LBL-33687
UC-402

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

Impacts of a Sub-Slab Aggregate Layer and a Sub-Aggregate Membrane on Radon Entry Rate: A Numerical Study

Y.C. Bonnefous, A.J. Gadgil, K.L. Revzan, W.J. Fisk, and W.J. Riley

January 1993

ENERGY & ENVIRONMENT
DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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-33687

Impacts of a Sub-Slab Aggregate Layer and a Sub-Aggregate Membrane on Radon Entry Rate: A Numerical Study

Yves C. Bonnefous[†,‡], Ashok J. Gadgil[†],
Kenneth L. Revzan[†], William J. Fisk[†], William J. Riley[†]

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

[‡]Groupe Informatique & Systèmes Energétiques
Ecole Nationale des Ponts et Chaussées
France

January 1993

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Partial Support for Yves Bonnefous' research participation was granted by ENTPE of Lyon, France.

IMPACTS OF A SUB-SLAB AGGREGATE LAYER AND A SUB-AGGREGATE MEMBRANE ON RADON ENTRY RATE : A NUMERICAL STUDY.

Yves C. Bonnefous[1,2], Ashok J.Gadgil[1], Kenneth L.Revzan[1], William J.Fisk[1], William J. Riley[1].

[1] Indoor Environment Program, Lawrence Berkeley Laboratory, California.
[2] Groupe Informatique & Systèmes Energétiques, Ecole Nationale des Ponts et Chaussées, France.

ABSTRACT

A subslab aggregate layer can increase the radon entry rate into a building by up to a factor of 5. We use a previously tested numerical technique to investigate and confirm this phenomenon. Then we demonstrate that a sub-aggregate membrane has the potential to significantly reduce the increase in radon entry rate due to the aggregate layer, even when a gap exists between the perimeter of the membrane and the footer. Such membranes greatly reduce diffusion of radon from the soil into the aggregate and are impermeable to flow. Radon entry through the basement floor slab is limited to radon entry through the holes in the membrane. In addition, a sub-aggregate membrane is predicted to improve the performance of active sub-slab ventilation systems and makes passive systems more promising.

INTRODUCTION

A permeable layer of aggregate under the basement slab is recommended or mandatory for new residences in some states of the USA (1, 2). This layer is placed as a provision for good subslab ventilation system performance, if such a system were to be later required.

However, previous modeling (3) and recent experiments (4) have shown that placement of such a layer can enhance the radon entry rate by up to a factor of 5. This work aims to better understand this phenomenon and to propose and quantitatively evaluate a counter measure.

METHOD

For this study, we used a numerical technique previously tested (5, 6). The model, "Non-Darcy STAR" (Non-Darcy Steady-state Transport of Air and Radon), is a three dimensional finite difference model on a rectilinear coordinate system, based on the SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm developed by Patankar (7). The model solves the Darcy-Forchheimer (8) equation for flow through permeable media

