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Direct Measurements of Soil-Gas Entry into an Experimental Basement Driven by Atmospheric Pressure Fluctuations

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DISCLAIMER

ABSTRACT

To study the importance of changes in atmospheric pressure on radon entry into houses, we have simultaneously measured the soil-gas entry into an experimental basement structure and the fluctuations in atmospheric pressure. Changes in atmospheric pressure drive soil-gas flow because of the finite response time of the soil gas to changes in pressure. Large semi-diurnal oscillations in atmospheric pressure were observed. However, small amplitude (~10 Pa), rapid (~20 min) fluctuations in atmospheric pressure were an important driving force for soil-gas entry because 1) the characteristic time for the propagation of a pressure disturbance in the soil gas was ~ 3 min, and 2) the time-rate-of-change of these small fluctuations is often larger than that of the semi-diurnal oscillations. An analytical model has been derived for a structure with a subslab gravel layer based on a one-dimensional solution to the transient pressure diffusion equation. This model correctly predicts the temporal response of the measured soil-gas entry into the experimental structure, but does not accurately predict the amplitude.

INTRODUCTION

Radon entry into houses has been traditionally understood as a steady-state process in which a slight (few Pa) but relatively steady under-pressure of the house draws radon-laden soil gas through openings in the substructure and into the building [e.g. Nazaroff et al., 1988]. However field studies [Holub et al., 1985; Turk et al., 1989; Hintenlang and Al-Ahmady, 1992] have observed elevated indoor radon concentrations during periods when steady-state driving forces were apparently small. Recent theoretical [Tsang and Narasimhan, 1992] and empirical [Hintenlang and Al-Ahmady, 1992] studies have suggested that periodic changes in atmospheric pressure can cause advective radon entry into houses.

We have directly measured the flow rate of soil gas into and out of an experimental basement structure driven by fluctuations in atmospheric pressure. To our knowledge direct measurement of soil-gas flow in a shallow soil system such as a building or across the soil surface have not been previously reported, although direct measurements of soil-gas flow rates have been reported for deep soil systems such as boreholes used for passive vapor extraction [Rohay et al., 1994]. In this paper, we report the air-flow measurement results and compare them with predictions of an analytical model based on a one-dimensional solution to the transient diffusion equation.

EXPERIMENTAL SETUP

The study was conducted with an experimental basement structure which was designed and constructed to study soil-gas and radon entry into houses [Fisk et al., 1992; Garbesi et al., 1993; Robinson and Sextro, 1994]. Fig. 1 shows a schematic of the soil-structure system. The structure is a single-chamber, primarily-below-grade, concrete structure with interior dimensions of 2.0 x 3.2 m and a height of 2.0 m. The structure rests on a 10-cm-thick, high-permeability gravel layer. All openings between the structure interior and the soil were sealed except for a 3.8-cm-diameter hole in the center of the structure floor. For openings exceeding ~5 cm^2 in area, the steady-state soil-gas entry rate into the structure is independent of the area or locations of the openings in the floor because the high-permeability gravel layer presents negligible resistance to flow in comparison with the soil [Robinson and Sextro, 1994]. Two 1.25-cm-diameter holes in the access hatch for the structure were open to the atmosphere to enable the interior of the structure to rapidly respond to changes in atmospheric pressure.

Differential soil-gas pressures with respect to the structure interior were monitored using probes which extend into the soil horizontally through all four walls and vertically through the floor of the structure. The atmospheric pressure was measured using a pressure transducer connected to an omnidirectional static pressure tap to correct for the effect of wind. The response time, accuracy, and resolution of this pressure transducer (Paroscientific model 1015a) are 1 s, 10 Pa, and 0.1 Pa respectively.

