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Project Summary

Feasibility of Characterizing Concealed Openings in the House-Soil Interface for Modeling Radon Gas Entry

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The report examines the feasibility of characterizing the total effective size of openings in the house-soil interface that permit indoor radon entry. Since many of these foundation openings are concealed by the building structure or consist of porous regions, they are characterized indirectly by their radon permeability rather than by direct observation.

A lumped-parameter model, based on the detailed RAETRAD model for radon entry, is the basis of the feasibility study. Sensitivity analyses conducted with the lumped-parameter model demonstrate a characteristic pattern of increasing indoor radon concentrations with increasingly negative indoor air pressures. A spike also occurs in the radon-pressure curves near zero pressure due to the very low dilution rate of indoor radon under passive, low-ventilation conditions. With sensitivity analyses, the lumped-parameter model indicates that the dominant parameters affecting indoor radon levels are the size of the foundation openings, the pressure-driven radon entry velocity, and the ventilation parameters for the house superstructure.

By rearranging the lumped-parameter model, measured indoor radon levels can be grouped with measured sub-slab radon levels and house ventilation parameters to express radon entry rates as a linear function of indoor air pressure. This provides a method for least-squares linear fitting of measured radon, pressure, and ventilation data to identify the effective size of foundation openings permitting radon entry. The method was applied to research-house data collected by the University of Florida, indicating a relatively large (2.5-m^2) effective opening in the soil-house interface. Air flow through the hollow-block stem wall and permeable block faces accounts for the large effective opening, which is probably also influenced by a perimeter shrinkage crack that usually occurs with floating-slab construction.

The minimum data for estimating total foundation leakage, including concealed leaks, include blower-door testing of house ventilation rates, sub-slab radon measurements, height measurements for the indoor volume, and steady-state indoor radon measurements at two or more suction pressures. Analysis of these data yields an effective radon entry velocity, which can be converted to a foundation leak area using soil moisture data or an estimate of the soil textural classification.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Radon (^{222}Rn) gas from decay of naturally occurring radium (^{226}Ra) in soils can move through pores and openings in a house understructure and enter the indoor atmosphere. If enough radon enters a house and if it is insufficiently diluted by outdoor air, it can accumulate to levels that pose significant risks of lung cancer with chronic exposure.

Because of the complexity of radon entry and accumulation processes, mathematical models have been used to simulate a broader range of soil, radon, and house conditions than could otherwise be studied empirically. In comparing empirical data with model calculations, excess radon entry has often been observed, despite good agreement of data and models for carefully constructed radon test cells. Because of its pressure dependence, the excess radon entry appears most consistent with larger openings in the house-soil interface, even though significant floor cracks have not been observed in most of these cases. Thus, radon entry measured from visible slab cracks does not sufficiently explain observed indoor radon levels. Perimeter shrinkage cracks around floating slabs and flow through hollow-block stem walls may constitute most of the concealed openings; however, openings around bath tubs and other plumbing penetrations also may be important in some cases.

Despite the difficulty of measuring the areas of concealed openings and permeable regions, characterization of these areas is important to understand and minimize the primary routes for radon entry. If the size of understructure openings is known, optimum radon control efforts can concentrate on closing large openings and on increasing ventilation or reducing slab diffusion in houses with small openings.

Theoretical Basis and Parameter Sensitivity

This feasibility study for estimating understructure radon leakage areas used a lumped-parameter model, which is based in turn on the detailed RAETRAD model. RAETRAD computes radon entry rates into a house by integrating the total radon transport across the floor surface area. It also estimates indoor radon concentrations from the computed entry rates by dividing them by the house volume and its air ventilation rate. The lumped-parameter model explicitly includes an understructure leakage-area factor. Since the lumped-parameter model can be used to estimate indoor radon concentrations using only a few house-related parameters, it also can be used to estimate the radon leakage area if suitable indoor radon concentrations are measured. The following analysis of its theoretical basis and parametric sensitivity demonstrates how the lumped-parameter model can be used to estimate understructure leakage areas.

The lumped-parameter model was developed primarily from RAETRAD sensitivity analyses, which identified the most significant house and soil parameters. The analyses suggested simplified approximations to express average indoor radon levels as a function of radon source strength and house radon-resistance and ventilation parameters. The radon source strength was defined in terms of the sub-slab radon concentration. The house radon resistance was defined from floor openings, pressure-driving forces, and slab diffusivity.

