Eng. & Tech. Journal, Vol. 28, No.10, 2010

Flow Zones In Unsaturated Soil Due To Barometric Pumping

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Received on: 19/11/2009
Accepted on:11 /3 /2010

Abstract

The study of gas flow in unsaturated soil is important for better modeling of volatile organic compounds (VOCs) transport. A gas flow in unsaturated soil can be induced naturally by the atmospheric pressure fluctuation. Oscillations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of longer time periods, resulting from the passage of weather fronts. Daily variations will average about 4 to 5 mbar while those due to weather front passage can be 25 mbar or more.

A one-dimensional conceptual model was used to investigate the advective gas flow zones in the subsurface induced by the natural atmospheric pressure fluctuation. From analytical solution, it is clear that the gas phase inside unsaturated zone moves with sinusoidal velocity whose amplitude decrease with depth. Two zones can be distinguished. First in which the gas phase can reach the soil surface and continuously mixed with clean air. The depth "Penetration Depth" of this zone may range from 0.05m to 0.8m. Second is "Oscillation Zone" in which the air oscillates around its original position but still remains in the soil. Maximum air displacement toward the upper boundary may reach 0.24m when the depth of the lower impermeable boundary is 10m. This displacement is more as the lower impermeable boundary is deeper. The mixing of air above penetration depth with clean air above soil surface and the oscillation of air below penetration depth may have a significant effect on natural VOCs transport and fate in the soil region within these depths.

Keywords: Barometric pumping; Volatile organic compounds; unsaturated zone; Mathematical modeling; Advective transport

مناطق الجريان في التربة غير المشبعة بفعل الضخ الجوي

الخلاصة

أن دراسة جريان الغاز في التربة غير المشبعة مهمة للوصول الى نمذجة رياضية أفضل لأنتقال المركبات العضوية المتطايرة. اذ يحصل جريان غاز في التربة غير المشبعة وبصورة طبيعية نتيجة التذبذبات في الضغط الجوي. حيث يحصل التذبذب في الضغط الجوي على نمطين، الأول تذبذب يومي يناغم التسخين والتبريد اليومي للهواء الجوي، والثاني تذبذب بفترات اطول ناتجا من مرور منخفظات أو مرتفعات ضغط جوي. يتراوح التذبذب اليومي للضغط الجوي حوالي 4 – 5 ملي بار، في حين ممكن أن يصل التذبذب الناتج من مرور منخفظات أو مرتفعات ضغط جوي الى 25 ملي بار أو أكثر.

تم اعتماد نموذج رياضي ذو بعد واحد لدراسة جريان الغاز تحت سطح التربة متأثرا بتذبذبات الضغط الجوي. يوضح الحل التحليلي للنموذج الرياضي أن الطور الغازي في المنطقة غير المشبعة من التربة يتحرك بسرعة جيبية تتناقص سعتها مع العمق. ويمكن تمييز منطقتين، الأولى يمكن للغاز الوصول الى سطح التربة ويختلط وبصورة مستمرة مع الهواء النظيف

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ويبلغ سمك هذه المنطقة من 0.05 الى 0.8 متر، والثانية والتي يتذبذب فيها الهواء حول موقعه الأصلي ويبقى داخل التربة. اذ من الممكن أن تصل سعة التذبذب في هذه المنطقة الى 0.24 متر عندما يكون عمق الحدود غيرالنفاذه السفلى 10 متر. وتزاد سعة التذبذب هذه كلما كان عمق الحدود غير النفاذه اكبر. أن اختلاط الهواء في المنطقة الأولى مع الهواء النظيف فوق سطح التربة وتذبذب الهواء في المنطقة الثانية ممكن أن يكون له تأثيرذو قيمة على الأنتقال الطبيعي للمركبات العضوية المتطايرة في التربة ضمن هاتين المنطقتين.

Introduction

Volatile organic compounds (VOCs) were identified as one of the more ubiquitous groups of hazardous chemical present in contaminated groundwater due to widespread uses of VOCs in the manufacturing of pesticides, plastics, paints, and pharmaceuticals, and textiles. These contaminants may enter the ground as separate phase liquid due to chemical spill, or leaking storage tanks [1]. In the unsaturated zone, VOCs constitute a health hazard when they reach groundwater through a multitude of transport processes. A detailed understanding of factors affecting the transport of VOCs in the unsaturated zone is necessary for better risk assessment.

