#5481

Paper V - 1

A MODELING EXAMINATION OF PARAMETERS AFFECTING RADON AND SOIL GAS ENTRY INTO FLORIDA-STYLE SLAB-ON-GRADE HOUSES

R.G. Sextro, K.L. Revzan and W.J. Fisk

Indoor Environment Program
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

This paper discusses the use of a finite-difference numerical model to examine the influence of soil, fill, and construction characteristics on convective entry of radon and soil gas into slab-on-grade houses. Such houses, built with a perimeter, hollow-core concrete block stem wall and an above-grade floor slab resting on fill, are typical of a portion of the Florida housing stock. When the building is depressurized with respect to the ambient pressure, radon-bearing soil air will flow through various combinations of soil, fill, and blockwall components, entering the house through perimeter slab-stem wall gaps or interior cracks or other openings in the floor slab. At a constant building depressurization, the model predicts the steady-state pressure, flow, and radon concentration fields for a soil block 10 m deep and extending 10 m beyond the 7-m-radius slab. From the concentration and pressure fields, radon and soil gas entry rates are then estimated for each entry location. Under base case conditions, approximately 93 percent of the soil gas entry is through the exterior section of the stem wall, 5 percent is through the interior section of the stem wall, 2 percent through an interior slab opening, and less than 1 percent through gaps assumed to exist between the stem wall and footing or the stem wall and floor slab. In contrast, 57 percent of the radon entry rate occurs through the interior section of the stem wall, 22 percent through the interior slab opening, 20 percent through the exterior section of the stem wall, and less than 0.5 percent through the gaps. Changes in fill permeability have significant effects on radon entry, while changes in blockwall permeability are largely offset by increased flow and entry through structural gaps. These results, along with those from other model configurations, will be discussed.

This work has been supported, in part, by the U.S. Environmental Protection Agency. This paper has been reviewed in accordance with the U.S. EPA peer and administrative review policies and has been approved for presentation and publication.

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INTRODUCTION

The role of convective flow of soil gas in transporting radon into buildings is widely acknowledged; however, the factors that affect radon entry can be complex. These flows will depend upon the driving pressure, the type and location of the openings connecting the building interior with the surrounding soil environment, and upon the characteristics of the soil medium (1,2). The nature of these openings is strongly influenced both by the type of building substructure and by the specific construction details. The driving pressure, which is the pressure difference between the surface of the soil surrounding the building and the building interior, is caused by the stack effect (due to temperature differences between the inside of the building and the outdoors), wind loading on the building shell, and the operation of heating and/or air conditioning systems.

In response to the discovery of elevated radon concentrations in a fraction of the Florida housing stock (3), the State of Florida and the U.S. Environmental Protection Agency have established the Florida Radon Research Program, with the broad goals of conducting research on radon entry into housing typical of that built in Florida and to investigate and develop techniques that limit radon entry into existing buildings or new construction (4). One objective of the research is to understand how indoor radon concentrations are influenced by details of the building substructure and the adjacent soils and fill materials.

We have developed and refined several detailed numerical models of radon transport through soil and entry into buildings (5,6,7) in order to investigate factors influencing soil gas and radon migration, including characteristics of the building and the surrounding soil. In the present study, a two-dimensional, steady-state finite-difference numerical model, utilizing cylindrical symmetry, has been assembled, with boundary conditions appropriate for one form of the slab-on-grade construction used in Florida housing. The model has been used to explore the influence of soil and building parameters on soil gas and radon entry. This paper summarizes the results of these simulations and discusses their implications for possible methods of limiting soil gas and radon entry. Greater detail is presented in reference (8).

MODEL DESCRIPTION AND APPROACH

MODEL OVERVIEW

The model used in this study is based upon a finite-difference numerical code in which the soil is assumed to be isothermal and the relationship between gas flow and driving pressure is assumed to be linear (Darcy's law) (5,6). We have used a form of the model in which the Cartesian coordinates are transformed into a cylindrical coordinate system. This, in effect, reduces the model to two dimensions for computing purposes. Since many of the structural elements of interest to our analysis are at the perimeter of the house or can be chosen to have cylindrical symmetry, there is little loss of generality in using cylindrical coordinates. This approach permits increased resolution and/or more rapid convergence with

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only modest loss in realism in moving from a fully three-dimensional treatment (6). Because we are interested in a parametric analysis, the benefit of greater speed outweighed the slight loss in accuracy compared with a fully three-dimensional configuration.