Equations for radon entry rates and house ventilation rates were combined to obtain the lumped-parameter expression that was used to relate indoor radon concentrations and house leakage data to the effective area of openings in the house-soil interface. The combined expression is:

$$C_{net} = 3.6\, C_{sub}\, [f_c\, (\upsilon_{dc} - \upsilon_{ac}\Delta P) + \upsilon_{slb}] \,/\, [h\, (a|\Delta P|^n + b)] \qquad (1)$$

where

C_{net} = net indoor radon concentration from sub-slab sources (pCi L^{-1})

C_{sub} = sub-slab radon concentration

f_c = area of floor openings as a fraction of total floor area (dimensionless)

υ_{dc} = equivalent velocity of radon diffusion through floor openings, dependent on radon diffusion coefficient of the soil (mm s^{-1})

υ_{ac} = equivalent velocity of radon advection through floor openings, dependent on the air permeability of the soil (mm s^{-1})

ΔP = indoor air pressure relative to outdoors (Pa)

υ_{slb} = equivalent velocity of radon diffusion through the floor slab, dependent on the radon diffusion coefficient of the slab concrete (mm s^{-1})

h = mean height of the interior volume of the house (m)

a = rate of air infiltration at a 1 Pa pressure differential (h^{-1})

n = pressure exponent from blower-door test (dimensionless)

b = rate of air infiltration under passive conditions (h^{-1}).

The effective area of openings in the house-soil interface is defined from f_c in Equation 1 as

$$A_o = f_c\, A_h, \qquad (2)$$

where

A_o = effective area of openings in the house-soil interface (m^2)

A_h = house area (m^2).

Estimating Radon Entry Areas

Successful estimates of effective radon entry areas, A_o, depend on a sensitive solution for the relative area, f_c, in Equation 1. Although four of the parameters in Equation 1 can be measured directly (C_{net}, C_{sub}, ΔP, and h), the other seven cannot, and must be inferred indirectly from the empirical measurements. Two of the seven (a and n) can be estimated from blower-door tests of house ventilation rates, leaving five unknowns in Equation 1.

The lumped-parameter expression in Equation 1 suggests a characteristic radon-pressure relation that depends on indoor air pressures in both the radon-entry term (numerator) and house ventilation term (denominator). The combined effects of indoor pressure are illustrated by estimating nominal reference values for the other parameters in Equation 1 and plotting the resulting net radon levels as a function of indoor air pressure.

Values for the measurable C_{sub} and h parameters, 1,000 pCi L^{-1} and 2.44 m, respectively, were assumed. The value f_c=0.002 is consistent with concealed cracks in houses with slab-in-stem-wall foundations, and the value f_c=0.01 is consistent with previous lumped-parameter analyses of floating-slab houses. A value of 0.0143 mm s^{-1} for υ_{dc} resulted from RAETRAD calculations using typical soil radon diffusion coefficients. The value for υ_{ac}, 0.0424 mm s^{-1} Pa^{-1}, is based on RAETRAD calculations for a house on sandy soil at a water matric potential of -30 kPa. The υ_{slb} parameter, 1.58 x 10^{-4} mm s^{-1}, is dominated by radon diffusion through the floor slab, but also includes lumped-parameter terms for house size and crack location. The value for υ_{slb} is for a floor slab with a radon diffusion coefficient of 8 x 10^{-4} $cm^2 s^{-1}$, as used previously. The value for *a*, 0.3 h^{-1}, is consistent with empirical values measured for Florida houses, and the values for *b* and *n*, 0.035 h^{-1} and 0.6, respectively, reflect the age trend and pressure-dependence determined previously for the lumped-parameter model.

Radon-pressure curves plotted for two radon entry areas, f_c=0.01 and 0.002, showed that net indoor radon concentrations decrease slowly as pressures approach passive conditions. However, at zero pressure, the curves showed a sharp increase in indoor radon caused by the house's baseline ventilation rate, *b*. Concentrations for the larger radon entry area were approximately 5 times higher than those for the smaller area at a pressure of -50 Pa. This difference indicates advective dominance of radon entry at this high suction pressure. At less negative pressures, however, the net indoor radon did not increase proportionately with f_c. Positive pressures were omitted because the lumped-parameter model is based on negative-pressure RAETRAD analyses and does not apply to positive pressures.

When the two radon-pressure curves were measured empirically, they provided a potential means of estimating f_c, if *b* was negligible compared to $a|\Delta P|^n$. This is illustrated by rearranging Equation 1 to obtain the following radon entry rate as a linear function of ΔP:

$$C_{net}\ h\ (a|\Delta P|^n + b) / (3.6\ C_{sub}) = (f_c \upsilon_{dc} + \upsilon_{slb}) - \Delta P\ (f_c \upsilon_{ac}) \qquad (3)$$

Calculating the left-hand side of Equation 3 for each measured radon and pressure point (ignoring *b*), the data can be fitted by least-squares to the pressures, ΔP, to plot radon entry rates as a function of indoor air pressures. The value of f_c can then be estimated from the slope of the resulting line as f_c=slope/υ_{ac} or from the intercept as f_c=(intercept-υ_{slb})υ_{dc} to obtain A_o from Equation 2.

