lateral distance. Depending on the building construction characteristics, VI may be promoted or reduced. The bare ground configuration may present a higher indoor concentration comparing to both slab on grade configurations. Comparing to the bare ground foundation type, the attenuation factor decreases of about 80% and 50% when a slab on grade without or with a peripheral crack are considered respectively. Slab on grade configurations promote contaminant dilution due to the slab low permeability characterizing these types of construction ( $k_g^{\text{sub-slab}} = 10^{-13} \text{ m}^2$ ). However, existing peripheral crack make sub-slab configuration relatively more permeable, promoting VI. Therefore, a supported sub-slab configuration may be more efficient against VI than a floating sub-slab one.

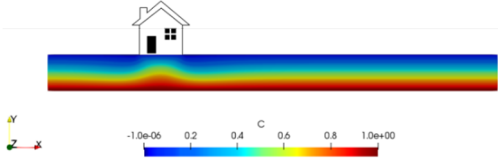
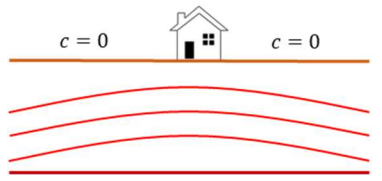
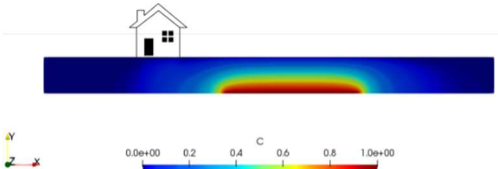
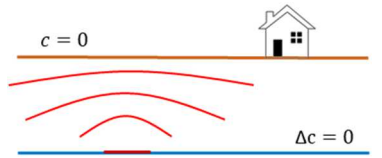
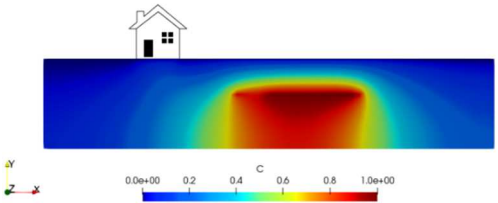
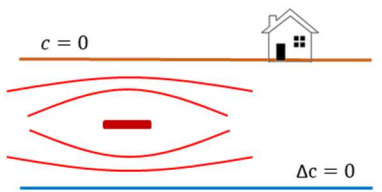
### 3.2.5. Conceptual modelling

Conceptual modelling scenarios are simplified representations according to the characteristics of different polluting configurations (source position, physic soil properties, boundary conditions, ...). Among the different pollution configurations, three representative scenarios have been identified:

- Infinite homogeneous source (generally associated with a contaminated groundwater),
- Finite source at the groundwater level or soil stratification,
- Finite source diffuse source in the vadose zone.

Depending on the pollution configuration, vapor may migrate differently. For example, a vapor source in the vadose zone may diffuse vapors in all directions, unlikely a contaminated groundwater that diffuses vapors only vertically towards the ground surface (Table 4).

Table 4 Description of the characteristics of the different pollution configurations.

POLLUTION SCENARIO	DESCRIPTION	NUMERICAL MODELLING
 <p>(a) Contaminated groundwater - <math>\alpha = 1.61 \times 10^{-2}</math>.</p>	<ul style="list-style-type: none"> <li>Homogeneous source underneath the building.</li> <li>Dissolved in the capillary fringe or in the water table.</li> <li>Spreading, spills, ...</li> </ul>	
 <p>(b) Lateral source at the groundwater level - <math>\alpha = 2.22 \times 10^{-3}</math>.</p>	<ul style="list-style-type: none"> <li>Finite source located at the groundwater level.</li> <li>Dissolved in the capillary fringe or contained by the soil stratifications.</li> <li>Spills, storage sites, ...</li> </ul>	
 <p>Source in the vadose zone - <math>\alpha = 3.93 \times 10^{-3}</math>.</p>	<ul style="list-style-type: none"> <li>Finite source located in the vadose zone.</li> <li>Soil stratifications, ...</li> <li>Gas leaks, storage sites, mine tailings, ...</li> </ul>	

Vapors attenuation is higher when the source is laterally offset from the building, comparing a continuous source under the building (Fig. 15).

