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2D Semi-empirical models for predicting the entry of soil gas pollutants into buildings

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ABSTRACT

The entry and the accumulation of soil gas pollutants (Radon, VOC's, ...) into indoor environments can cause significant health risks. Some analytical and numerical models have been developed to quantify the soil gas indoor concentrations in order to assess their health risks. However, the different models include large uncertainties in understanding and assessing the indoor soil gas concentrations. Firstly, this study presents a general understanding of the behavior of these pollutants near building foundations. Secondly, it describes semi-empirical models developed to quantity the entry of these pollutants into buildings. These models consider the most encountered building substructures: supported slab, floating slab and crawl space. Particularly, these models consider the strong coupling of convection and diffusion phenomena near building foundations. The two-dimensional aspect of the phenomena is considered. The models have been evaluated by comparison with experimental data. These models can be easily integrated into building simulation tools in order to assess the soil gas concentration in indoor environments.

1. Introduction

Soil gas pollutants (VOC's, radon) enter into buildings mainly by convective and diffusive transports, through various leakages: cracks, openings due to different pipes, ducts through the foundation and porosity of floors (slabs). The different models used to quantify the transport of soil gas pollutants include large uncertainties in assessing the impact of these pollutants on indoor air quality [1]. There is a need to improve these existing models to better assess health risks associated with these pollutants. The convective transport of soil gas pollutants into buildings is due to small pressure differences between indoor and outdoor environments created by stack effect, wind interaction with the building shell, heating, ventilation and air-conditioning systems [2]. The diffusive transport is due to concentration gradient of the pollutant between the soil and the indoor environment. In the literature, since 1980s, some analytical and numerical models have been developed, initially with the emphasis focus on the radon entry into the buildings [2–7]. In the field of VOC's intrusion into buildings, a range of analytical [8–17] and numerical models [18–24] have been developed. In this paper, we focus on the analytical models used as screening tools to assess the entry of the soil gas pollutants into buildings. These analytical models are more accessible to the field practitioners, in the sense that they do not require running a 3-dimensional numerical model [18,24]. Three-dimensional numerical models are used to examine in more detail the influence of environmental factors in the contaminant vapor concentration attenuation processes [18]. Most existing analytical models are 1-dimensional [8–15]. Some 2-dimensional analytical models have been developed recently [16,17]. The analysis of the widely used analytical models, the Johnson Ettinger model [9], the Volasoil model [11] and the improved Volasoil model [14], to assess the entry of the pollutants regarding the transport mechanism shows:

(1) A lack of clarity on the consideration of transfer mechanisms at the soil/building interface for the most frequent building substructures: crawl space (cs), supported slab (ss) and floating slab (fs).
(2) Some uncertainty in the boundary conditions for the main phenomena, convection and diffusion, near foundations.
(3) A failure in taking into account the 2-dimensional or 3-dimensional aspect of the combined transfer phenomena, which could overestimate the entry rate of the pollutants into the building.

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(4) A no consideration of the mass flux of pollutants toward atmosphere, which could overestimate the entry of pollutants into the building, especially for a pollution source nearby the building foundations.

More Recently Yao et al. [16] developed a 2-dimensional model to estimate the sub slab vapor concentration near a sub slab perimeter crack by using conformal transformation of the Schwarz-Christoffel [25]. In this model, the convection transfer is neglected in the soil and is only considered to estimate of soil gas flux through the crack in order to quantify the indoor air vapor concentration. The diffusion is assumed as the main contaminant gas transport mechanism in soil. Shen et al. [17] also used Schwarz-Christoffel mapping to estimate sub slab volatile organic vapor concentration from a non-uniform source. The convection transfer is not considered in this model. It assumes that the indoor air vapor concentration can be calculated by using the average sub slab vapor concentration [13] or vapor concentration near the crack [24].

Given the above shortcomings regards the transfer mechanisms, we propose to bring in this study:

- A better understanding of the behavior of pollutants in the vicinity of foundations through a numerical study performed by using numerical simulation of the combined gas transfer in the soil. This two-dimensional numerical study considers the strong coupling of the convection and diffusion phenomena near building foundations.
- Based on the understanding of transfer mechanisms involved, semi-empirical models which consider the above gaps to improve the transport of soil gas pollutants into buildings are presented. The developed models were confronted with experimental data found in the literature.