Modeling VOCs transport in the unsaturated zone involves a number of transport (advection, dispersion, diffusion) phenomena coupled with phase change and reaction processes (volatilization, sorption, and biodegradation). These processes and phenomena are usually important in both the aqueous and gas phases. However, some of these transport mechanisms, such as, density driven gas flow, sorption from the gas phase to the solid phase, and NAPL capillary rise, may not be critical in each contamination case or their importance may not be fully realized [2]. Study of gas flow in unsaturated soils is important for better modeling of VOCs transport. Gas flow induced either naturally by the atmospheric pressure fluctuation or artificially by vapor extraction which is the major mechanism for cleaning up vadose zone contamination with volatile organic chemicals [3]. Gas flow induced by the atmospheric pressure fluctuation is the process on which the passive soil vapor extraction (PSVE) is based and being developed as an in-situ contaminant extraction methodology for sites where the volatile contaminants reside in the vadose zone [4,5] However, unavoidable gas flow (in uncapped soils), induced naturally by the atmospheric pressure fluctuation, has not been considered or quantified in previous studies delt with VOCs transport in upper region of unsaturated zone. Jury et al. [6] introduced a screening analytical model intended to classify and screen organic chemicals for their relative susceptibility to different loss pathways (volatilization, leaching, and degradation) in soil. The illustrative calculations in this study deal with initial depth of incorporation of chemicals in soil of 1cm and 10cm from soil surface. The transport in gas phase was considered to be governed by diffusion process only.

Jury et al. [7] introduced a screening analytical model which evaluates the relative volatilization losses of a number of organic compounds under typical soil conditions. The model identifies those compounds with high potential for loss during 1 year after incorporation under 100cm of soil cover. The same study deals with incorporation depth ranges from 1mm to 166m. The transport in gas phase was considered to be governed by diffusion process only.

Grathwohl and Mair [8] performed numerical simulations in order to assess the diffusive spreading of volatile fuel constituents, their biodegradation in unsaturated zone and degassing to the atmosphere. This is especially important in arid region where the groundwater table is far below the surface and groundwater recharge is limited. In these simulations the source was emplaced in the subsurface at 1m depth. No advective gas phase transport was considered. Poulsen et al. [9] used numerical model to evaluate the impact of vapor sorption on VOC transport from the unsaturated zone to the atmosphere. Model simulations deal with soil-water content in the few centimeters depth below the soil surface. Barometric pressure variations effect on advective gas flux in this region did not considered in these simulations.

Natural atmospheric pressure fluctuation are transmitted through the unsaturated subsurface. These pressure waves are damped and delayed in phase to degree dependent on the effective vertical permeability of the formation. As a result, at a given time the atmospheric pressure at the surface and soil gas pressure in the subsurface are different [10]. Shan [3] developed one dimensional analytical solution to the air pressure in the unsaturated zone driven by time-dependent air pressure at the upper boundary using field data to determine vertical air permeability in unsaturated soils. The solution can also be used to calculate the gas flow rate crossing the land surface under natural conditions. This natural air flow is determined by barometric pressure fluctuations, permeability of the subsurface, and depth of lower impermeable boundary.

The purpose of this paper is to present a conceptual study to the advective gas flow zones in the subsurface induced by the atmospheric pressure fluctuation that may be useful for VOCs transport and fate modeling studies.

Mathematical Model

Oscillations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of longer time periods, resulting from the passage of weather fronts. Daily variations will average about 4 to 5 mbar while those due to weather front passage can be 25 mbar or more [4].

A typical record of atmospheric pressure pattern is shown in Fig. (1). Barometric pressure record for Baghdad city for year 2007, obtained from Iraqi meteorological office and seismology organization show pattern approximate. Although, the record shows inherently random meteorological conditions, a time series analysis may be used to capture the main features of the variation.

Daily variation component and weather front passage component can be captured. It is clear that the weather front passage component is the most significant component.

Due to linearity (superposition feature) of mathematical model used to predict pressure variation in soil (next section), this study deals with a hypothetical sinusoidal component of amplitude 12.5 mbar with a period of 10 days. A one-dimensional model is useful to capture the main features of gas flow phenomena induced in the upper region of unsaturated zone.