The soil-gas flow rate through the 3.8-cm-diameter hole in the center of the structure's slab floor was measured using the flow sensor shown in Fig. 1. The sensor consists of two omnidirectional hot-film velocity transducers (TSI model 8470) mounted in a U-shaped tube (1.9-cm ID copper tubing) and measures the magnitude and direction of gas flow as small as 0.15 L min^{-1}. The sensor was calibrated with a bubble flow meter. The response time, accuracy, and resolution of the flow sensor are 2 s, 1% of reading, and 0.02 L min^{-1} respectively. At low flow rates (< 1 L min^{-1}) the velocity measured by a hot-film velocity transducer depends on the orientation of the flow with respect to gravity. At the same flow rate, the upward velocity measured by one transducer will be greater than the downward velocity measured by the other transducer, due to the effect of buoyancy induced by the hot film. Therefore the direction of the soil-gas flow is determined by which transducer measures a higher velocity. When the transducer labeled I in Fig. 1 measures a higher velocity, the flow is into the structure; conversely, when the transducer labeled O in Fig. 1 measures a higher velocity, the flow is out of the structure. As the flow rate increases (> 1 L min^{-1}) the effect of buoyancy becomes insignificant and this directional distinction disappears. However, we assume that our data sampling frequency of 0.2 Hz is much more rapid than the changes in flow direction, allowing us to record the lower velocities that accompany these changes.

ANALYTICAL MODEL

The model predicts the soil-gas flow and pressure field underneath the floor slab of the structure by approximating the flow as one-dimensional in the vertical plane between the deep soil and the gravel layer. We have approximated the soil-gas flow *underneath* the gravel layer as one-dimensional because: 1) the gravel layer is an isobaric plenum [Robinson and Sextro, 1994] with a horizontal dimension on the same order as the depth of the basement, and 2) the flow driven by atmospheric pressure variations arises from the compressibility of the soil gas. Although the flow *within* the gravel layer is not one-dimensional because of the convergence of the flow field into the hole in the center of the structure floor, we are assuming that this does not affect the flow rate into the structure because the gravel provides negligible resistance to flow in comparison with the soil. The permeability of the soil is approximately three orders of magnitude smaller than the permeability of the gravel. The time-dependent soil-gas flow rate into the structure is assumed to be equivalent to the flow rate into the gravel layer.

The response of the soil gas to changes in atmospheric pressure can be approximated with the transient diffusion equation because the atmospheric pressure fluctuations are small relative to the absolute pressure (<1%) [Massmann, 1989];

$$\frac{\partial p}{\partial t} = D_p \nabla^2 p \qquad \text{where} \qquad D_p = \frac{k\,P_{atm}}{\mu \varepsilon} \tag{1}$$

where p is the soil-gas pressure, D_p is the pressure diffusivity defined by the soil permeability (k), mean atmospheric pressure (P_{atm}), air-filled porosity of the soil (ε) and the dynamic viscosity of the soil gas (μ). Table 1 lists the important soil properties for the structure site. Assuming one-dimensional flow in the soil below the gravel layer, the soil-gas pressure field in this region is predicted by the solution of eqn. (1) for the following boundary conditions:

$P(z = 0, t) = P_{gravel}$; the pressure in the gravel layer is assumed to be spatially uniform, and (2a)

$\frac{\partial P}{\partial z}(z = L, t) = 0$; no flow boundary at the water table, located at $z = L$. (2b)

The solution of eqn. (1) for the boundary conditions stated in eqns. (2a) and (2b) can be derived by first determining the pressure response of the soil gas to a unit-step change in pressure in the gravel layer. Assuming a homogeneous soil, the pressure response of the soil gas to a unit-step change in pressure in the gravel layer is [Carslaw and Jaeger, 1959]

$$P_{step}(z,t) = -\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{\sin\left[(2n+1)\frac{\pi}{2}\frac{z}{L}\right]}{(2n+1)}\exp\left[-(2n+1)^2\left(\frac{\pi^2}{4}\right)\left(\frac{D_p t}{L^2}\right)\right] \tag{3}$$

where $P_{step}(z,t)$ is the pressure difference between the gravel layer and the soil gas at depth z, and L is the distance between bottom of the gravel layer and the water table (in our case, L = 6.5 m). Unit-step change solutions are then combined using Duhamel's theorem to match the time dependent pressure in the gravel layer [Carslaw and Jaeger, 1959]. The pressure difference between the gravel layer and the soil at depth z caused by the time varying pressure in the gravel layer is

$$p(z,t) = \int_{-\infty}^{t} P_{step}(z, t-\theta) \frac{dP_g(\theta)}{d\theta} d\theta \tag{4}$$

where $\frac{dP_g(\theta)}{d\theta}$ is the time-rate-of-change of the pressure in the gravel, and θ is the dummy variable of integration.