Details of the model, including the appropriate governing equations, are presented in references (6,8). We discuss here some of the major features and assumptions of the model. Boundaries for the soil block have been chosen to be 10 m from the footing in both the radial (r) and vertical (z) directions, as indicated in Figure 1. The bottom surface of the slab and the outer surfaces of the footing are assumed to be no-flow boundaries. Thus the model does not explicitly account for radon entry by diffusion through the concrete slab; rather, this entry rate is calculated separately (9). The model does, however, include migration of radon in the soil and fill by diffusion.

A static pressure difference is applied between the surface of the soil exterior to the building and the floor slab (top) surface, the mouth of the interior slab gap and the opening between the slab edge and the outer element of the stem wall (subsequently referred to as the slab edge opening). These geometries are illustrated in Figures 1 and 2, and are discussed in greater detail in the next section. In the general case we have assumed that the slab edge opening is sufficiently large so there is no pressure drop associated with flow through this opening. Thus, the static pressure difference is effectively between the inner surfaces of the stem wall, the mouth of any of the gaps, and the exterior soil surface. We have also modeled two cases where this general picture is altered. In the first case, the stem wall is assumed to be filled with impermeable concrete, so that the only gap is between the top of the interior element of the stem wall and the bottom of the floor slab. In the second case, we reduce the size of the slab edge opening so that pressure drop does occur across it, reducing the pressure difference between the exterior soil surface and the stem wall interior.

We assume that all air and radon entering the stem wall interior also passes through the slab edge opening into the house. Soil gas and radon can also enter the house through the interior floor slab gap. In order to compute the static pressure at the soil or fill surface located at the bottom of the various gaps, we use an algorithm (10) to compute the pressure drop across a gap, ΔP_g:

$$|\Delta P_g| = \frac{12\mu t}{w^2}|\vec{v}| + \frac{\rho(1.5+n)}{2}v^2. \quad (1)$$

where t is the length of the gap in the flow direction, w is the gap width perpendicular to the flow, n is the number of bends in the gap, and v is the average air velocity in the gap (*i.e.*, the flow rate through the gap divided by the gap area). The constants μ and ρ are the dynamic viscosity and density of air, respectively.

The model computes the pressure field throughout the soil and fill region by solving the Laplace equation. Soil gas transport is then calculated, from Darcy's law, which assumes a linear relation between applied pressure and fluid velocity. The mass balance equation describing radon migration, including radon generation, radioactive decay, and both convective and diffusive radon transport, is solved to determine the radon concentration field. The model then yields soil gas and radon entry rates at each entry point. This paper presents only the soil gas and radon entry rates at selected entry locations and, for the base case, the radon concentration in the fill adjacent to the entry locations.

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BUILDING SUBSTRUCTURE AND SOIL GEOMETRY

A large fraction of houses built in Florida are constructed with a slab-on-grade substructure, of which there several variants (11,12). For this work, we have modeled an above-grade concrete slab floor which rests on a perimeter hollow-core concrete block stem wall. The slab edge rests on a chair block, which is the top course of blocks in the stem wall. There is an opening between the edge of the floor slab and the outer section of the stem wall, as noted earlier. The floor is also supported by fill material placed within the boundaries of the stem wall and elevated above the natural grade. A vertical section of the substructure is shown in Figure 1. As indicated in Figure 2, where the floor and stem wall are shown in greater detail, gaps are assumed to exist between both the inner and outer elements of the stem wall and the footing, and between the inner portion of the stem wall and the bottom of the floor slab. The gap dimensions are chosen as an input parameter. We also examined the effect on soil gas and radon entry of eliminating the gaps at the bottom of the stem wall.