Analytical determination of pressure variation with time and space

The governing equation of the problem of gas flow in a porous medium is driven from the conservation-of-mass principle as follows [11, 12]:

$$n\frac{\partial P}{\partial t} = \frac{k_r}{m}\nabla.\left(P\nabla P\right) \qquad \ldots\ldots\ (1)$$

n = soil porosity
P = pressure (Pa)
t = time (sec)
k = intrinsic soil permeability (m^2)
k_r = dimensionless relative permeability (-)
m = gas viscosity (Pa.sec)

This equation is nonlinear. Under circumstance where the gas pressure in the whole system does not vary by a large magnitude (e.g., less than 20% of the mean pressure), Eq.(1) can be simplified to a linear form without causing significant error. The expected magnitude of atmospheric pressure variation is less than 2.5% of the mean pressure. Therefore for the purpose of conceptual study, one can start ith a linearized governing equation. In case of one-dimensional gas flow, such an equation is [11, 12]:

$$\frac{\partial P}{\partial t} = a\,\frac{\partial^2 P}{\partial x^2} \qquad \ldots\ldots\ldots\ (2)$$

Where

$$a = \frac{k_r P_a}{nm} \quad (m^2/sec)$$

P_a = mean pressure (Pa)

The system under consideration is conceptualized as shown in Fig. (2). As described in the previous section a uniform sinusoidal pressure fluctuation is assumed at the upper boundary. No flow is assumed at the lower boundary:

$$\left(\frac{\partial P}{\partial x}\right)_{x=0} = 0 \qquad \ldots\ldots\ldots\ (3)$$

x = distance from lower boundary (m)

$$P(l,t) = P_a + A Sin(wt) \qquad \ldots\ldots\ldots\ (4)$$

where
A = Amplitude of pressure fluctuation (Pa)
w = Angular frequency of fluctuation (sec^{-1})

and

$$P(x,0) = P_a \qquad \ldots\ldots\ldots\ (5)$$

The analytical solution for the problem described by Eq.'s (2)-(5) is in accordance with [13].

$$P = P_a + A^{'} Sin(wt + f) +$$
$$+ 4pk^{'}\sum_{n-0}^{\infty}\frac{\left(\left(-1\right)^{n+1}\left(2n+1\right)\left(4l^2 w\right)\right)}{16l^4 w^2 + k^{'2} p^4 \left(2n+1\right)^4} *$$
$$* Exp\left(-k^{'}\left(2n+1\right)^2 p^2 t/4l^2\right) *$$
$$Cos\frac{\left(2n+1\right)px}{2l} \qquad \ldots\ldots\ldots\ (6)$$

where

$$A^{'} = A\left\{\frac{Cosh2k^{'}x + Cos2k^{'}x}{Cosh2k^{'}l + Cos2k^{'}l}\right\}^{\frac{1}{2}} \ldots(7)$$

$$f = \arg\left\{\frac{Coshk'x\left(1+i\right)}{Coshk'l\left(1+i\right)}\right\} \qquad \ldots\ldots\ldots\ (8)$$

$$k^{'} = \left(\frac{w}{2a}\right)^{\frac{1}{2}} \quad ,\ w = \frac{2p}{T_o} \qquad \ldots\ldots\ldots\ (9)$$

T_o = time for complete pressure variation period (sec).

l = depth of unsaturated zone (m).

The first term of Eq.(6) is the steady state solution, the second term the transient and the last term drop to zero after a short time. The steady periodic solution of the pressure for the system considered is:

$$P(x,t) = P_a + A^{'}Sin(wt+f) \quad \ldots (10)$$

The quantities $A^{'}$ and f are the amplitude and phase of the steady pressure oscillation at the point x. These are functions of the two dimensionless quantities x/l and $k^{'}l$.

If the surface pressure can be represented by the Fourier series

$$\sum_{m=1}^{\propto} a_m Sin(mwt) \quad \ldots\ldots\ldots. (11)$$

The steady periodic part of the solution is

$$\sum_{m=1}^{\propto} a_m A_m Sin(mwt + f_m) \ldots\ldots. (12)$$

Although Shan [3] presented an analytical solution that can be used to calculate the gas pressure in the unsaturated soil under normal natural conditions using barometric pressure pattern in tabulated form, Eq.(12) suggests that the same result can be reached when dealing with the problem mathematically in frequency domain, using methodology that is well developed for theory of communication engineering. In the frequency domain, we determine the response by multiplying the Fourier transform of forcing function by the system function [14] as follows:

