

Lawrence Berkeley National Laboratory

Recent Work

Title

Toward Resolving the Model-Measurement Discrepancy of Radon Entry into Houses: A Study of the Scale Dependence of Soil Permeability to Air

Permalink

<https://escholarship.org/uc/item/73r8c403>

Authors

Garbesi, K.
Sextro, R.G.
Fisk, W.J.
et al.

Publication Date

1993



Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

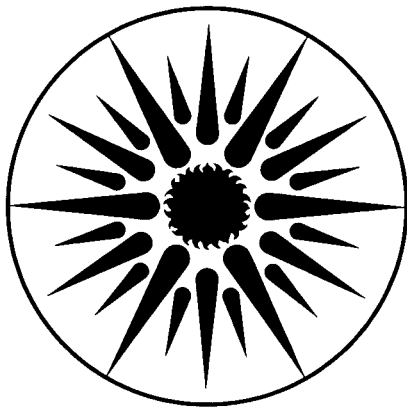
ENERGY & ENVIRONMENT DIVISION

To be presented at the Indoor Air '93, The Sixth International Conference
on Indoor Air Quality and Climate, Helsinki, Finland, July 5-8, 1993,
and to be published in the Proceedings

Toward Resolving the Model-Measurement Discrepancy of Radon Entry into Houses: A Study of the Scale Dependence of Soil Permeability

K. Garbesi, R.G. Sextro, W.J. Fisk, and W.W. Nazaroff

January 1993



ENERGY & ENVIRONMENT
DIVISION

REFERENCE COPY |
Does Not |
Circulate |
Bldg. 50 Library. |

LBL-33522

Copy 1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. Neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California and shall not be used for advertising or product endorsement purposes.

Lawrence Berkeley Laboratory is an equal opportunity employer.



DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

*To be Published in Proceedings of
Indoor Air '93, the 6th International
Conference on Indoor Air Quality
and Climate, July 5-8, 1993, Helsinki, Finland*

LBL-33522

**Toward Resolving the Model-Measurement
Discrepancy of Radon Entry into Houses: A Study of
the Scale Dependence of Soil Permeability to Air**

Karina Garbesi[†], Richard Sextro[†], William J. Fisk[†], and William W. Nazaroff[‡]

**[†]Indoor Environment Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California**

**[‡]Department of Civil Engineering
University of California
Berkeley, California**

January 1993

This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

TOWARD RESOLVING THE MODEL-MEASUREMENT DISCREPANCY OF RADON ENTRY INTO HOUSES: A STUDY OF THE SCALE DEPENDENCE OF SOIL PERMEABILITY TO AIR

Karina Garbesi¹, Richard G. Sextro¹, William F. Fisk¹, and William W. Nazaroff²

¹Lawrence Berkeley Laboratory, University of California, Berkeley, California.

²Department of Civil Engineering University of California, Berkeley, California.

ABSTRACT

We studied natural soil at a site used to study radon entry into basement structures, in order to determine why models of radon entry into houses significantly and consistently underpredict measured radon and soil-gas entry rates. We found soil air-permeability to be strongly scale dependent, increasing monotonically with length scale. Therefore, soil-gas flows occurring at scales of ~3 - 5 m around houses can be seriously underestimated by traditional techniques that assess permeability by averaging over multiple small scale measurements (~0.1 - 0.5 m). Scale-dependence appears to be a result of networks of relatively homogeneously distributed fast flow paths caused by roots, burrows, and weathering channels. When permeability assessed at the appropriate scale is used as input to the model, ~80% of the model-measurement discrepancy previously observed at the site is resolved.

INTRODUCTION

For houses with high indoor radon levels, the dominant source is radon-laden soil gas entering the building substructure by pressure-driven flow. Many models have been developed to simulate radon entry. These models have consistently and significantly underpredicted entry rates relative to those observed at real houses (Table I, entries a and b). Previously attributed to poor understanding of inherently complex field sites, these discrepancies have more recently been validated at well characterized and controlled test structures (Table I, entries c and d).

Table 1. The ratio of measured to modeled soil-gas entry rates for measurements made at real houses and test structures in various studies.

	Entry rate ratio (meas./mod.)	Description and references
(a)	4	7 houses (1) vs. 2-D finite difference model (2)
(b)	10	1 house vs. 2-D finite element model and analytical model using usual assumptions (3)
(c)	8	Full-scale experimental structure vs. 3-D finite difference model (4)
(d)	15	Small-test structure vs. 2-D finite difference model (5)

The models cited include analytical and numerical types; the latter including both finite-difference and finite-element methods. The models assume the soil is homogeneous and isotropic within defined regions, that the soil-structure interface is perfectly discontinuous, and that soil-gas entry occurs only through gaps or cracks in the substructure floor. A critical input to the models is an empirical assessment of regional permeability of soil to air.