The inner and outer elements of the concrete blocks that comprise the stem wall are assumed to be permeable to air flow; this permeability is another input parameter for the model. These wall elements are modeled as vertically homogeneous; that is, no provision is made for differences due to mortar joints between the blocks. In order to simplify the model, we have not included the block webs -- sections of the block that connect the inner and outer wall elements. In the general case, the interior of the block is open and flow through the webs themselves should be not significantly affect our results. In the cases where the stem wall is filled with concrete, we also assume that these webs are not present and thus no flow path is provided. The concrete footing and floor slab are assumed to be impermeable to gas flow. An interior gap in the slab floor is included in the model, with radial location and gap width as model inputs. The length of this gap is defined by the radial location.

As can be seen in Figure 2, the fill below the slab and on top of the footing is defined as a separate region to enable us to specify fill properties that may differ from those of the natural soil. The two parameters of greatest interest here are both the air permeability and the radium content of the soil or fill.

BASE CONFIGURATION

We have chosen a set of parameters that constitute a base case for our modeling. These have been selected based on reviews of the available data on Florida housing (11,12) and on soil and fill properties (13,14). Because we were interested in evaluating the effects of varying several of the soil and/or building substructure features on soil gas and radon entry, we also established a range over which each parameter was varied. The base case values and ranges are summarized in Table 1. As noted earlier, the fixed dimensions for the slab, soil block, and the stem wall details are indicated in Figure 2.

In the base case, we have used an effective radon diffusion coefficient of 2×10^{-6} m^2 s^{-1} for the soil and fill and an 'infinite depth' radon concentration, C_∞, of 37 kBq m^{-3} which is equivalent to soil or fill with a radium concentration of 46.5 Bq kg^{-1} and an emanation coefficient and porosity of 0.2 and 0.4, respectively. The pressure difference between the top of the slab and the top of the soil outside the building was chosen to be -2.4 Pa.

The parametric investigation was carried out using two approaches. First, each parameter was varied individually, with the remaining parameters held fixed at their respective base case values. Second, in some cases we varied more than one parameter at the same time in order to explore more fully the effects of the parameters of interest. In these cases we varied:

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1) the soil permeability for high (10^{-9} m^2) and low (10^{-15} m^2) fill permeabilities;

2) independently the soil and fill permeabilities when the slab gap is the only soil gas entry path;

3) the soil, fill, and stem wall permeabilities independently when the core of the concrete blocks making up the stem wall is filled with impermeable concrete;

4) the stem wall permeability when both gaps between the bottom of the stem wall and the concrete wall footing are completely closed; and

5) the size of the slab edge opening.

RESULTS AND DISCUSSION

In the base case, the predicted soil gas and radon entry rates due to convective flow are 5.1×10^{-4} m^3 s^{-1} and 1.6 Bq s^{-1}, respectively. The distribution of soil gas and radon flows through the various entry points shown in Figure 2 are summarized in Table 2. The model simulations predict that 93 percent of the total soil gas entry occurs through the exterior side of the stem wall, while about 6 percent proceeds through the interior surface of the stem wall. Most of the gas flow is through the sides of the stem wall, rather than through the 3 mm wide gaps at the top and bottom of the stem wall. Only 1.6 percent of the total soil gas entry is predicted to occur at the interior slab gap, which in the base case is located at 3 m radius. This corresponds to a crack length of 18.8 m. These relative entry rates are consistent with the path length of the flow lines -- and therefore the resistance to flow -- connecting the exterior soil surface and the specific entry point.

The distribution of the radon entry rates associated with this air flow is different, with almost 59 percent predicted to occur through the interior side of the stem wall, 21 percent through the exterior side of the stem wall, and 20 percent through the interior slab crack. The predicted radon concentrations at each of the entry points, shown in Table 2, indicate that, although the largest fraction of gas flow occurs through the exterior side of the stem wall, the radon concentration in the adjacent soil is low due to diffusion to the atmosphere and to dilution by the atmospheric air entering the soil through a short flow path. In contrast, the radon concentrations are much higher in the fill materials located adjacent to the interior side of the stem wall and below the interior of the slab.

