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Can atmospheric pressure and water table fluctuations be neglected in soil vapor extraction?

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ABSTRACT

Solutions to soil vapor extraction (SVE) are indispensable to characterize the unsaturated zone and to optimize SVE. Most of the existing solutions neglect the fluctuations of atmospheric pressure and water table. This study presents a new semi-analytical solution for SVE by considering the atmospheric pressure and water table fluctuations. Comparisons between the new and previous solutions indicate that the water table effect is negligible but the atmospheric pressure effect is non-negligible for the interpretation of gas pressure in a non-coastal site where the daily water table fluctuation is in centimeters scale; both the water table and atmospheric pressure fluctuations need to be considered in a coastal site where the daily water table fluctuation is in tens of centimeters scale. Tidal-induced downward moving water table increases the depth-averaged radius of influence, which is insensitive to atmospheric pressure fluctuation. Less vertical gas permeability leads to greater atmospheric pressure and water table effect.

1. Introduction

Gas flow in the unsaturated zone is a very important research subject in many disciplines including hydrology, soil science, environmental engineering, geotechnical engineering, etc. [1–5]. The atmospheric pressure on the ground surface and the water table serve as the upper Dirichlet type and lower variable flux type boundary conditions for such a gas flow problem. Traditionally, for the convenience of mathematical treatment, these two boundary conditions are assumed to be fixed and independent of time [2,3,5]. In reality, gas flow in the unsaturated zone will inevitably be affected by atmospheric pressure fluctuations on the ground surface. In addition to this, it will be affected by water table fluctuations, particularly when the unsaturated zone is close to an ocean where the daily tide may induce considerable water table fluctuations. Now the question is: can we neglect the effects of atmospheric pressure and water table fluctuations when dealing with gas flow in the unsaturated zone? If the answer is yes, under what constrains? This article tries to answer these questions based on a rigorous analysis.

Generally, there are two types of atmospheric pressure fluctuation. One is the diurnal change induced by solar/terrestrial heating and cooling effects. This diurnal atmospheric pressure fluctuation has been described by a sinusoidal function [6]. The other is the irregular transit of a cold or warm front, which can cause atmospheric pressure to change as high as 20–30 mbar within 24 h [7]. This type of atmospheric pressure fluctuation is sometimes described by a first order linear function.

Water table fluctuation could be induced by seasonal variations of precipitation, melt-frozen effect, evapotranspiration, cyclic pumping of near-by wells, stream stage change, earthquake, land usage, climate change, ocean tides, etc. [8–11]. The increase of temperature decreases surface tension and expands air volume entrapped in capillary pores, drives water down to the phreatic surface, and increases water level, and vice versa [8]. This effect lags in time depending on the depth to water table. The diurnal barometric cycles resulting from the solar heating/cooling effect can also cause the contraction or expansion of air volume in the capillary fringe and the fluctuation of water level in a shallow aquifer [8]. Turk [8] found that the water table varied daily up to 1.5–6 cm in summer and 0.5–1.0 cm in winter, the highest one occurred in late afternoon and the lowest in middle morning in a shallow aquifer at the Bonneville Salt Flats, Utah. Besides, water level is found to change with plant water usage, which is controlled daily by the global irradiance and seasonally by global irradiance and temperature. However, if the primary source of plant water is unsaturated zone, water table fluctuation will be greatly diminished [10]. At a non-coastal site, water level does not necessarily fluctuate in a given aquifer setting (for example, a deep water table), and the fluctuations are usually limited to a few centimeters in amplitude. However, at a coastal site, water table fluctuates regularly with the diurnal and semi-diurnal tidal effects [12,13].

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Atmospheric pressure and water table fluctuations usually have a small influence on subsurface gas pressure change and mass transport compared with that induced by well extraction or injection. However, pressure fluctuation could significantly increase the rate of vapor-phase contaminant transport in fractured media and can be an important mechanism for driving vapor-phase contaminant out of the unsaturated zone without active pumping [14–16]. It is the dominant driving force in passive soil vapor extraction [1,6,17,18]. Dixon and Nichols [19] suggested that when interpreting data from the unsaturated zone gas pumping test, atmospheric pressure fluctuation should be carefully examined.

The high-frequency, and often high-amplitude water table fluctuation in a coastal area plays an important role in gas flow in unsaturated zone. It causes the dome-shaped heave feature in the extensively paved coastal areas of Hong Kong [20,21]. The increase of the magnitude and frequency of the water table fluctuation could nonlinearly increase the advective flux of volatile organic compounds (VOCs) in the subsurface [22].

In soil vapor extraction (SVE) analyses, atmospheric pressure and water table fluctuations are commonly neglected [2,3,5,23–32]. However, some salient questions remain unanswered. Should we really ignore the terms of atmospheric pressure and water table fluctuations in SVE? How much error will be induced from neglecting their effects? The purpose of this study was to build a theoretical basis or evaluation criterion for determining if atmospheric pressure and water table fluctuations can be neglected in SVE models. A new two-dimensional (2D) semi-analytical solution taking into account the atmospheric pressure and water table fluctuations in SVE will be developed and analyzed to answer the questions above.

2. Mathematical models

2.1. Development of the new solution

The coordinate system for 2D gas flow in SVE in an unsaturated zone is set as follows. The origin of the coordinate system is set at ground surface. The z-axis is vertical, positive downward and through the axis of the gas injection/extraction well [18], where gas flows at a rate of Q (L^3T^{-1}) and Q is positive for injection. The r-axis is horizontally radial. The unsaturated zone is open to the atmosphere, and has a thickness of h (L). The gas injection/extraction well is screened from the depth of a to b (L).

