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Unidirectional gas flow in soil porosity resulting from barometric pressure cycles

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Abstract

During numerical simulation of air flow in the vadose zone, it was noticed that a small sinusoidal pressure would cause a gradual one-way migration of the pore gas. This was found to be a physical phenomenon, not a numerical artifact of the finite element simulation. The one-way migration occurs because the atmospheric pressure, and hence the air density, is slightly greater when air is flowing into the ground than when air is flowing out of the ground. A simple analytic theory of the phenomenon is presented, together with analytic calculations using actual barometric pressure data. In soil of one Darcy permeability, the one-way migration is of the order of a few tenths of a meter per year for either plane flow from ground surface or for radial flow from an open borehole. The migration is sufficiently small that it will have no practical consequences in most circumstances; however, investigators who conduct detailed numerical modeling should recognize that this phenomenon is not a numerical artifact in an apparently linear system.

Keywords: Soil venting; Atmospheric pressure; Vadose zone; Harmonic analysis; Barometric pumping

1. Introduction

Measurement of the penetration of barometric pressure variations into subsurface soil can reveal its hydrologic properties (Weeks, 1978; Rousseau et al., 1999; Neeper, 2002).

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Various authors have investigated barometric flows in open boreholes, for the purpose of extracting contaminant vapors (Ellerd et al., 1999; Rossabi and Falta, 2002; Neeper, 2003). In a continuing investigation of vapor transport due to barometric flow, we simulated a deliberately exaggerated sinusoidal, isothermal one-dimensional flow of pore gas with the FEHM code (Zyvoloski et al., 1997). FEHM includes the nonlinear effect of compressibility that occurs with gas flow in porous media, although in this case the pressure variation was sufficiently small that the flow was proportional to the pressure amplitude. The purpose of this particular simulation was to investigate numerical dispersion; however, we noticed that a purely sinusoidal pressure variation gradually displaced the pore gas in a direction away from the source of the varying pressure. This small unidirectional displacement was superimposed upon the expected larger periodic motion. Without critical evaluation, one might expect that a small sinusoidal pressure would cause only a sinusoidal motion of the pore gas. Because the unidirectional displacement was unexpected, we conducted an analytic investigation, finding that this displacement has a physical basis, even in the regime of small pressure variations. We report our findings here so that other investigators will not suspect a numerical artifact when such unidirectional flow appears in their simulations.

2. Example of a simulation

Fig. 1 presents the simulated concentration of an inert vapor-phase tracer in a 40-m isothermal column of soil that is exposed to a sinusoidal pressure at one end, with a constant pressure at the opposite end. Numerically, the tracer does not contribute to the total pressure of the gas. Gravity was not present in the simulation. Advective transport of the tracer was started only after the periodic motion nearly achieved steady state. Initially, the tracer concentration (in arbitrary units) was zero at depths less than 10 m, and one at greater depths. Fig. 1 shows that the profile of concentration appeared deeper in the column at times near the end of each 5-day pressure cycle. In this simulation, both the diffusivity and mechanical dispersivity were set to zero, so the increasing width of the concentration profile was caused by numerical dispersion. With transport by diffusion only, the location at which the concentration equals 0.5 would remain at the original

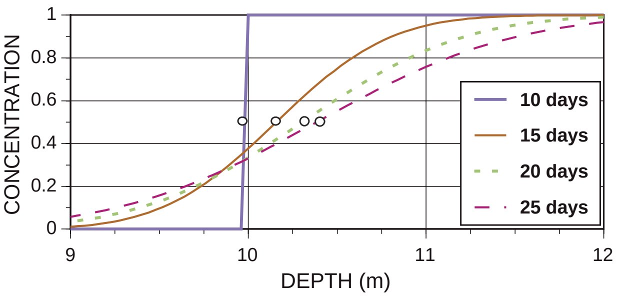

Fig. 1. Profiles of concentration (in relative units) at the end of successive 5-day cycles. Transport started after the flow had achieved steady state at 10 days. Points mark the successive locations of gas with concentration 0.5.

location of the step in concentration (Carslaw and Jaeger, 1959); that is, at the 10 m depth. To the extent that numerical dispersion is similar to diffusion, we therefore expected the concentration profile to remain centered at 10 m. This is an example of the problem that led us to the analytic investigation reported below. In part, we wished to discover under what conditions the unidirectional flow might be of practical concern.