Sensitivity Analyses

Sensitivity analyses were conducted to evaluate which estimate of f_c is preferable and to examine the validity of ignoring *b* in calculating the left-hand side of Equation 3 for empirical data fits. The sensitivity analyses used the lumped-parameter expression in Equation 1 to demonstrate the effects of each parameter on the radon-pressure curves. In each analysis, only one parameter was varied (the others were held constant). This approach illustrated the effects of a specific parameter in connection with typical values of the other parameters. The measurable parameters (C_{sub} and h) were not varied because they were specified explicitly in the calculations. Only two example values, 0.01 and 0.002, were used for f_c in the analyses since it was the main parameter to be estimated. The range of variation for the parameters was chosen to include a realistic range of values that could occur in connection with Florida housing.

The sensitivity analyses showed that varying the equivalent diffusive radon velocity through foundation openings, υ_{dc}, generally had little effect on the radon pressure curves. In contrast, varying the equivalent advective radon velocity through foundation openings revealed that the curves had a strong dependence on the value of υ_{ac}. Analyses for the equivalent diffusive radon velocity through the concrete slab, υ_{slb}, showed that varying υ_{slb} affected the radon-pressure curves only slightly, with the dependence being strongest in the zero-pressure spike.

Sensitivity curves plotted for different reference (1 Pa) air infiltration rates, *a*, showed a very strong dependence on *a*, except in the zero-pressure spike. Likewise, sensitivity curves plotted for the air pressure exponent, *n*, showed a strong dependence on *n*, with the least dependence occurring in the zero-pressure spike. Finally, varying the value of the passive-condition air infiltration rate, *b*, showed very little dependence on *b* throughout the negative pressure range, but a very strong dependence in the zero-pressure spike.

The sensitivity analyses for the *b* parameter indicated that it can reasonably be ignored in computing the radon entry fitting parameter on the left-hand side of Equation 3. The strong sensitivity of radon-pressure curves to υ_{ac} indicates that the slope of the line fitted to Equation 3 is the preferable parameter for estimating f_c and the associated area, A_o. The minimal sensitivity of the radon-pressure curves to υ_{dc} and to υ_{slb} indicates that the intercept of the line fitted to Equation 3 is not a good parameter for estimating f_c.

Radon-Pressure Analysis of the University of Florida Research House

In addition to its use in the sensitivity analyses, the lumped-parameter equation (Equation 1) was applied to empirical data measured at a University of Florida research house. The empirical data were measured by the university as part of its Florida Radon Research Program study of radon dynamics in a house dedicated for research in Gainesville, FL. The data included radon-pressure curves obtained by using a blower door to induce a sustained, “whole-house” indoor suction pressure while monitoring indoor radon levels until they reached steady-state values.

The radon concentration and building air pressure measurements taken in the research house analysis showed overall consistency with the shapes of the theoretical, lumped-parameter radon-pressure curves. The measured data exhibited the same increasingly negative slopes throughout the ΔP=-50 to -5 Pa range, and the same large zero-pressure spike near ΔP=0. The results of this analysis confirm that the slope of the line fitted to Equation 3 is a much more sensitive parameter than the line’s intercept for determining f_c and the associated area, A_o. However, the analysis also determined that the ΔP = 0 point is not directly useful for estimating radon leakage because of the greater sensitivity of data points at more negative pressures.

Conclusions

Fitting measured radon-pressure data to the parameters in Equation 3 proved to be the most direct and sensitive approach for estimating the product of f_c and υ_{ac}, which is a unique estimator of the effect of foundation leaks on indoor radon. Even though uncertainty in the precise value of υ_{ac} may cause uncertainty in estimating A_o, the $f_c\upsilon_{ac}$ product is the parameter of greatest importance for modeling indoor radon entry.

Because of the potential time and expense of conducting radon-pressure measurements, the feasibility of taking such measurements for routine use in diagnosing houses may be limited. However, for characterizing the magnitudes of typical soil-house leakage areas for different types of construction, measurement and analysis of radon-pressure data may be very useful. In fact, this approach is probably the only method presently available for empirically characterizing the magnitudes of concealed leaks or high-permeability regions in the foundations of houses with different types of foundation construction. Such characterization is vital to estimating the true performance of passive barriers such as conventional and improved (monolithic) floor slabs. This performance data is vital, in turn, for defining and implementing standards for radon-protective building construction.

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David C. Sanchez *is the EPA Project Officer (see below).*

The complete report, entitled "Feasibility of Characterizing Concealed Openings in the House-Soil Interface for Modeling Radon Gas Entry," (Order No. PB95-178414; Cost: $17.50, subject to change) will be available only from:

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