$$\vec{\nabla} p = -\frac{\mu}{k}(1 + c|\vec{V}|)\vec{V} \ , \tag{1}$$

together with the equation of continuity

$$\vec{\nabla} \bullet \vec{V} = 0 \ , \tag{2}$$

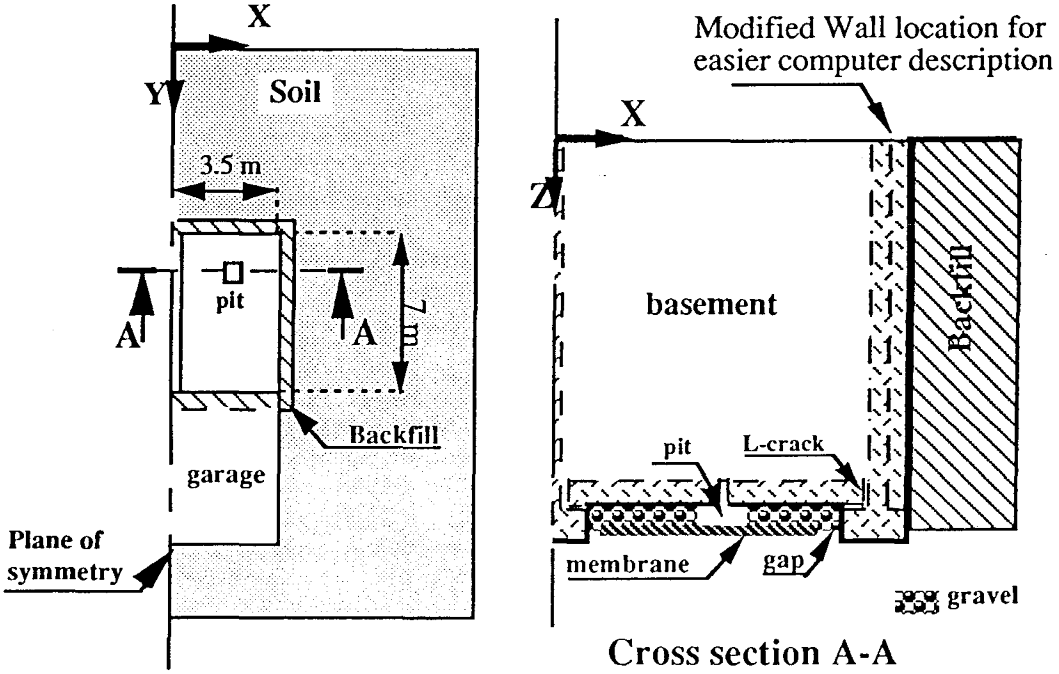
where p is the disturbance pressure (i.e. the change in soil-gas pressure owing to the depressurization of the basement and the pressure applied by a sub-slab ventilation (SSV) system), μ is the dynamic viscosity of soil-gas, k is the permeability of the porous medium (i.e. soil or gravel), c is the Forchheimer term, and $\vec{V}$ is the bulk velocity of soil-gas. For low velocities (e.g. in absence of a SSV system) the Forchheimer correction term ($c|\vec{V}|$) is negligible and equation (1) simplifies to Darcy's law.

Once the velocity field for the soil-gas is calculated, the radon concentration field is calculated by solving the radon mass balance equation:

$$\vec{\nabla} \bullet (D\vec{\nabla}C_{Rn}) - \vec{V} \bullet \vec{\nabla}C_{Rn} + \varepsilon(S - \lambda_{Rn}) = 0 \ , \tag{3}$$

where D is the bulk diffusivity of radon in the porous medium, C_{Rn} is the concentration of radon in the soil-gas, S is the release rate of radon into the soil-gas per unit volume of the porous medium, ε is the porosity of the medium, and λ_{Rn} is the radon decay constant. The model is described in detail by Gadgil et al. (9). The solution approach used to solve eq. (3) is similar to that used by Loureiro (10). The rate of radon entry into the basement is calculated by integrating the product of the soil-gas entry rate and the local concentration in the soil-gas over the area of the crack at the perimeter of the basement slab. Finally, the radon concentration in the building is evaluated using two simplifying assumptions: A) the air in the building is perfectly and instantaneously mixed and B) when a SSV system is operated, the air exchange rate in the building is obtained by summing in quadrature (11) the fixed typical air exchange rate and the air exchange rate induced by the SSV system. To simplify the model and make the results easier to understand, we have neglected diffusive transport of radon through the concrete, radon entry through the basement walls and the radon in the outdoor air. Buoyancy effects are neglected for the present study.

Figure 1 shows the geometry of the "typical" house used for this work. The computational domain is bounded at 10 m below the basement slab, by a no-flow boundary, and for three sides by no-flow vertical surfaces at 10 m horizontal distance from the basement walls. The fourth vertical surface represents the plane of symmetry of the problem and vertically bisects the basement and an internal footer. This fourth vertical surface is also a no-flow boundary owing to symmetry. The computational domain is bounded from above by the basement slab, the wall and footers (with a joint defined between the slab/wall and the footers), and the soil surface outside the basement. The concrete is impermeable. The soil surface outside the basement slab is defined to be at zero disturbance pressure, except for the garage slab which is impermeable. When a sub-aggregate membrane is placed, it is assumed to be impermeable with a gap at its periphery.