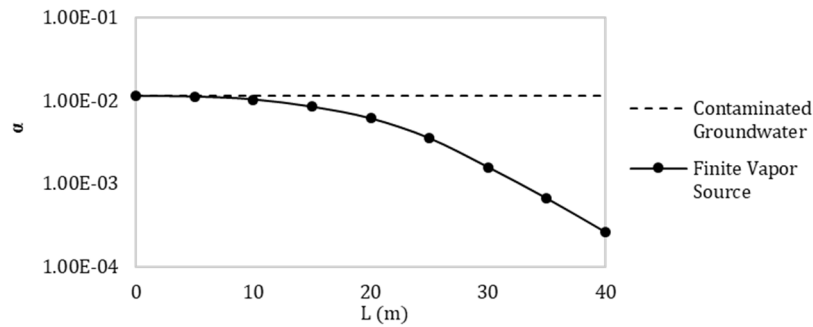
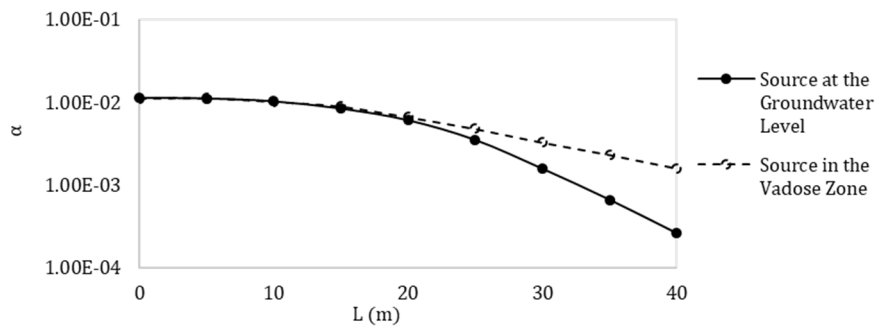


Fig. 15 Attenuation factor evolution as a function of the lateral source/building distance for a contaminated groundwater and a finite vapor source ( $H = 8$  m).

As explained before, vapors migrate more to the atmosphere and less to the indoor environments when they are laterally offset from the building. Differences between both scenarios are greater when lateral distance increase, even if under the building both

configurations may generate a similar indoor concentration. This confirms that homogenous source assumption may not be satisfactory to compute lateral migrations.

On the other hand, most VI models including lateral distance are specific to groundwater vapor sources at the groundwater level (Little et al., 1992; S. Lowell and Eklund, 2004; Abreu and Johnson, 2005a; Yao et al., 2013a; Verginelli et al., 2016), and different assumptions may affect their results and conclusions. For example, considering a pollution source located in the vadose zone and not at the groundwater table level may generate different vapors migration in the subsurface and VI. Abreu et al. (US EPA, 2015) showed qualitative differences on the ground concentration profile (diffusion) when considering a source at the groundwater level positioned at  $H = 8 \text{ m}$  ;  $L = 40 \text{ m}$  and a source in the vadose zone at  $H = 2 \text{ m}$  ;  $L = 30 \text{ m}$ . Here, both pollution scenarios were compared when increasing the lateral separation for a given depth ( $H = 8 \text{ m}$ ) (Fig. 16).



*Fig. 16 Attenuation factor evolution as a function of the source/building lateral distance for a source at the groundwater level and a source in the vadose zone ( $H = 8 \text{ m}$ ).*

In both cases, vapors attenuation increases with the lateral distance as seen earlier. The attenuation of the indoor concentration is not the same and the differences may be more significant with the increasing lateral source/building distance. In particular, underneath the building ( $L < 20 \text{ m}$ ), both configurations present similar indoor concentration. Here, the attenuation factor varies slightly with the lateral source/building distance. However, when the source is no longer underneath the building ( $L > 20 \text{ m}$ ), vapors may migrate differently

generating differences in their estimations. For a source at  $L = 40$  m, vapors attenuation is about 10 times higher when the source is positioned at the groundwater level comparing a source at the vadose zone. In fact, the former configuration promotes upward migration towards the ground surface (building and/or atmosphere), although the space between the source and the water table when the source is in the vadose zone, allows the vapors to migrate in all directions and not just preferentially upwards increasing the indoor concentration. Finally, the results show that the lateral separation influences the most VI process when the source is no longer underneath the building highlighting the differences between both scenarios producing different analyses and interpretations.