2. Material and methods

2.1. Numerical study: comprehension of the soil gas pollutants transport near building foundations

2.1.1. Equations

The models developed in this study are called semi-empirical because they are obtained by combination of numerical experiments and analytical models. The numerical experiments are performed using Comsol code [26]. The study is done under the following assumptions:

- The transfer is two-dimensional and stationary.
- The soil and the floor slab are treated as homogenous and isotropic porous media.

The pollutant transport from the pollutant source to the indoor building is governed by the continuity equation and the stationary convection–diffusion equation [22,23]:

$$\vec{\nabla}\vec{u} = 0 \qquad (1)$$

$$D_{\mathrm{eff}}\vec{\nabla}C + \vec{u}C = 0 \qquad (2)$$

where u (m/s) is the velocity vector, C (mol/s) the soil gas concentration and D_{eff}, the effective diffusion coefficient.

- The airflow in the soil and slab is governed by Darcy's law.
- The pollutant is located either in the soil underneath building or at the level of the capillary zone, the transport in the saturated soil is not modeled.
- The pollutant is located directly underneath the building, a lateral source to the building is not considered in this study.

Indoor air is ideally mixed, so any pollutant entering the building is distributed immediately by the airflow and evenly [9]. The transfer of pollutant to the atmosphere is considered, the pollutant is assumed fully diluted when it reaches the atmosphere. Thus, at the air-ground interface, the concentration of pollutant is assumed to be constant and equal to zero [27]. With this condition, the diffusive flux to atmosphere becomes maximal. Physically, it correspond to a very high value of surface transfer coefficient. Sometimes, the transfer from soil to air can be attenuated by a boundary layer. Some authors considered a notion of concentration boundary layer at the air-ground interface [11,14]. This boundary layer is considered via a mass transfer coefficient. The difficulty is then to estimate this mass transfer coefficient that depends on many parameters like the thickness of the boundary layer or the airflow regime at the air-ground interface.

- The diffusion coefficient of the soil is not influenced by the variation of the soil permeability; the diffusion coefficient of the slab is not affected by the variation of the permeability of the slab. The assumption that considers the soil diffusion coefficient is not correlated with its permeability is acceptable according to the Fen's study [28] for the studied soil permeability range from 10^{-9} to 10^{-14} m^2. Concerning the floor slab diffusion coefficient, the absence of a clear correlation with the permeability in the literature leads to assume that these two parameters are not correlated.
- The biodegradation of pollutants and chemical interaction of the pollutant with the different media are not considered.
- In this study in a first approximation, the variation of the soil humidity can be taken into account via the effective diffusion coefficient and the permeability of the soil. The variation of the soil humidity can affect the soil permeability. In the unsaturated zone, the pores can partially be occupied by the air and the water. In the saturated zone, the pores are fully occupied by the water. The variation of the humidity can also affect the diffusion of pollutants, indeed for pollutants with a weak constant Henry. The presence of a small soil layer with weak diffusion coefficient leads to the reduction of diffusive flux to many orders of magnitude [22]. Some authors indicated that in certain cases, the density driven advection may be a significant transport mechanism in natural soils. Cotel et al. [29] and Marzougui et al. [30] indicated that with soil column containing high vapor concentrations without significantly increased vapor pressures, the dominant transport mechanism is advection caused by the vapor density effect. In this paper, the thermal and humidity gradients are not considered.

2.1.2. Studied domains and boundary conditions

The studied domain and the boundary conditions are presented for each substructure. The substructures are presented in symmetrical configurations. The width of the soil domain outside the building is equal to the half of the bare soil width of the crawl space. This limitation of the width of the soil outside the building has a negligible impact on airflows from outside the building [32,33]. For each substructure, the boundary conditions are summarized in Table 1.

The indoor pollutant concentrations (C_{cs}, C_{ss} and C_{fs}) and pollutant fluxes (J_{cs}, J_{ss} and J_{fs}) are obtained iteratively by the