Cross section A-A

Fig. 1. The plan and the section of the "typical" house modeled for the parametric simulations with Non-Darcy STAR. Owing to the assumed plane of symmetry of the house, only half of the house is shown in the plan and the section. The L-shaped crack dimensions are shown greatly exaggerated here for clearer illustration.

The layout and dimensions of the "typical" house are based on common single family houses with a basement, but are not based on a statistical survey. The cracks in the basement slab are represented with a single equivalent crack of width 1 mm, located at the joint of the slab with the wall and footer. This crack has an L shape in cross-section, its resistance to flow was calculated according to Baker et al. (12). In the model, the exterior surface of the basement walls is assumed to be displaced outwards to line up with the footer edge (see Fig. 1). This allows some reduction in the number of computational control-volumes required in the model, and a corresponding reduction in the computational time.

We used three gravel types representing the range used in housing construction in the state of Washington. The permeabilities and Forchheimer terms for the three kinds of gravels were measured previously in the laboratory (6, 9). For the present study, the backfill region is assumed to have the same permeability as the soil, and is assumed to be in firm contact with the exterior of the basement wall. The basement is assumed to be under a fixed depressurization of -10 Pa. When a SSV system is installed, a pit (0.25 m radius) is excavated at the SSV pipe penetration point under the basement floor. We assumed a deep soil radon concentration of 59,000 Bq/m^3, equal to three times the average deep soil radon concentration measured by Turk et al. (12) in the region of Spokane, Washington. The sub-slab gravel layer is assumed to release no radon into the soil-gas. The half building modeled has a volume of 122.5 m^3, and a fixed air exchange rate (in absence of a SSV system) of 0.4 ACH.

The choice of the degree of resolution of the computational domain into control volumes is determined by the trade-off between computational time and residual errors owing to inadequate resolution of regions with large gradients of velocity and pressure. In most of the runs for this work, the computational domain had 37,260 control volumes. We estimate that the error in radon entry rate resulting from inadequate grid resolution is less than 20% (6).

RESULTS

Revzan et al. (3) have shown that placement of a subslab gravel layer can increase radon entry rate in the basement by up to a factor 5, depending on the gravel to soil permeability ratio. Robinson et al. (4) find a factor 5 increase in the radon entry between two well characterized and instrumented structures located at the same site, the only difference between the two experimental basements being the presence of a subslab gravel layer.

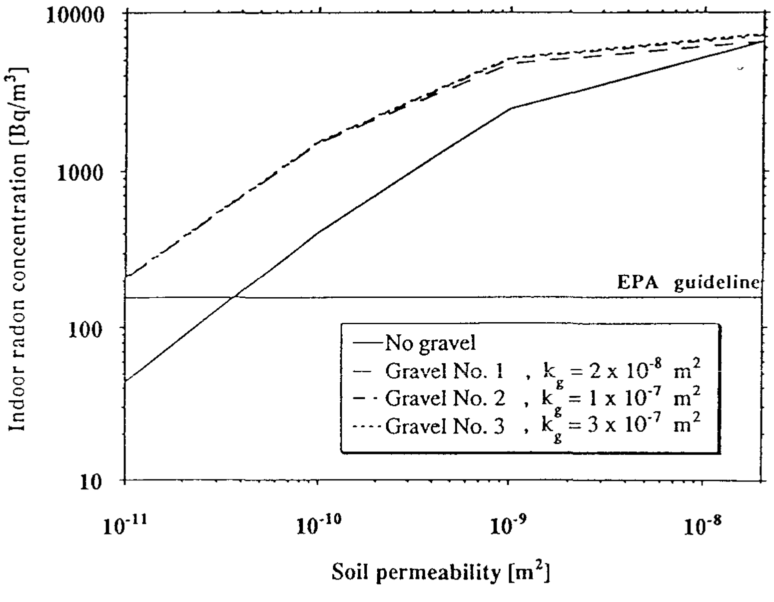


Fig. 2. Indoor radon concentration in the "typical" house with a 1 mm L-Shaped crack at the slab periphery. The assumed deep soil radon concentration is 59,000 Bq/m^3. k_g is the gravel permeability.