3. Analytic investigation of plane periodic flow

3.1. Displacement due to a single frequency

We consider an infinitely deep, isothermal, uniform soil exposed to a small sinusoidal pressure variation at its surface. Although the flow is not in phase with the pressure, the atmospheric pressure is higher, and the air density consequently larger, during most of the time when air is flowing into the ground than when air is flowing out of the ground. This is the physical origin of the unidirectional flow. For a small particular pressure component of amplitude P_{n0} and angular frequency ω_n, the total pressure at any depth, y, is (Neeper, 2003)

$$P(y,t) = P_{00} + P_{n0}e^{-\beta_n y}\cos(\omega_n t + \phi_n - \beta_n y). \quad (1)$$

The resulting face velocity (so-called “superficial velocity” or “Darcy velocity”) is

$$V_n(y,t) = \sqrt{2}\frac{k}{\mu}\beta_n P_{n0}e^{-\beta_n y}\cos(\omega_n t + \phi_n - \beta_n y + \Phi). \quad (2)$$

In plane geometry, the phase lead of velocity ahead of pressure, Φ, is $\pi/4$.

At ground surface ($y=0$) the air density is

$$\rho(0,t) = \rho_0\frac{P(0,t)}{P_{00}} = \rho_0\left[1 + \frac{P_{n0}}{P_{00}}\cos(\omega_n t + \phi_n)\right], \quad (3)$$

and the mass flux into the surface is

$$\frac{dM_n}{dt} = \rho(0,t)V_n(0,t). \quad (4)$$

The net transfer of mass per unit area, during one cycle, is obtained by integrating Eq. (4) through time for one cycle. The result is

$$M_n = \sqrt{2}\pi\rho_0\frac{k}{\mu}\frac{\beta_n}{\omega_n}\frac{P_{n0}^2}{P_{00}}\cos(\Phi). \quad (5)$$

The net volume of air transferred into the ground in one cycle, per unit area, is M_n/ρ_0. If the flow is uniform throughout the porosity and the small variation of air density with depth is neglected, the air injected during one cycle of this single frequency component would occupy all porosity within a distance, D, of the surface, given by:

$$D = \frac{\pi}{\sqrt{2}}\left(\frac{P_{n0}}{P_{00}}\right)^2\delta_n\cos(\Phi). \quad (6)$$

In Eq. (6), δ_n is the exponential penetration distance for a pressure component of angular frequency ω_n. ($\delta_n = 1/\beta_n$). The pore gas velocity is assumed to be V_n/θ. Eq. (6) may also be obtained (although with greater mathematical effort) by integrating $V_n(y)/\theta$ through one cycle and discarding small terms.

To estimate the magnitude of D, we consider a sinusoidal pressure component with amplitude 500 Pa (5 mbar), period of 5 days, and an average pressure of 1×10^5 Pa, acting on soil of permeability 1×10^{-12} m^2 (1 Darcy) and porosity 0.5. In this case, δ_n and D are approximately 39 m and 1.5 mm, respectively. D is less than a characteristic distance for diffusion of many volatile organic contaminants during the 5 days.

In infinitely deep soil, the unidirectional motion could continue indefinitely in time. However, for any geometry with an impermeable lower boundary, such as a water table, a small steady pressure gradient would develop to oppose the motion. Furthermore, this calculation presumes that the actual gas velocity is uniform throughout the porosity, which does not necessarily represent the microscopic situation.

3.2. Displacement due to a barometric spectrum

For small pressure variations, the velocity of the pore gas at a fixed location depends linearly on the pressure at ground surface. However, a particle of gas encounters different phases of pressure as it moves to different locations, so its velocity depends on its instantaneous position as determined by its previous motion. Therefore, the displacement from an initial position due to a harmonic set of pressure components is not the sum of displacements calculated for each component independently. To investigate the effect of actual barometric variations, we formed the Fourier transform of a selected 256-day window of measured, winter season barometric pressure history, and numerically integrated the pore gas movement. (This analytic investigation did not involve the FEHM code).

At each time, the superficial velocity is given by a sum of terms like that of Eq. (2). For any initial depth, y_i, the position and velocity of a gas particle at time t are given by the pair of equations

$$U(t) = \frac{1}{\theta} \sum_n V_n(y, t) \tag{7}$$

$$y(t) = y_i + \int_0^t U(t')dt', \tag{8}$$

in which the sum is over the Fourier frequency components.

The data window was selected so as to have no trend in the pressure (Neeper, 2002, Appendix A). Thus, at the end of the 256-day window, all components of the Fourier spectrum have progressed through an integral number of cycles and the pressure is equal to that at the start of the window. If the motion were a linear function of pressure, any particle of gas that did not emerge from the ground would have returned to its initial position. However, at the end of 256 days, the gas is displaced from its initial position. Fig. 2 presents the barometric pressure history and the motion of gas particles initially located at