In comparison with the convective radon entry rate, the diffusive entry rate, based on a radon diffusion coefficient for concrete of 5×10^{-8} m^2 s^{-1} and a concrete porosity of 0.2, is 0.5 Bq s^{-1} (9). Thus, for a single-story house with a volume of 500 m^3 and an average air exchange rate of 0.5 h^{-1}, the total indoor radon concentration would be 31 Bq m^{-3} for this base case soil and substructure.

Results of selected model runs in which the effects of different parameters are evaluated are shown in Table 3 and in Figure 3. We extensively investigated the effects of changes in permeability of the soil, both alone and in conjunction with variations in other parameters or assumptions. Changes in soil permeability alone had a somewhat modest effect on radon entry in the base case, since flows at the higher soil permeabilities are then limited by the fill permeability. The role of the fill in determining flows is demonstrated by comparing the predicted radon entry rates when the fill permeability is chosen to be either high (10^{-9} m^2) or low (10^{-15} m^2). For high fill permeability, radon entry is limited by the permeability of the underlying soil. When both are high, the increased radon entry rate is significant, almost 30 times the base case. On the other hand, if the fill has a low permeability, total radon entry is quite low

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and is essentially unaffected by changes in soil permeability.

Another effect that arises when soil permeability is varied is the change in the importance of the various radon entry locations. As soil permeabilities are reduced below that of the base case, radon entry through the exterior of the stem wall changes only slightly as soil permeabilities range from 10^{-12} to 10^{-9} m^2. However, entry through the interior side of the stem wall is reduced as the soil permeability is reduced below the base case, and increases as the soil permeability increases. Radon entry at the interior slab gap behaves in a similar fashion, though it does not increase as much with increasing soil permeability. Thus at the low end of the range of soil permeabilities modeled here, radon entry through the exterior side of the stem wall is the largest single component; as soil permeability increases, the relative importance of this entry pathway decreases. At the high end of the soil permeability range, approximately 88 percent of the radon entry occurs through the interior side of the stem wall, almost 10 percent is through the interior slab gap, and about 2 percent occurs through the exterior side of the stem wall.

If the soil is layered, the effects on radon entry of variations in the permeability of the layer depend upon the location of the layer. We modeled two different layered soil cases in which the permeability of the soil layer was varied while those of the fill and the remaining soil were held fixed at the base case values. In the first configuration, the soil layer began at grade level (*i.e.*, in direct contact with the fill material) and extended 1 m deep. In the second case, the soil layer began at 0.5 m below grade (which is the depth of the bottom of the footing) and extended to 1.5 m below grade. As shown by the results in Table 3, when the layer is in contact with the fill (assuming the fill has the base case permeability), the layer has a larger effect on radon entry than when the soil layer is deeper.

Interestingly, filling the stem wall interior with impermeable concrete has only a modest effect on total radon entry. In this case, we assume that there is still a gap between the top of the concrete-filled stem wall and the bottom of the floor slab. As shown in Table 3 and Figure 3, total radon entry still increases with increasing soil permeability, though for a given permeability the radon entry rate is lower than in the base case. One can also see that the effects on radon entry of changing the fill permeability when the stem wall is filled with concrete are also modest. These results can, in general, be explained by the fact that the pressure field distribution in the adjacent fill is altered when the stem wall interior is impermeable. The larger pressure gradient at the remaining entry point, which compensates somewhat for the reduced number of entry points, results in a higher soil gas and radon entry rate.

Similarly, changing the permeability of the stem wall itself has very little effect on total radon entry, as can be seen from Figure 3. Again, this is due to compensating effects. As long as the wall permeability is greater than that of the adjacent fill, flow through the wall is the most important. As the wall permeability decreases below that of the fill, the gaps between the wall and the footing and between the wall and the floor slab become increasingly important flow pathways as the pressure field is altered due to the changing wall permeability.