Our hypothesis to explain the model-measurement discrepancy was that soil air-permeability depends on length scale. Therefore, typical small scale (0.1 - 0.5 m) probe measurements of

permeability do not reflect soil characteristics at the larger scales (~3 - 5 m or more) that houses interact with soils. To test this hypothesis, we developed a *dual-probe dynamic pressure technique* that determines the effective soil permeability along a path between the two probes.(6) The technique uses the measured time lag of a sinusoidally varying pressure signal traveling from a source to a detector probe to determine the permeability along the path between them. By varying the location of the detector probe we can investigate permeability at different scale lengths and spatial orientations.

As with any technique to measure permeability, the data must be interpreted by a model. Since we have no fore-knowledge of the medium, the model itself is homogeneous and isotropic. The value that we obtain from the model is therefore an *effective* permeability that a homogeneous medium would have to produce the same measured physical quantities (time lag for dynamic measurements or pressure amplitude for static measurements).

METHODS

Model development

Consider first the propagation of a dynamic pressure signal through the air space of an infinite homogeneous soil. For a compressible fluid, and neglecting the hydrostatic gradient which will not result in gas flow, the governing equation is:

$$\frac{\partial P}{\partial t} = \frac{k}{\epsilon\mu} \left(\frac{\rho RT}{M} \nabla^2 P + \left(\frac{\partial P}{\partial x} \right)^2 + \left(\frac{\partial P}{\partial y} \right)^2 + \left(\frac{\partial P}{\partial z} \right)^2 \right) \quad (1)$$

where P is the disturbance pressure, k is the permeability of the soil to air, μ is the dynamic viscosity of air, ρ is the density of air, R is the ideal gas constant, T is temperature, M is the molar mass of air. Since the imposed pressure signal is $\leq 10^3$ Pa, and $\rho RT/M \sim 10^5$ Pa (mean atmospheric pressure, P_a), the estimated error from neglecting the non-linear terms is ~1% or less. We are left with a 3-dimensional diffusion equation

$$\frac{\partial P}{\partial t} = D_p \nabla^2 P \quad \text{with} \quad D_p = \frac{kP_o}{\epsilon\mu} \quad (2)$$

Using the transformation $W(r,t) = r P(r,t)$, Eq. 2 is reduced to the 1-dimensional diffusion equation, for which an analytical solution $W(r,t)$ is available. Using the inverse transformation, we then obtain the solution for $P(r,t)$. For our infinite medium, with a source signal, with driving frequency ω , imposed at a spherical surface of radius b , the solution to this problem is given by:

$$P(r,t) = bA \frac{\exp \frac{\lambda(r-b)}{\sqrt{2}}}{r} \sin \left(\omega t - \frac{\lambda(r-b)}{\sqrt{2}} \right) \quad \text{with} \quad \lambda = \sqrt{\frac{\omega}{D_p}} \quad (3)$$

To simulate the experimental set up we need to establish the proper boundary condition of zero disturbance pressure at the soil surface. We use the standard *method of images*: the real source is placed at its actual depth below the surface, and an image source of equal magnitude but opposite sign is placed opposite it an equal distance above the surface. By symmetry arguments each point along the surface then cancels to zero. For an arbitrary detector location a distance r from the real source and r' from the image source, the effect of the image source is:

$$P_I(r',t) = bA \frac{\exp \frac{\lambda(r'-b)}{\sqrt{2}}}{r'} \sin \left(\omega t - \frac{\lambda(r'-b)}{\sqrt{2}} \right) \quad (4)$$

The full solution at the detector location in the semi-infinite medium is given by the sum of the real and image solutions:

$$P_{\text{det}}(t)|_{k,\omega} = P(r,t) + P_I(r',t) \quad (5)$$

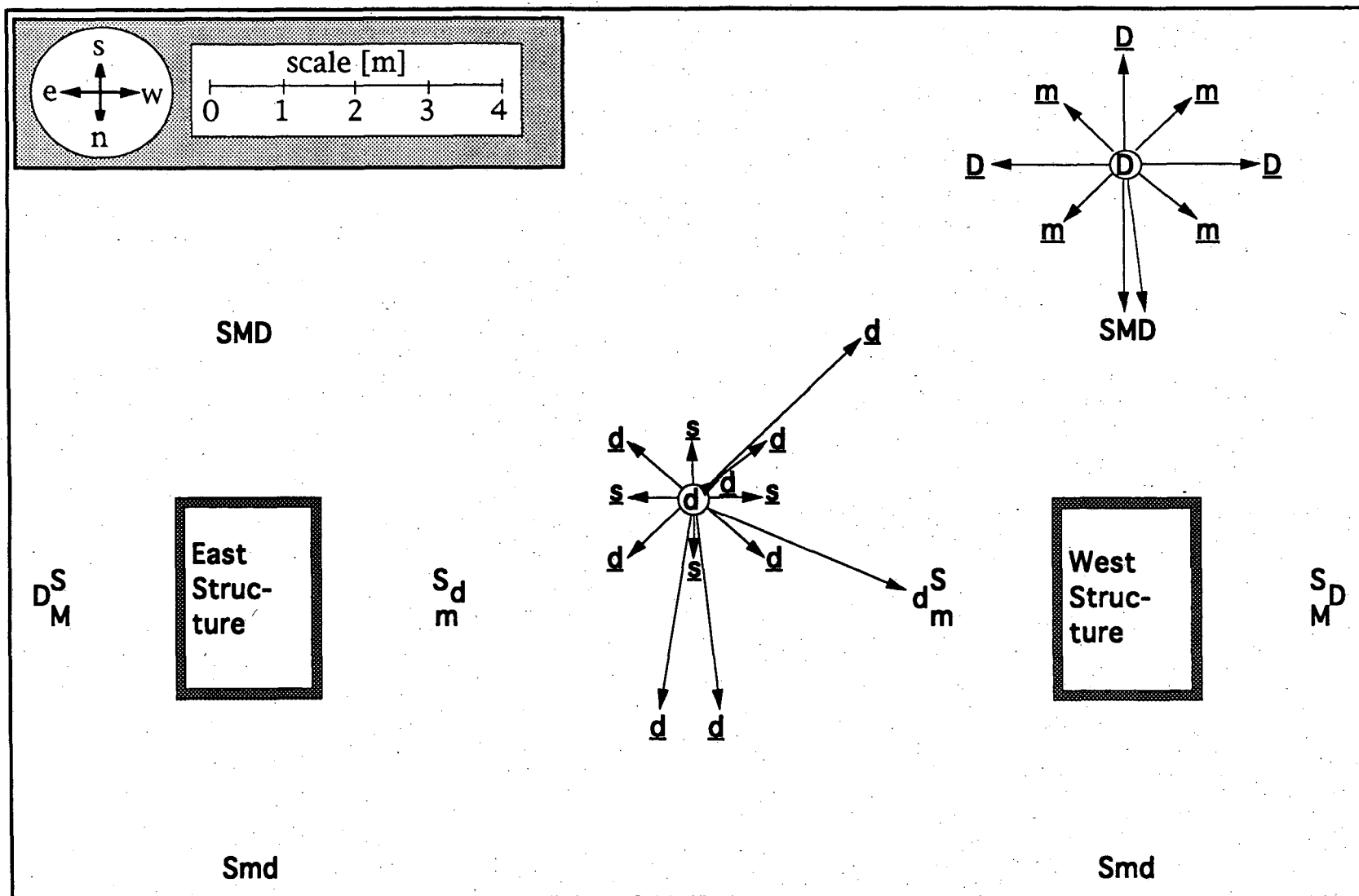


Figure 1. Plan View of Experiment Site. Characters indicate probe locations (underlined = blunt-end probe; non-underlined = cylindrical probe). Arrows indicated dynamic measurement paths. Probes, indicated by letter codes have depths, in meters: D(2.0), M(0.8), S(0.18), d(1.5), m(0.59), and s(0.44).

$P_{det}(t)$ has the same sinusoidal form as the driving signal but it is phase shifted and diminished in amplitude. Comparing the phase with the source signal we estimate the time lag for given k and ω , $T(k,\omega)$. Inverting, k is therefore uniquely determined by an experiment in which T is measured, and ω is imposed.

Data acquisition and analysis

The experiment is carried out by directing a sinusoidal pressure signal to the source probe beginning at time $t = 0$. The source and detector probes are simultaneously monitored with pressure transducers. Fourier transform and comparison of these signals at the source driving frequency allows precise determination of the time lag, T , from the phase shift between the signals.