Our model confirms these results. Figure 2 shows an increase in the indoor radon concentration (proportional to the radon entry rate with our assumptions) by up to a factor of 5 for high ratios of gravel to soil permeability. Figure 2 is similar to Fig. 4 from Revzan and Fisk (3). We conducted in addition a parametric study on the effect of the crack width on radon entry rate (including the limiting case of radon entry rate in absence of the basement slab). The results are shown in Figure 3.

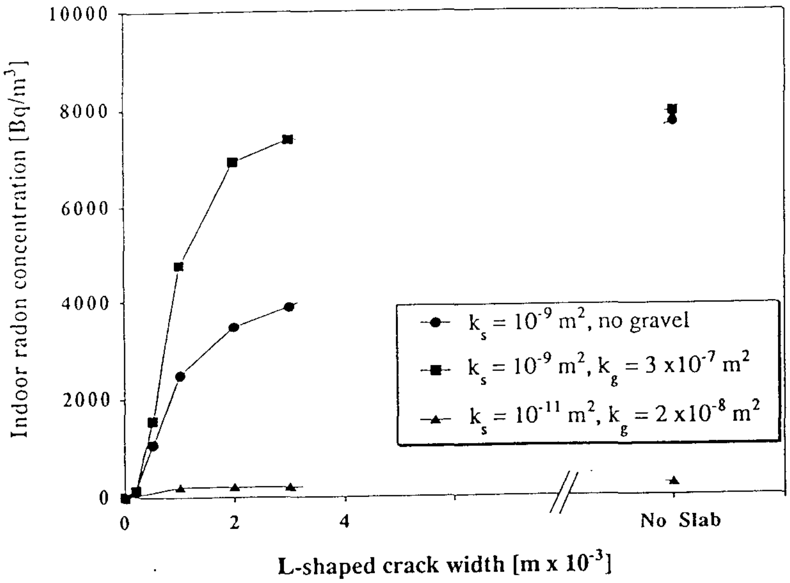


Fig. 3. Indoor radon concentration in the "typical" house for various width of the L-Shaped crack at the slab periphery and in the absence of the slab. The assumed deep soil radon concentration is 59,000 Bq/m^3. k_s and k_g are the soil and gravel permeability, respectively.

For low permeability soils, the crack resistance and the gravel resistance to the flow are negligible compared to the soil resistance to the flow. As a consequence, the gravel layer acts like a manifold at the basement pressure, increasing the zone of influence of the basement (zone from which radon can be drawn into the basement). We found that the radon entry rate into the basement is then equal to the radon entry rate into the gravel layer, which is roughly the radon entry rate in the absence of a slab. Sealing the cracks in the slab, unless nearly perfect, doesn't seem to be an efficient technique by itself to reduce the radon entry rate, as the crack resistance to flow needs to be brought to the level of the soil resistance to flow to be effective (see Fig. 3, lower curve). The magnitude of the increase in radon entry rate is not sensitive to the gravel permeability. As soon as the ratio of gravel to soil permeability is over 100 (which is most often the case), the gravel layer acts like a uniform pressure manifold and the radon entry rate is essentially independent of the gravel type. This is shown in Fig. 2: curves for various gravels coincide at low soil permeabilities.

Requiring a sub-slab gravel layer as a provision for good SSV system performances, if one were later necessary, will increase the average radon concentration in houses. The number of houses needing radon mitigation would increase as well as the number of houses with radon concentration just below the action limit. On the other hand, a high permeability sub-slab gravel is a key factor for good SSV system performance (5, 14), and may be necessary for good passive SSV system performances. In addition, a gravel layer is often placed under the slab anyhow as a moisture barrier.