The soil-gas flow rate into the structure is determined using Darcy's law and Duhamel's theorem. The soil-gas flux into the gravel layer caused by a unit-step change in pressure in the gravel layer is

$$Q_{step} = -\frac{k}{\mu} \frac{\partial P_{step}(z,t)}{\partial z} \bigg|_{z=0} \tag{5}$$

where k is the permeability of the soil, μ is the dynamic viscosity of the soil gas, and $\left.\frac{\partial P_{step}(z,t)}{\partial z}\right|_{z=0}$ is the pressure gradient of the soil gas at the edge of the gravel layer caused by a unit step change in pressure in the gravel layer. The soil-gas flux into the gravel layer caused by the time varying pressure in the gravel layer is computed using Duhamel's theorem (eqn. (4) with Q_{step} substituted for P_{step}). The soil-gas flow rate into the structure is the soil-gas flux into the gravel layer multiplied by the cross-sectional area of the gravel layer, 5.0 m^2.

Since the atmospheric pressure is discretely sampled, the convolutions required to calculate the soil-gas pressure field and the soil-gas flux into the gravel layer are evaluated numerically. The time-rate of change of atmospheric pressure is approximated using a central difference. Although these convolutions require evaluation of an infinite sum and an infinite integral, only a limited number of terms need to be evaluated to obtain a high degree of accuracy because the exponential term in eqn. (3) rapidly approaches zero as time increases.

RESULTS AND DISCUSSION

Measurements of atmospheric pressure made during a five-day experiment, shown in Fig. 2, indicate that atmospheric pressure fluctuations occur at a variety of amplitudes and time scales. Between 0 and 16 hours a passing weather front caused a 1000 Pa rise in atmospheric pressure. Fig. 2 also shows a semi-diurnal atmospheric pressure oscillation with an amplitude of ~100 Pa, and smaller-amplitude fluctuations occurring over shorter time scales.

Although atmospheric pressure fluctuations occur at a variety of time scales, the response of the soil-structure system to changes in atmospheric pressure depends on the characteristic time of the soil gas to changes in pressure. A characteristic time for response of the soil-structure system to changes in atmospheric pressure can be defined based on the time for a pressure disturbance to propagate the characteristic length of the system;

$$\tau = \frac{L_c^2}{D_p} \tag{6}$$

where L_c is the representative length scale of the system. Using the depth of the water table for L_c, the longest length scale in our system, the characteristic time of our soil to a change in surface pressure is ~ 3 min ($L_c = 8.5$ m, $D_p = 0.39$ m^2 s^{-1}) --- much shorter than the time scale of the large atmospheric pressure fluctuations shown in Fig. 2.

Fig. 3 shows the atmospheric pressure and the response of the soil-structure system for a one hour period between hours 18 and 19 of the five-day experiment. At this shorter time scale, comparable to the response time of the soil gas to changes in pressure, the details of the atmospheric pressure signal emerge. Fig. 3a shows pressure oscillations with a period of ~20 minutes and an amplitude of ~10 Pa. The time-rate-of-change in atmospheric pressure, approximated with a central difference, is shown in Fig. 3b. Recall that eqn. (4) defined the response of the soil gas to fluctuations in atmospheric pressure as the convolution of the step-response solution and the time-rate-of-change of the atmospheric pressure. The time-rate-of-change of the *small, rapid* fluctuations of atmospheric pressure shown in Fig. 3a is much larger than that of the large amplitude semi-diurnal oscillations shown in Fig. 2.