The dual-probe dynamic-pressure technique was used to measure permeabilities at the radon transport test facility in Ben Lomond, California.(7, 8) Figure 1 shows locations of measurements made at various length scales in horizontal and non-horizontal orientations (solid lines). The locations of the experimental basements are also shown. Dynamic measurements were made from two sources located south and east of the west structure at 2.0- and 1.5-m depth, respectively. Single-probe static measurements were also made at all probes using blunt-end and well-screen-type probes that integrate over 0.1- and 0.5-m radii, respectively.(8)

The scales of the different measurements are inherent in the physics of the experiments. In the static measurements, air is injected into a probe at fixed rate, creating a static pressure field, the magnitude of which gives a measure of the soil permeability. Because the static field falls off as $\sim 1/r$ from the probe tip, the information about the soil is strongly weighted to the immediate vicinity of the probe. In contrast, in the dynamic measurements, the propagation velocity of the pressure signal is the "measuring stick". As with an acoustic wave traveling in air, that velocity is relatively independent of distance from the source. Therefore, the dynamic signal is relatively unweighted along its path.

RESULTS

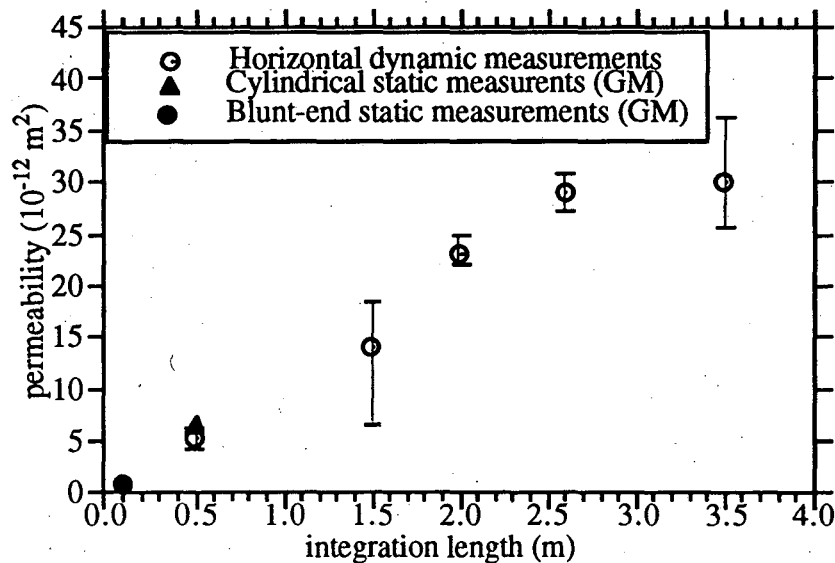


Figure 2. Effective permeability of soil to air measured over different path lengths using static and dynamic techniques.

Figure 2 plots the effective permeabilities determined by the dynamic technique for different horizontal integration paths, and the range of values (or uncertainty, if $n=1$) measured at each

length scale. The geometric mean permeabilities, weighted by the uncertainties in the individual measurements, are also shown for measurements made at 14 blunt-end probes and 22 cylindrical probes. The figure indicates that soil-permeability at the site depends strongly on length scale, with permeability at the 3-m scale ~40 times larger than that at the 0.1-m scale. Vertical estimates of permeability were made using the concept of a hydraulic conductivity ellipse, which employs data from both horizontal and non-horizontal paths. The results indicate a similar magnitude of scale dependence in the vertical direction, but with vertical permeabilities ~2 times smaller than horizontal.

The smooth trend of Figure 2 and the consistency between the static and dynamic measurements indicates that there are no systematic biases in the different measurement techniques. The observed differences in permeability appear to reflect real scale dependence resulting from characteristics of the soil medium.

DISCUSSION

The scale dependence of soil permeability to air explained 80% of the model-measurement discrepancy in soil gas entry measured at the experimental basement in Ben Lomond and reported in (4). Scale-dependent permeability has also been observed in aquifers, but the magnitude of reported scale dependence is considerably smaller over the same range of length scales.(9) Our study is unique in that scale dependence was demonstrated with high resolution, with a *single* technique, for gas-phase flow in unsaturated soil. Our data provide strong evidence that scale-dependence is not an anomaly of the sampling technique as suggested in (9), but is an inherent property of the porous medium. Scale dependence at the Ben Lomond site appears to be caused by networks of fast flow paths distributed relatively uniformly throughout the soil, probably due to plant roots, animal burrows, and channels from water movement through soil. Such sources could create nested scales of heterogeneity. When flow occurs through such a medium, effective permeability is expected to increase as larger scales of heterogeneity are encountered.