In general, for any function $f(t)$:

$$F(iw) = \int_{-\propto}^{\propto} Exp(-iwt).f(t).dt \quad \ldots.. (13)$$

$$f(t) = \frac{1}{2p}\int_{-\propto}^{\propto} Exp(iwt).F(iw).dw \quad \ldots.. (14)$$

Where $F(iw)$ is the integral Fourier transform of $f(t)$

For the system considered in this study, the system function $H(iw)$ can be obtained from Eq. (10) as:

$$H(iw) = \frac{A^{'}}{A} Exp(if) \quad \ldots\ldots. (15)$$

$$F\{P(x,t)\} = F\{P(l,t)\}.H(iw) \quad \ldots\ldots (16)$$

Where $F\{P(l,t)\}$ is the integral Fourier transform of the forcing function. Then:

$$P(x,t) = F^{-1}[F\{P(l,t)\}.H(iw)] \ldots (17)$$

Gas flow velocity, travel time, and flow lines

After the gas flow equation is solved , interstitial gas velocity can be calculated using Darcy's law:

$$v = -\frac{k}{nm}\frac{\partial P}{\partial x} \quad \ldots\ldots.. (18)$$

v = interstitial gas velocity (m/sec).

For pressure given by Eq.(10):

$$v = -\frac{k}{nm}\left[\begin{array}{l}\frac{\partial A'}{\partial x} Sin(wt+f) + \\ A' Cos(wt+f).\frac{\partial f}{\partial x}\end{array}\right] \ldots (19)$$

An analytical expression of v can be obtained from Eq.(19) after substitution from Eq.'s (7) & (8). The interstitial gas velocity is a sinusoidal function of $A, l, k, w, and\ n$.

Any particle in any depth will oscillate up and down near its original position. The oscillatory particle location with time, starting from any point can be calculated using simple particle tracking technique [15, 16]. The technique is initiated by specifying the coordinates of the starting point from which, the velocity is calculated using Eq.(19). This velocity is used to calculate the incremental distance moved by particle through a small increment of time. This incremental travel distance is stored, and the location of the "particle" is updated based on the velocities and the incremental travel time. This procedure is repeated until the "particle" completes the cycle. Maximum distance toward the upper boundary is stored:

$$x_{\max} = \int_0^{\infty} v(x,t)dt \,|_{\max} \qquad \ldots\ldots. (20)$$

As shown in Fig.(3), if the "penetration depth" is defined as a distance from upper boundary in which the particle can reach the soil surface and the "oscillation zone" is zone in which the particle oscillates around its original position but still remains in the soil, the penetration depth for any system can be determined.

Results and Discussion

Fig.(4) shows the way in which the penetration depth varies for a range of soil settings. It is clear that the increase in depth of the lower impermeable boundary cause increase in penetration depth. The range of penetration depth is 0.05m to 0.78m. In order for barometric pressure variation creates significant penetration depth the gas phase permeability should be at least on order of 1E-13m^2 (.1 darcy). Fig.(5) shows the way in which maximum particle displacement, toward the upper boundary, varies as a function of original particle depth. The soil permeability considered is 1E-11 m^2 and depth of the lower boundary is 10m. The maximum particle displacement is more significant in the upper soil zone and may reach as high as .24 m.

Conclusions

A one-dimensional conceptual model was used to investigate the advective gas flow zones in the subsurface induced by the natural atmospheric pressure fluctuation. From analytical solution it is clear that the gas phase inside unsaturated zone moves with sinusoidal velocity whose amplitude decrease with depth. Two zones can be distinguished. First in which the gas phase can reach the soil surface and continuously mixed with clean air. The depth "Penetration Depth" of this zone may range from .05m to .8m. Second is "Oscillation Zone" in which the air oscillates around its original position but still remains in the soil. Maximum air displacement toward the upper boundary may reach .24m when the depth of the lower impermeable boundary is 10m. This displacement is more as the lower impermeable boundary is deeper.

In order for barometric pressure variation creates significant penetration depth the gas phase permeability should be at least on order of 1E-13 m^2 (.1 darcy). The time for complete cycle considered is 10 days.

The mixing of air above penetration depth with clean air above soil surface and the oscillation of air below penetration depth may have a significant effect on natural VOCs transport and fate in the soil region within these depths. Traditionally, the time scale of natural transport of VOCs considered in previous studies is of order of months or years. This time scale is much higher than time for one complete cycle considered in this study. Further theoretical and experimental investigation is necessary for more understanding of the effect of barometric pumping on VOCs transport in the upper region of soil.