The measured pressure difference between the gravel layer and the soil gas 1.7 m below the floor slab is shown in Fig. 3c. This pressure difference is caused by the finite response time of the soil-gas pressure to changes in atmospheric pressure. Both the structure interior and the gravel layer respond nearly instantaneously to changes in atmospheric pressure relative to the soil because of the openings in the hatch of the structure and the high permeability of the gravel layer. Fig. 3d shows the soil-gas flow through the opening in the floor of the structure driven by atmospheric pressure fluctuations. Falling atmospheric pressure draws soil gas into the structure; rising atmospheric pressure drives air out of the structure into the soil. A comparison of Figs. 3b and 3d indicates the soil-gas flow rate into the structure generally follows the time-rate-of-change of atmospheric pressure. Therefore, the time-rate-of-change of atmospheric pressure provides a better indication of the response of the soil gas to changes atmospheric pressure than a qualitative inspection of the raw atmospheric pressure signal. The soil gas does not respond to the high frequency fluctuations in atmospheric pressure because the finite response time of the soil gas to changes in pressure acts as a high frequency filter. The measured indoor-outdoor pressure difference was essentially zero during this period.

The predictions of the analytical model and the measured soil-gas pressure and flow rate are also compared in Figs. 3c and 3d. Fig. 3c shows that the model accurately predicts the pressure difference between the gravel layer and the soil gas 1.7 m below the slab. Fig. 3d shows that the model correctly predicts the temporal response of the soil-gas flow rate into the structure but underestimates the amplitude. The model underpredicts the soil-gas flow rate by a factor of ~2.3. There are several possible explanations for this underprediction: 1) the permeability of the soil in the subslab region may be greater than the assigned value, 2) the flow into the gravel layer is not entirely one-dimensional but has significant two-dimensional components near the edges of the gravel, or 3) the gravel layer is not an isobaric plenum under these transient conditions. We plan to examine the cause of this underprediction by using a numerical model.

Although the time averaged gas flow between the soil and the structure driven by fluctuations in atmospheric pressure is zero, these fluctuations can produce a net radon entry into the structure because the radon concentration of the soil gas is generally orders of magnitude larger than that of the air inside the ventilated structure. Neglecting the small dilution of the radon concentration of the soil gas caused by air flowing out of the structure into the soil, the total radon entry caused by fluctuations in atmospheric pressure can be approximated by the total volume of the soil gas flowing unidirectionally into the structure. During the five-day experiment described above, the total (unidirectional) soil-gas entry into the structure driven by fluctuations in atmospheric pressure was equivalent to the entry that would be caused by a steady 0.7 Pa structure depressurization over the same period.

CONCLUSIONS

We have directly measured flow into and out of the experimental structure in response to relatively small (~10 Pa), rapid (~20 min) fluctuations in atmospheric pressure. Although much larger fluctuations in atmospheric pressure occur at longer time scales, small oscillations in atmospheric pressure dominated the response of the system because of their large time-rate-of-change, and the short response time of the soil gas to changes in pressure. The importance of these small, rapid fluctuations in determining the response of our system underscores the importance of examining the effects of changes in atmospheric pressure on the appropriate time scale.

Even though the assumption of one-dimensional flow is not entirely valid, the analytical model provides insight into the nature of the transient flows driven by atmospheric pressure fluctuations. The model prediction of the temporal response of the soil-gas flow to fluctuations in atmospheric pressure emphasizes the fundamental difference between these transient flows and steady-state soil-gas flow into houses. Atmospheric pressure fluctuations drive approximately one-dimensional flow between the structure and the deep soil because of the compressibility of the soil gas. However the steady-state soil-gas flow is fundamentally multi-dimensional because air flows from the soil surface through the soil and into the structure driven by the indoor-outdoor pressure difference.

This study indicates that fluctuations in atmospheric pressure drive soil-gas flow into and out of our experimental structure. Soil-gas entry driven by atmospheric pressure fluctuations can result in radon entry and may help explain the observed radon concentrations in houses during periods of low steady-state building depressurization.

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Table 1. Properties of the soil and soil gas at the structure site.