### *3.3. Limitations of existing VI models*

Site characterization is carried out using in-situ methods allowing to specify pollution features and soil properties. These data are used as inputs to the modeling tools (either analytical or numerical) to estimate the potential VI and thus to determine indoor concentration levels and associated exposure risks in the building. Different site characteristics may result in great variations on the predicted indoor concentrations. Therefore, a wrong characterization of the pollution scenario (i.e. imprecisions in the description of the source characteristics, soil properties or building features) may generate differences between modelling and reality. On the other hand, assumptions from classic VI models (i.e. homogeneous source distribution), not always meet in reality, are not justified in many cases and may also generate differences in the estimations as shown before (3.2.5).

Existing VI models allowing to compute lateral sources also present strong assumptions limiting their accuracy in the evaluation of indoor air concentrations. For example, Little et al. (Little et al., 1992) considered convection as the main transfer mechanism limited by high pressure gradients not adapted to the study of pollutant transfer in buildings. As explained before, advection may play an important role on VI process under certain conditions (i.e. high

building negative pressure or permeable soils). However, diffusion remains the main transfer mechanism and this approach may not be relevant. S. Lowell and Eklund (S. Lowell and Eklund, 2004) proposed an analytical solution of the diffusion equation to estimate the concentration at the soil surface. Here, soil properties and even building's presence are neglected. This approach can be used to predict vapor diffusion transfer in the soil but it is not adequate to compute VI into buildings. Verginelli et al. (Verginelli et al., 2016) developed a 1D analytical solution including chemical reaction. However, 1D solution are not adapted to compute lateral migrations in many cases (Yao et al., 2013a).

Based on a Schwarz-Christoffel mapping (Schwarz-Christoffel Mapping, 1959) as shown before, Yao et al.'s semi-empirical model (Yao et al., 2013a) can compute the sub-slab concentration by combining both analytical and numerical approaches and can be considered as the most advanced models relative to VI due to lateral sources. However, this model cannot compute other characteristics as building pressure nor construction type than those used in their numerical study to define their empirical factor (i.e. negative pressure of -5 Pa and slab on grade construction type including a peripheral crack). Therefore, deviations in the estimation of indoor air concentrations may occur according to the building features. Layered soil features have been recently included in its latest version (Yao et al., 2015), but then again building features as building pressure, air exchange, volume or even foundation construction type are still not explicitly considered.

To quantify the potential limitations of Yao et al.'s approach (Yao et al., 2013a), the attenuation factor has been calculated for three different construction types and various source locations (Table 5).

Table 5 Comparison of the attenuation factors obtained with Yao et al. model (Yao et al., 2013a) and the present numerical calculations.