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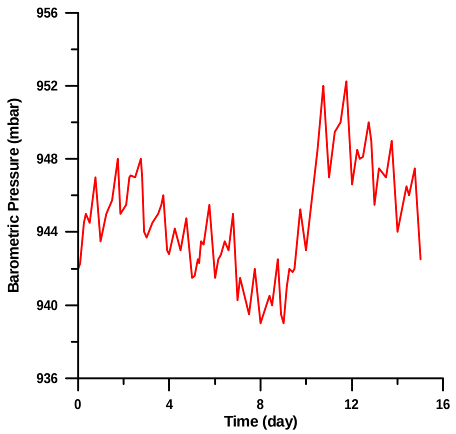

Figure (1) Typical Barometric Pressure Record measured in Shallow well [3].

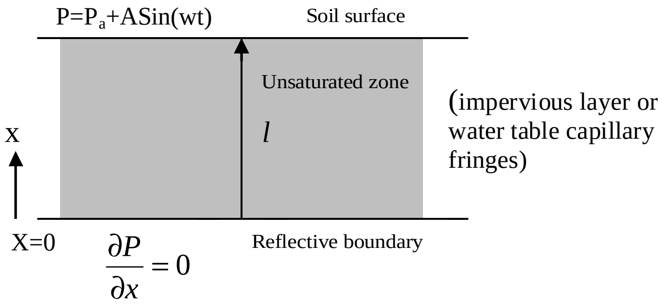

Figure (2) Flow System Considered in this Study

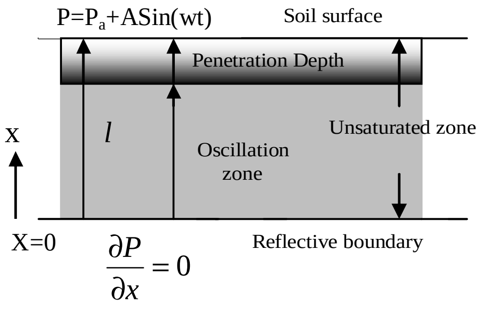

Figure (3) Flow Zones Induced by Barometric Pressure Variation

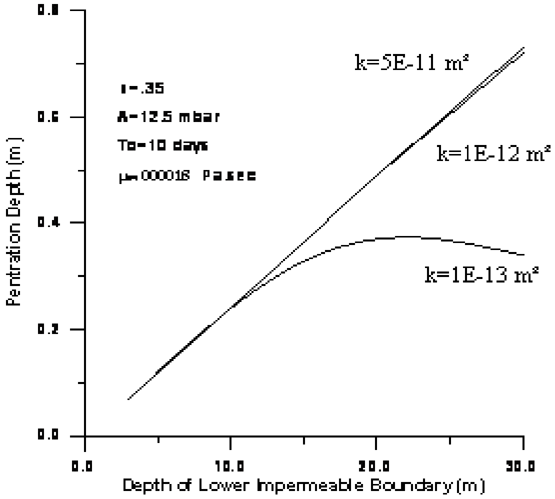

Figure (4) Penetration Depth or
Different Soil Settings

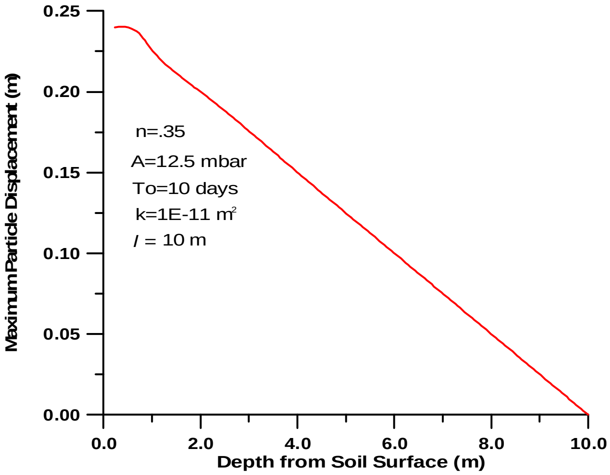

Figure (5) Maximum Particle Displacement
toward the Upper Boundary for Different
Depths from Soil Surface.