We also parametrically examined the effect of the size of the slab edge opening on the radon entry rate. In our initial problem definition, we assumed that this opening was sufficiently large so that no pressure drop occurred at this point -- effectively applying the full -2.4 Pa static pressure difference between the exterior soil surface and the inner surfaces of the stem wall. In actual construction practice this opening may in fact be much smaller, in effect reducing the driving force for convective flow into the stem wall interior. Holding all the soil and wall parameters at their base case values, the effect of closing this opening to 1 mm reduced the total radon entry by about 40 percent. Radon entry via this opening drops

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by about a factor of 4 in this case, but the predicted entry via the interior slab gap increases by almost a factor of 2, compensating somewhat for the reduction at the stem wall. This increased entry rate at the interior slab gap arises because the pressure gradient in the fill region near the stem wall is reduced, thus more of the air flow through the soil is directed toward this interior opening.

In addition to the flow of soil gas into the stem wall, via the wall material itself or through the gaps indicated in Figure 2, there is air flow through that portion of the exterior wall that is above grade. In fact, in the base case, this flow is 6.3×10^{-3} m^3 s^{-1}, which is about 12 times the total predicted soil gas flow from the soil into the house (we have not included this entering outdoor air as a source of radon, just as we have not included infiltration through the house superstructure as a radon source). In order to investigate the effects of changing the flow balance between the inner and outer stem wall elements we increased the permeability of the above-grade portion of the exterior stem wall element to 10^{-9} m^2 and fixed the permeability of the remainder of the wall at 10^{-12} m^2 (as might be achieved with a wall coating or sealant). With the slab edge opening reduced to 1 mm, the the radon entry rate through the stem wall is reduced dramatically to 0.01 Bq s^{-1} from 0.9 Bq s^{-1} in the base case. Total radon entry predicted for the entire substructure is not reduced as much, to about 37 percent of the base case rate, because radon entry through the interior slab gap increases in response to the changes in the pressure field distribution, as described earlier.

The effect of water table depth on the predicted radon entry rate was found to be small. For a water table (modeled as a change in the position of the no-flow boundary at the bottom of the soil block) depth between 2.5 and 10.5 m below grade, the radon entry rate was essentially unchanged. At depths less than 2.5 m, the entry rate reduction was small; at 0.5 m deep, the radon entry rate was predicted to be 0.88 Bq s^{-1}.

Finally, we investigated the effect on predicted radon entry of changes in the radium content of the soil and fill. First, it should be noted that, if the radium content (and thereby the soil gas radon concentration) was increased uniformly in both the soil and fill, the radon entry rate would increase proportionately (except for minor reductions due to the slight increase in diffusive losses from the soil surface). If the fill radium content is changed from the base case, the radon entry rate does not change proportionately, as can be seen from Table 3. Larger changes in radon entry can occur if the radium content of the soil below 1.5 m were to increase, as might be the case where a high radium soil layer was close to the surface. The effects of similar changes in radium content of soil below 5.5 m are diminished, reflecting the fact that any additional radon from the enhanced radium content is transported through the soil by means of diffusion into the soil and fill region where convective transport into the structure becomes important.

CONCLUSIONS

Application of our finite-difference models, incorporating key features of the soil, fill, and substructure, has provided additional insight into transport of soil gas and radon through the soil and into a building. The model results have also shown that changes in the characteristics of various entry locations or pathways can impact radon migration and entry at other locations, leading to compensating effects. As one example of this, a reduction in the permeability of the stem wall elements reduces flow through the wall materials, but soil gas and radon entry increases through the gaps at the top and bottom of the stem wall in response to the changes in the pressure field in the adjacent fill. Thus the total radon entry rate is

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not significantly affected. Similarly, a reduction in the size of the opening at the slab edge to 1 mm or less is necessary to effect any significant reduction in the total radon entry rate. If the interior opening in the floor slab is eliminated (but the stem wall entry is unchanged), the total radon entry rate is reduced by only 10 percent over the base case rate. If, on the other hand, all entry points at the stem wall are eliminated (as might be accomplished by use of a solid, one-piece wall and floor slab) the total radon entry rate is reduced by 66 percent (assuming that the floor-slab gap is present).