Soil Permeability[1], k	3 x 10^{-11} m^{2}
Gravel Permeability[2]	2.0 x 10^{-8} m^{2}
Air filled porosity of the soil, ε	0.40
Mean atmospheric pressure, P_{atm}	92 kPa
Dynamic viscosity of soil gas, μ	1.8 x 10^{-5} Pa s
Pressure Diffusivity, Dp	0.39 m^{2} s^{-1}
Water table depth	8.5 m

[1] [Garbesi, 1993]

[2] [Fisk et al., 1992]

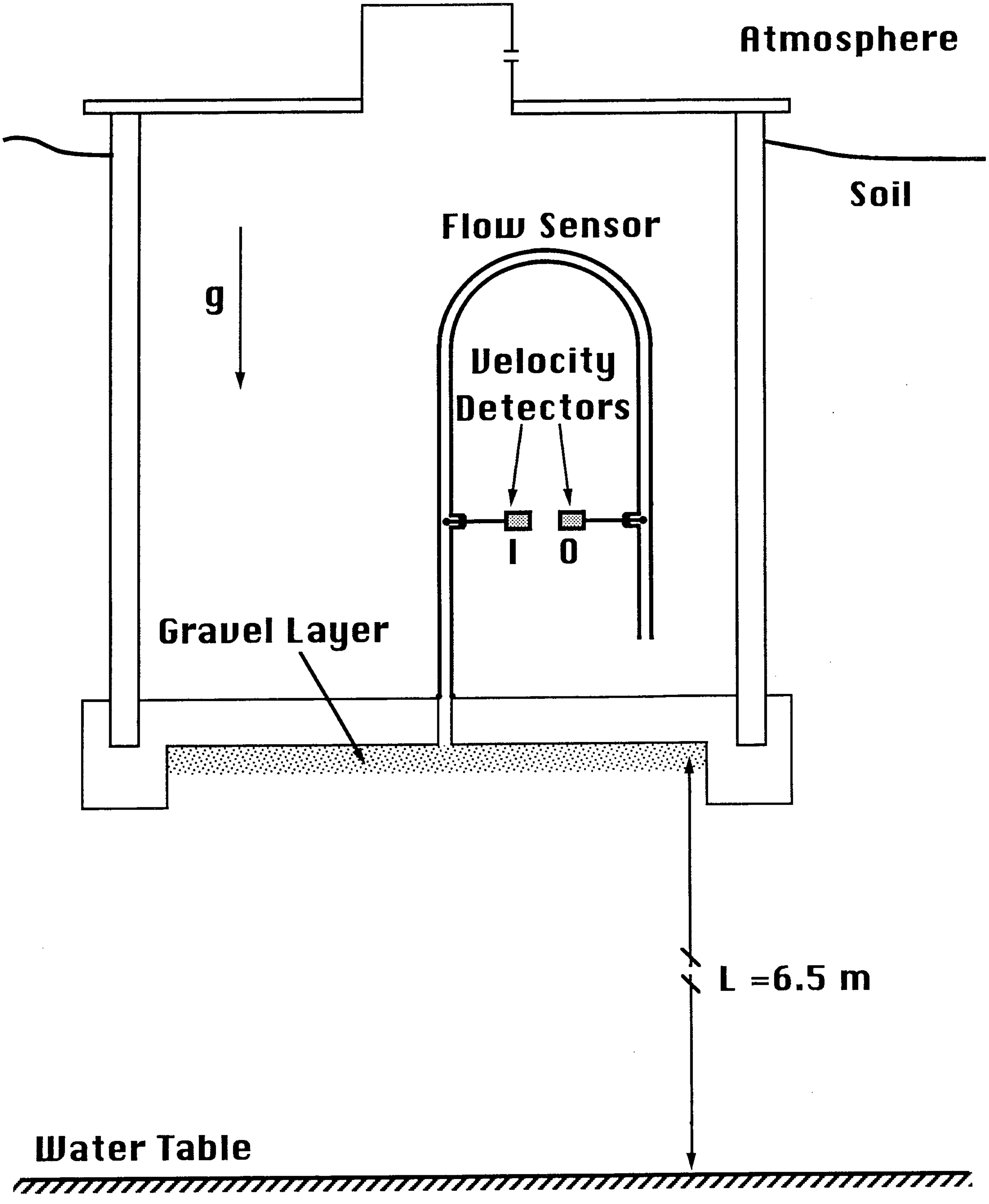

Fig. 1 Schematic of east-west cross-section of the experimental basement structure. The flow sensor measures the magnitude and direction of the air flow through the 3.8-cm-diameter hole in the center of the floor slab. The figure is not drawn to scale.