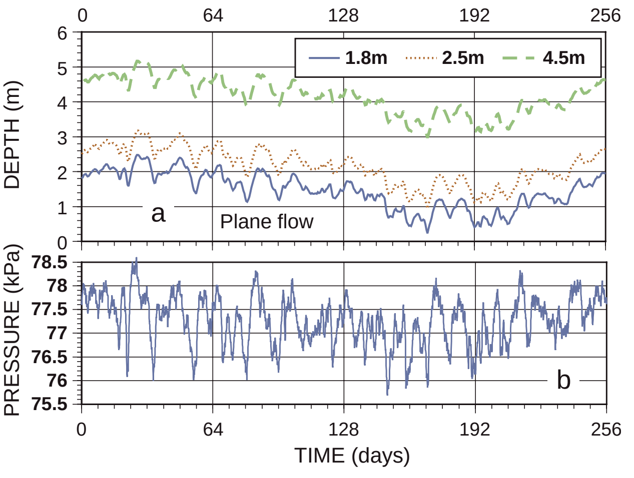

Fig. 2. a) Depth vs. time, for three values of initial depth. b) Pressure history.

depths of 1.8, 2.5, and 4.5 m. Gas at smaller initial depths emerges from ground surface at $y=0$ at some time during the window, thereby interrupting the progression of the unidirectional flow. Fig. 3 presents the displacement after 256 days as a function of the initial depth. Figs. 2 and 3 show that barometric variations cause the pore gas to move back and forth by approximately 1 m in each direction, but the unidirectional displacement is much smaller.

As mentioned above, the continuous accumulation of air in soil with an impermeable lower boundary would eventually result in a steady pressure gradient that would exactly oppose the incoming flux. Thus, the unidirectional flow is usually of little practical consequence. However, the unidirectional flow might be significant above a cavity or geologic stratum that can dissipate the slow accumulation. The basalt described by Neeper (2002) may be a physical example of such a stratum.

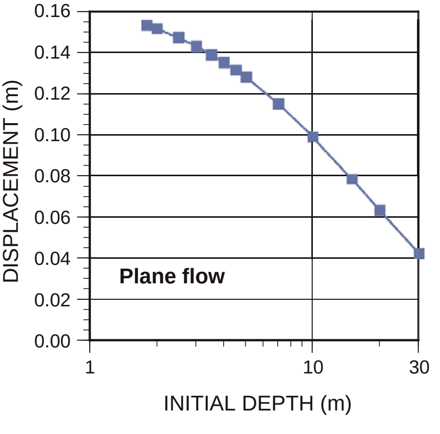

Fig. 3. Displacement after 256 days.

4. Radial flow at a borehole

The unidirectional flow outward from a cylindrical borehole may be estimated by a calculation analogous to that for infinitely deep soil. If there were no penetration of pressure from ground surface (e.g. a sealed surface), the superficial radial velocity near a vertical borehole corresponding to Eq. (2) for plane flow, would be (Neeper, 2003)

$$V_n(r,t) = \sqrt{2}\frac{k}{\mu}\beta_n P_{n0}\frac{N_1(r)}{N_0(r_b)}\cos(\omega_n t + \phi_n + \Phi), \tag{9}$$

in which Φ is usually $< \pi/4$ and N_1/N_0 is >1 near $r = r_b$. Thus, near a borehole, the phase of velocity is closer to the phase of pressure, and the magnitude of velocity is larger than at a plane ground surface. To investigate whether the unidirectional flow from a borehole might be significant, we integrated the motion of pore gas, using the same barometric history and soil properties as the calculation for plane flow. Fig. 4 presents the pore gas motion for three initial values of radius, with a borehole radius of 0.1 m. As expected, gas moves back and forth over a larger distance than that of the plane case illustrated in Fig. 2. Gas initially at a radius less than 5.5 m emerges into the borehole.

In the first 60 days of the window, the pressure is generally rising and the flow is predominantly from the borehole into the ground. The location of a gas particle depends upon the prior pressure history; therefore the unidirectional displacement depends on the prior pressure history. Consequently, we made a second calculation starting at Day 139, after which the pressure is generally decreasing and the predominant flow is toward the borehole for the subsequent 60 days. The Fourier transform represents an endless sequence of 256-day cycles, so this second calculation started at Day 139 and continued to Day 395. In effect, the pressure history subsequent to Day 256 is the pressure history subsequent to Day 0. This procedure enables a calculation using the same pressure spectrum as the first radial calculation, but with a different initial direction of flow. Fig. 5 presents the motion. All gas at an initial radius less than 7.5 m emerges into the borehole.

The solid curve in Fig. 6 presents the displacement after 256 days, which is somewhat smaller than the displacement shown in Fig. 3 for the plane case. The

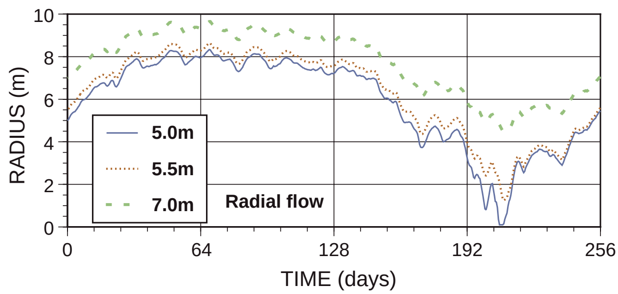

Fig. 4. Location vs. time for three initial values of radius.