The past decade has witnessed a proliferation of transport models for heterogeneous porous media. Two major classes of models have arisen: typical stochastic models, the dominant class, treat the permeability field as a random distribution of elements with larger scale structure incorporated using the concept of a finite correlation length; other models incorporate nested scales of heterogeneity in which connectivity of high permeability elements is treated explicitly.(10-15) Fractal models are included in this latter class. It is widely recognized that models often fail to predict important aspects of contaminant transport. The problem of scaling effects has also been an active area of research.(10) Ironically, despite the fact that there has been considerable investigation of model behavior in regard to scale-dependent *dispersivity*, to our knowledge the models have not been tested for predictions of scale dependent *permeability*, which is likely to be considerably more important for relatively homogeneously distributed 'pollutants' like radon. Our work indicates that simulation of scale-dependent permeability might be an important validation criterion of transport models.

Scale dependent permeability presents serious problems for both site assessment of contaminant transport potential and for numerical simulation of transport. An accurate assessment can only be obtained if both the nature of the scaling, and the scale at which the system operates, are known. However, even if the scaling 'function' is known, numerical simulation can still be problematic unless the soil heterogeneity obeys some tractable scaling law, *e.g.*, fractal. The problem is exacerbated in systems that operate over a large range of scales. The problems presented for site assessment and simulation of the entry of radon and other soil-gas contaminants indoors argues that priority be placed on experimental and theoretical research of scale dependent flow. Field studies are required that investigate the prevalence, magnitude, and sources of scale-dependent permeability at other sites, and transport models should be validated with respect to their predictions for scale dependence.

ACKNOWLEDGEMENTS

We thank John Wooley and Marc Fischer for experimental assistance and Ashok Gadgil and Yvonne Tsang for their review of paper. This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems and Materials Division of the U.S. Department (DOE), under Contract DE-AC03-76SF00098.

REFERENCES

1. Turk BH, Prill RJ, Grimsrud DT, Moed BA, Sextro RG. Radon and remedial action in Spokane Valley homes, volume I: experimental design and data analysis, Lawrence Berkeley Laboratory, Berkeley, CA, LBL-23430. 1987.
2. Revzan KL, Fisk WJ, Gadgil AJ. Modeling radon entry into houses with basements: model description and verification. *Indoor Air* 1991;1:173-189.
3. Garbesi K, Sextro RG. Modeling and field evidence of pressure-driven entry of soil gas into a house through permeable below-grade walls. *Environmental Science and Technology* 1989;23:1481-1487.
4. Garbesi K, Sextro RG, Fisk WJ, Modera MP, Revzan KL. Soil-gas entry into an experimental basement: model-measurement comparisons and seasonal effects. *Environmental Science and Technology* 1993 (in press) and Andersen CE. Entry of Soil-Gas and Radon into Houses, Riso National Laboratory, Roskilde, Denmark, RISO-R-623(EN). 1992.
6. Garbesi K, Sextro RG, Nazaroff WW. A dynamic pressure technique for estimating permeability and anisotropy of soil to air flow over a scale of several meters, Lawrence Berkeley Laboratory, LBL-32723. 1992.
7. Fisk WJ, Flexser S, Gadgil AJ, *et al.* Monitoring and modeling for radon entry into basements: a status report for the small structures project, Lawrence Berkeley Laboratory: Berkeley, CA, LBL-27692. 1989.
8. Fisk WJ, Modera MP, Sextro RG, *et al.* Radon entry into basements: approach, experimental structures, and instrumentation of the Small Structures Project, Lawrence Berkeley Laboratory: Berkeley, CA, LBL-31864. 1992.
9. Bradbury KR, Muldoon MA. Hydraulic conductivity determinations in unlithified glacial and fluvial materials. In: DM Nielson and AI Johnson, ed., *Ground Water and Vadose Zone Monitoring*. Vol. American Society for Testing and Materials, Philadelphia, 1990:138-151.
10. Cushman JH. An introduction to hierarchical porous media. In: JH Cushman, ed., *Dynamics of Fluids in Hierarchical Porous Media*. Vol. Academic Press, London, 1990:1-6.
11. de Marsily G. *Quantitative Hydrogeology*. Academic Press, Inc., New York, 1986.
12. Burrough PA. Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels of soil variation. *Journal of Soil Science* 1983;34:577-597.
13. Sposito G, Jury WA. Fundamental problems in the stochastic convection-dispersion model of solute transport in aquifers and field soils. *Water Resources Research* 1986;22:77-88.
14. Wheatcraft SW, Tyler SW. An explanation of scale-dependent dispersivity in heterogeneous aquifers using concepts of fractal geometry. *Water Resources Research* 1988;24:566-578.
15. Wheatcraft SW, Sharp GA, Tyler SW. Fluid flow and solute transport in fractal heterogeneous porous media. In: JH Cushman, ed., *Dynamics of Fluids in Hierarchical Porous Media*. Vol. Academic Press, London, 1990:305-326.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720