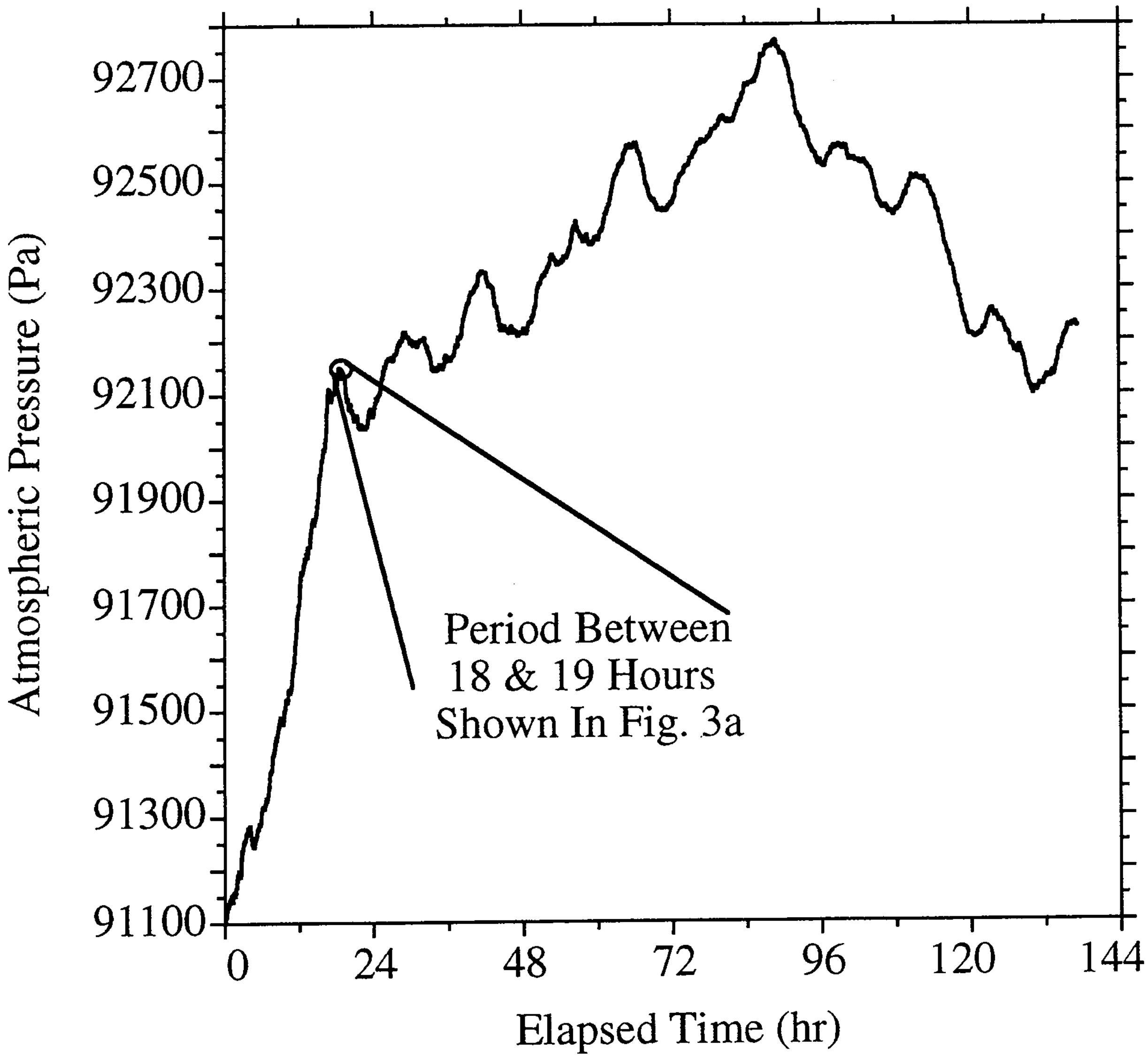

Fig. 2 Atmospheric pressure measured during a five-day experiment.