Assuming the unsaturated zone to be homogenous but vertically anisotropic, the linearized governing equation for the transient gas flow is [2,5,18]:

$$\frac{nS_g\mu_g}{P_{\rm avg}}\frac{\partial P^2}{\partial t} = k_r\frac{\partial^2 P^2}{\partial r^2} + \frac{k_r}{r}\frac{\partial P^2}{\partial r} + k_z\frac{\partial^2 P^2}{\partial z^2}, \tag{1}$$

where t is time (T); P is the subsurface gas pressure ($ML^{-1}T^{-2}$); $P_{\rm avg}$ is the average gas pressure ($ML^{-1}T^{-2}$); k_r and k_z are the radial and vertical gas permeabilities (L^2), respectively; n is the porosity (dimensionless); S_g is the volumetric gas-phase saturation (dimensionless); μ_g is the gas dynamic viscosity ($ML^{-1}T^{-1}$).

Eq. (1) is a linearized gas flow equation simplified from the nonlinear one by assuming a constant gas compressibility $1/P_{\rm avg}$ [2,32,33]. The study of Massmann [32,33] demonstrated that the error induced from this approximation is only a few percent of the exact solution for a vacuum being less than 0.5 atm.

The radial and vertical gas permeabilities k_r and k_z are dependent on soil moisture, which could be redistributed by water movement induced by gas injection or extraction through the well in SVE [5]. Therefore, k_r and k_z vary with space and time, which complicates the problem greatly. In order to obtain a simple semi-analytical solution, we neglect the heterogeneity of k_r and k_z in this study as in previous studies, such as Baehr and Hult [5].

When the fluctuation of the atmospheric pressure is taken into account, the gas pressure at the upper boundary should be altered from the common treatment of a constant average pressure to the time-dependent atmospheric pressure $P_{\rm atm}(t)$, that is,

$$P^2 = P^2_{\rm atm}(t), \quad z = 0. \tag{2}$$

When the fluctuation of the water table is taken into account, the lower boundary condition should be altered from the common treatment of no-flux boundary to

$$\left.\frac{\partial P^2}{\partial z}\right|_{z=h} = -\frac{2P_{\rm avg}nS_g\mu_g v_{\rm wt}(t)}{k_z}, \quad z = h, \tag{3}$$

where $v_{wt}(t)$ is the velocity of the water table movement (LT^{-1}). Eq. (3) is derived by applying Darcy's law to the water table to calculate the water table movement velocity from the pressure gradient. This same treatment is employed in Choi and Smith [22]. One should note that in Eq. (3), the depth of the water table is fixed to be h, and the shape of the water table is assumed to be horizontal. However, the depth and the shape of the water table or the unsaturated zone thickness actually fluctuate. The error induced by this assumption will be checked in Section 2.2.

The well casing is a no-flux boundary, while the well screen is a fixed-flux boundary, which are described by

$$\lim_{r\to 0} r\frac{\partial P^2}{\partial r} = 0, \quad 0 < z < b,\ a < z < h, \tag{4a}$$

$$\lim_{r\to 0} r\frac{\partial P^2}{\partial r} = -\frac{QP^*\mu_g}{\pi k_r(a-b)}, \quad b \leqslant z \leqslant a, \tag{4b}$$

where P^* is the gas pressure where Q is measured ($ML^{-1}T^{-2}$).

The lateral boundary is infinitely far from the well, thus will not affect gas flow to/from the well [18]. We arbitrarily choose a fixed-pressure boundary at the lateral infinity [18]. Therefore,

$$P^2 = P^2_{\rm avg}, \quad r \to \infty. \tag{5}$$

Increasing the initial subsurface gas pressure would increase the average value of the subsurface gas pressure the same amount as that of the initial one uniformly across the unsaturated zone at steady state, and vice versa. For convenience, the initial subsurface gas pressure is assumed to be uniform and equals the average gas pressure [18]. Thus, one has

$$P^2(t=0,r,z) = P^2_{\rm avg}. \tag{6}$$

For simplicity, we use the following parameters to transform Eqs. (1)–(6) into dimensionless ones:

$$t_D = \frac{k_zP_{\rm avg}}{h^2nS_g\mu_g}t, \quad r_D = \frac{r}{h}\sqrt{\frac{k_z}{k_r}}, \quad z_D = \frac{z}{h}, \quad a_D = \frac{a}{h}, \quad b_D = \frac{b}{h},$$
$$\phi_D = \frac{P^2 - P^2_{\rm avg}}{P^2_{\rm avg}}, v_{\rm wtD} = -\frac{2hnS_g\mu_g}{P_{\rm avg}k_z}v_{\rm wt}, \quad f_D = \frac{P^2_{\rm atm} - P^2_{\rm avg}}{P^2_{\rm avg}},$$
$$Q_D = -\frac{QP^*\mu_g}{\pi k_r(a-b)P^2_{\rm avg}}. \tag{7}$$

Substituting Eq. (7) into Eqs. (1)–(6), one has

$$\frac{\partial\phi_D}{\partial t_D} = \frac{\partial^2\phi_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial\phi_D}{\partial r_D} + \frac{\partial^2\phi_D}{\partial z_D^2}, \tag{8}$$

$$\phi_D(t_D=0,r_D,z_D) = 0, \tag{9}$$

$$\phi_D = f_D, \quad z_D = 0, \tag{10}$$