We propose a technique to reduce the increase in the radon entry rate in the house due to the presence of a subslab aggregate layer. The technique consists of reducing the radon entry rate into the gravel layer by placing an impermeable, low-diffusivity membrane under it. With the sub-aggregate membrane, radon entry into the gravel layer (and as a consequence, into the basement) would be limited to radon entry through the gaps and holes in the membrane.

Preliminary laboratory tests determined radon diffusivity constants for two commercially available membranes: 0.015 mm (0.006 in) thick polyethylene and 0.015 mm thick material with the trade name "Tu-Tuff". Measured radon diffusion coefficients are in the range 10^{-11} m^2/s to 10^{-12} m^2/s. Such membranes are satisfactory as radon diffusive barriers. We therefore could ignore radon diffusion through the membrane in our numerical simulations.

We conducted additional numerical simulations of the "typical" house with a sub-aggregate membrane. We assumed gaps at the periphery of the membrane (see Figure 1) of 0.1 m and

0.01 m. The size of this gap in a real installation would depend on the attention given to the membrane placement by the construction crew. In the simulations, the two sizes of the assumed gap also account for any cracks and holes made in the membrane during installation.

Table 1 shows that the membrane reduces the radon entry as expected. The radon entry rate into the basement is equal to the radon entry rate into the gravel through the gap at the membrane periphery (see col 5 and col 6 of Table 1). For high permeability soils, the gap at the membrane periphery must be small for the membrane to significantly reduce the radon entry rate. For low permeability soils, even a 10 cm gap at the membrane periphery cut the increase in radon entry due to aggregate by 40%. We think that the size of the gap could be easily minimized with a good construction methodology. The membrane should be placed before the concrete footers are poured, and it should extend underneath the footers.

Table 1. Membrane effect on Radon Entry in the typical house, in absence of a SSV system, for various soil and gravel permeabilities. Details of house definition are given in (9).

Soil Permeability [m^2]	Gravel Permeability [m^2]	Membrane Gap [m]	Soil-Gas Entry Rate [m^3/s]	Normalized Rn Entry Rate [m^3/s] x 10^{-6}		Indoor Rn Concentration [Bq/m^3]
				gravel layer	basement	
10^{-9}	no gravel	no membrane	8.9×10^{-4}	-	570	2470
10^{-9}	2×10^{-8}	no membrane	2.2×10^{-3}	1200	1110	4770
10^{-9}	2×10^{-8}	0.1	1.9×10^{-3}	970	970	4170
10^{-9}	2×10^{-8}	0.01	1.5×10^{-3}	820	820	3530
10^{-11}	no gravel	no membrane	1.1×10^{-5}	-	10	44
10^{-11}	3×10^{-7}	no membrane	5.4×10^{-5}	49	49	210
10^{-11}	3×10^{-7}	0.1	3.7×10^{-5}	32	32	140
10^{-11}	3×10^{-7}	0.01	2.4×10^{-5}	22	22	96

Lastly, we added a SSV system in the typical house and conducted another set of numerical simulations. We show that the sub-gravel membrane significantly improves SSV system performance. Gadgil et al. (14) showed that a key parameter for good SSV performance is a good pressure field extension beneath the slab floor. In addition, they showed that for low permeability soils, sub-slab pressurization (SSP) system performance deteriorates owing to diffusive entry of radon into the gravel layer. We show that for high permeability soils, a sub-gravel membrane improves significantly the sub-slab pressure field extension and as a consequence the SSV system performance. The magnitude of this improvement depends on the ratio of gravel to soil permeability and on the ratio of crack to gravel resistance to flow. In addition, for low permeability soils, the membrane, being a radon diffusive barrier, improves SSP system performance. A complete parametric study of SSV systems operating in houses with a sub-aggregate membrane is currently underway.