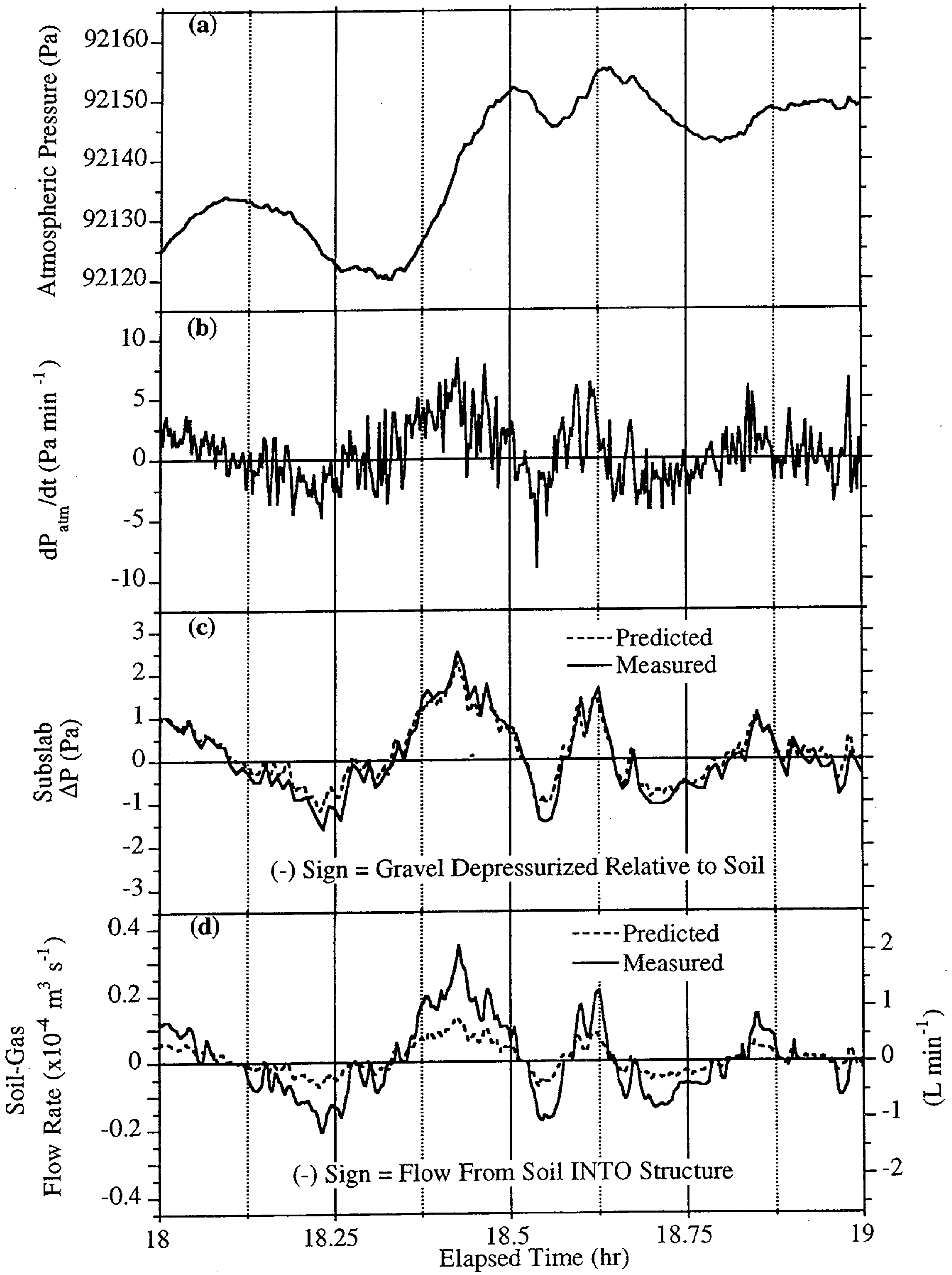

Fig. 3 Atmospheric pressure and the response of soil-structure system between 18 and 19 hours of the five-day experiment. (a) Measured atmospheric pressure. (b) Time-rate-of-change of atmospheric pressure. (c) Comparison of the measured and predicted pressure difference between the gravel layer and a point 1.7 m beneath the slab. (d) Comparison of the measured and predicted soil-gas entry rate into the structure.