Construction type			Sub-slab (crack)	Sub-slab (crack)	Sub-slab	Bare ground
Approach			Yao et al.	CFD		
L (m)	L* (m)	H (m)	Attenuation factor ( $\alpha$ )			
0	0	8	1.12 x10 <sup>-2</sup>	1.13 x10 <sup>-2</sup>	4.10 x10 <sup>-3</sup>	1.83 x10 <sup>-2</sup>
5	0	8	1.12 x10 <sup>-2</sup>	1.11 x10 <sup>-2</sup>	4.00 x10 <sup>-3</sup>	1.80 x10 <sup>-2</sup>
10	0	8	1.12 x10 <sup>-2</sup>	1.03 x10 <sup>-2</sup>	3.70 x10 <sup>-3</sup>	1.66 x10 <sup>-2</sup>
15	0	8	1.12 x10 <sup>-2</sup>	8.42 x10 <sup>-3</sup>	3.00 x10 <sup>-3</sup>	1.36 x10 <sup>-2</sup>
20	0	8	1.12 x10 <sup>-2</sup>	6.08 x10 <sup>-3</sup>	2.20 x10 <sup>-3</sup>	9.81 x10 <sup>-3</sup>
25	5	8	4.19 x10 <sup>-3</sup>	3.51 x10 <sup>-3</sup>	1.20 x10 <sup>-3</sup>	5.66 x10 <sup>-3</sup>
30	10	8	1.57 x10 <sup>-3</sup>	1.57 x10 <sup>-3</sup>	5.70 x10 <sup>-4</sup>	2.54 x10 <sup>-3</sup>
35	15	8	5.88 x10 <sup>-4</sup>	6.63 x10 <sup>-4</sup>	2.40 x10 <sup>-4</sup>	1.07 x10 <sup>-3</sup>
40	20	8	2.20 x10 <sup>-4</sup>	2.60 x10 <sup>-4</sup>	9.40 x10 <sup>-5</sup>	4.20 x10 <sup>-4</sup>

\*Equivalent lateral distance for Yao et al. approach.

These difference are mainly associated with the characteristics of the construction type as mentioned earlier (3.2.4). Semi-empirical model generates until 91% lower indoor concentrations comparing to a building on bare ground and until 80% higher indoor concentrations comparing to a sub-slab on grade (Fig. 17). These values are specific of the assumptions made in this study ( $p_{\text{indoor}} = -5 \text{ Pa}$ ;  $A_{\text{ex}} = 0.5 \text{ h}^{-1}$ ), however, these differences may even increase under more extreme conditions (i.e. permeable sub-slab).

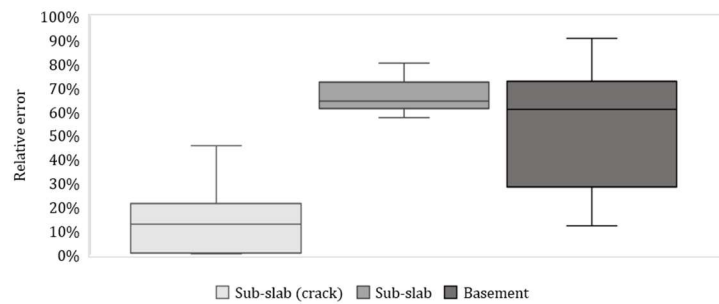


Fig. 17 Relative error between Yao et al. model (Yao et al., 2013a) and the present numerical calculations.

Therefore, even if these models are able to compute vapors transfer in the soil (i.e. sub-slab concentration), they present notable errors when building features (construction type, building pressure, air exchange, ...) move away from the ones considered in their conceptions.

#### **4. CONCLUSION**

A numerical model was developed to compute VI process for non-degrading chemicals. The accuracy of this model was validated by comparisons with both experimental and analytical studies. This model was then used to study the main drivers of VI in buildings i.e. source depth and distance from the building of interest, type of source modeling, soil physical properties, building pressure and foundation construction. Results show that the accuracy of VI estimations depends on the precision of the description of the pollution scenario and that changes in its characteristics (i.e. source position and distribution, soil properties, building pressure or type of construction) may lead to variations of several orders of magnitude in the predicting pollutant concentration in the building. Moreover, VI models including source lateral separation are unable to account for the diversity of building constructions in terms of foundation type and building pressure. As those models are limited to conditions close to the assumptions taken during their elaborations, more precise calculations, such as those presented here, are required when moving away from their limitations. The present study also shows that building pressure and building-soil interface (i.e. foundation type) have to be considered in the evaluation of VI in buildings. Tools combining pollutant transfer from the soil with ventilation codes would allow to evaluate indoor concentration levels over time as a function of building features (ventilation system, air permeability, ...) and meteorological conditions (wind, temperature, ...). However, numerical calculations such as those used in this study are too time-consuming so that analytical or semi-empirical models are still to be improved to properly account to lateral sources and building features.

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