DISCUSSION

Placement of a sub-aggregate membrane during building construction would significantly reduce the increase in radon entry due to the subslab aggregate layer and increase the performance of a SSV system if one were to be installed. It may even allow successful operation of passive SSV systems. We are conducting numerical as well as experimental studies on passive systems including a sub-aggregate membrane (15).

More work is needed to address the concerns regarding radon and sub-slab water (moisture, drainage) when placing a sub-aggregate membrane. We also need to characterize an acceptable degree of membrane imperfections in terms of holes punched during placement, gaps between sheets and gaps at the periphery of the membrane. Ongoing research on passive SSV systems may also add more requirements for the membrane. We do not recommend placement of a sub-aggregate membrane yet, but this technique appears very promising.

ACKNOWLEDGMENTS

This work was supported at the Indoor Program of Lawrence Berkeley Laboratory by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098. Partial support for Yves Bonnefous's research participation was granted by ENTPE of Lyon, France.

REFERENCES

1. Washington State Building Code Council. Radon resistive construction standards. Washington State ventilation and indoor air quality code; State of Washington: Olympia, 1990; chapter 5.
2. Nuess M. Northwest residential radon standard, Volume 1: project report. Bonneville Power Administration Report; Portland, OR, 1989.
3. Revzan K.L., Fisk W.J. Modeling Radon Entry into Houses with Basements: The Influence of the Structural Factors. Indoor Air 1992; 2: 40-48.
4. Robinson A., Sextro R.J., Fisk W.J., Garbesi K., Wooley J., Wollenberg H.A. A Comparison of Soil Gas and Radon Entry into Two Basement Structures Under Controlled Conditions. Submitted to Indoor air '93, Helsinki, Finland, July 4-8, 1993.
5. Bonnefous Y.C., Gadgil A. J., Fisk W.J., Prill R.J., Nematollahi A. Field Study & Numerical simulation of subslab ventilation systems. Environ. Sci. & Technol. 1992; 26: 1752-1759.
6. Bonnefous Y.C. Etude numérique des systèmes de ventilation du sol pour diminuer la concentration en radon dans l'habitat. PhD thesis No ISAL-0055 : Génie Civil : INSA de Lyon, France, 1992. 261 p.
7. Patankar S.V. Numerical heat transfer and fluid flow. Hemisphere Publishing corporation: New York, 1980.
8. Forchheimer P.H. Z. Ver. Dtsch. Ing. 1901; 45: 1782-1788.
9. Gadgil A.J., Bonnefous Y.C., Fisk W.J., Prill R.J., Nematollahi A. Influence of subslab aggregate permeability on SSV performance. LBL-31160; Lawrence Berkeley Laboratory, Berkeley, CA, 1991.
10. Loureiro C.O., Abriola L.M., Martin J.E., Sextro R.G. Environ. Sci. and Technol. 1990; 24: 1338-1348.
11. Sherman M.H. Superposition in infiltration modeling. Indoor Air 1992; 2: 101-114.
12. Baker P.H., Sharples S., Ward I.C. Air flow through cracks Building and Environment 1987; 22:.293-304.
13. Turk, B. H., Prill, R. J., Grimsrud, D. T., Moed, B. A., et Sextro, R. G. Characterizing the occurence, sources, and variability of radon in Pacific Northwest homes J. Air Waste Manage. Assoc. 1990; 40: 498-506.
14. Gadgil A.J., Bonnefous Y.C., Fisk W.J. Relative effectiveness of Sub-Slab Pressurization and Depressurization Systems for Indoor Radon Mitigation: Studies with an Experimentally Verified Numerical Model. In: Proceedings of the 1992 international symposium on Radon and Radon Reduction Technology, Mineapolis , Minesotta, 22-25 September 1992.
15. Kunz C. Radon Reduction in New Construction: Double-Barrier Approach. In : Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, PA, April 2 - 5, Research Triangle Park (North Carolina) : Environmental Protection Agency, vol. 4, EPA-600/9-91-026b.