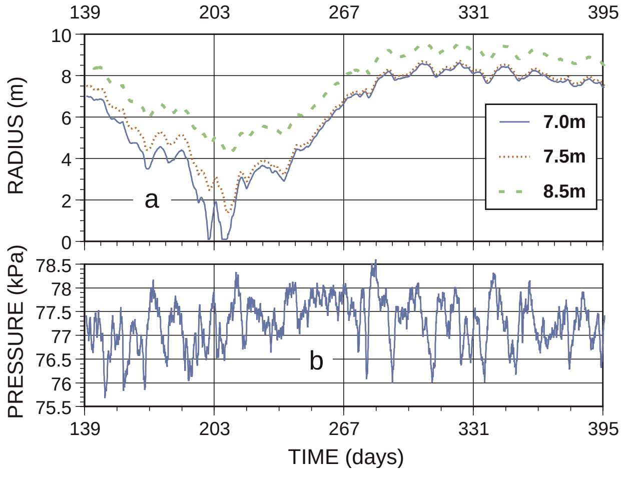

Fig. 5. a) Radius vs. time for three values of initial radius. b) Pressure history, starting at Day 139.

dashed curve in Fig. 6 presents the final displacement after 256 days of movement for the calculation that began at Day 139. Despite the great difference in the initial motions of the two calculations presented in Fig. 6, the final displacements are similar. This leads us to conclude that a particular pressure spectrum will generate approximately the same long-term unidirectional displacement, no matter when the motion is initiated. The unidirectional displacement is always much smaller than the transient displacement due to the diurnal and synoptic pressure variations, and is probably negligible when compared to the effects of mechanical dispersion and flow in preferential pathways.

As noted by Rossabi and Falta (2002), and by Neeper (2003), a realistic analysis of barometric flow in an open borehole must consider not only the radial pressure gradient

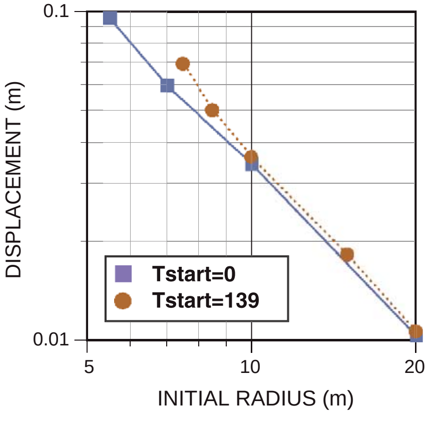

Fig. 6. Displacement after 256 days of motion vs. initial radius, starting either at zero or 139 days.

from the borehole itself, but also the competing pressure that penetrates from ground surface in a nearly plane fashion. The calculations presented here ignored the competing pressure, and thereby exaggerate the estimated flow at a borehole.

As illustrated in Neeper (2003), the amplitudes (P_{n0}) of barometric pressure components generally increase with period. The penetration length, δ_n, also increases with period. Therefore, by Eq. (5), the components with longer periods are more influential in causing unidirectional plane flow. A similar argument applies to radial flow. In general, an investigator should be cautious in ascribing influence to individual Fourier components. For example, the displacement cannot be represented as a linear sum of displacements due to individual frequency components, because the particle velocity at any time depends on the location, as determined by the previous time-integral of the sum of all velocity components.

5. Conclusion

A cyclic history of pressure will cause a small, progressive displacement of pore gas into the soil from ground surface or from an open borehole. In most circumstances of practical interest, the unidirectional gas flow will be negligible. However, when conducting simulations, investigators should be aware of this phenomenon.

Notation

D	Unidirectional displacement of the pore gas from ground surface
k	Permeability
M	Mass per unit area of air entering the ground
N_0, N_1	Magnitudes of Bessel functions
n	Subscript denoting a frequency component
P	Pressure
P_{n0}	Amplitude of a sinusoidal component of pressure at zero depth
P_{00}	Time-averaged atmospheric pressure
r	Radius from center of a borehole
r_b	Radius of a borehole
t	Time
U	Actual velocity of gas within the soil porosity
V	Face velocity of the pore gas
y	Vertical depth below ground surface
β	$(\omega\mu\theta/2kP_{00})^{1/2}$, exponential factor for pressure attenuation
δ	$1/\beta$, exponential characteristic length for pressure attenuation
θ	Porosity
μ	Viscosity of air
Φ	Phase of the velocity relative to phase of pressure
ϕ	Phase of a frequency component of atmospheric pressure
ρ	Density of air
ρ_o	Density of air at the average pressure, P_{00}
ω	Angular frequency

Acknowledgment

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