Changes in the air permeability of the soil and fill can have the most significant effect on radon entry. Increased soil permeability (above the 10^{-11} m^2 value assumed in the base case) will increase total radon entry; if accompanied by an increase in fill permeability, the increase in radon entry rate is more dramatic. On the other hand, if the fill permeability alone is reduced below the base case value (4×10^{-11} m^2), radon entry is reduced substantially. At very low fill permeabilities, convective flow of radon from the soil is essentially negligible, and is largely invariant with regard to changes in other parameters. Even at a more modest fill permeability of 10^{-12} m^2, total radon entry is reduced by 80 percent from the base case rate. It should be noted that these results assume that the fill material maintains its integrity; that is, no cracks or gaps develop in the fill or in those regions of the fill penetrated by utility pipes or conduit.

Changes in radium content of the fill have some effect on total radon entry, though the more significant effects occur for fill radium contents more than 3 times the base case. Changes in the soil radium concentration can have a more important effect, depending upon the depth of the radium-bearing layer. In the case where the radium content of the soil below 1.5 m is a factor of 5 times that of the base case, radon entry increases by more than 3 times the base case value, while a 10-fold increase in radium provides a radon entry rate that is 6 times greater than in the base case. For a radium-rich soil layer below 5.5 m, the changes are less pronounced, with only a 25 percent increase in radon entry arising from a 10-fold increase in the radium content.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Environmental Protection Agency through Interagency Agreement DW89934620-0 with the U.S. Department of Energy. The work was also supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Ecological Research Division of DOE, under contract DE-AC03-76SF00098.

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TABLE 1. BASE CASE VALUE AND RANGE FOR MODEL PARAMETERS

Parameter	Base Case Value	Range
Soil air permeability:		
a. total soil block b. soil layer 0-1 m deep* c. soil layer 0.5-1.5 m deep*	10^{-11} m^2	10^{-12} - 10^{-9} m^2
Fill air permeability:		
a. all fill b. exterior to stem wall	4×10^{-11} m^2	10^{-15} - 10^{-9} m^2
Stem wall air permeability:		
a. both vertical wall elements b. inner wall element c. outer wall element	10^{-10} m^2	10^{-15} - 10^{-9} m^2
Slab opening:		
a. width	3 mm	1 mm - 10 cm
b. radial distance	3 m	0 - 7 m
Radium content (relative to base case):		
a. fill b. soil below 0.6 m depth* c. soil below 4.6 m depth*	1	0.1 - 10
Water table:		
a. depth below surface	10 m	0.5 - 10 m

*Depth with respect to grade level

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TABLE 2. BASE CASE SOIL GAS AND RADON ENTRY AT VARIOUS ENTRY POINTS

Entry Location	Fraction of Soil Gas Entry* (percent)	Radon Concentration (percent of C_∞)	Fraction of Radon Entry† (percent)
Interior side of the stem wall:			
a. top gap	0.06	88	0.65
b. bottom gap	0.06	87	0.65
c. side of wall	5.0	88	53.
d. bottom of wall	0.23	87	2.5
e. top of wall	0.24	88	2.6
Exterior side of the stem wall:			
a. bottom gap	0.98	5	0.67
b. side of wall	88.	3	18.
c. bottom of wall	4.	5	2.7
Slab opening	1.6	98	20.

* Total base case soil gas entry = 5.1×10^{-4} m^3 s^{-1}

† Total base case radon entry = 1.6 Bq s^{-1}

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TABLE 3. EFFECTS OF SELECTED PARAMETERS ON RADON ENTRY

Parameter	Radon Entry (Bq s^{-1})			
Soil air permeability (m^2):	10^{-12}	10^{-11}	10^{-10}	10^{-9}
a. all other parameters = base case	0.4	1.6	6.6	13
b. fill permeability = 10^{-9} m^2	0.63	2.1	13	47
c. fill permeability = 10^{-15} m^2	$5. \times 10^{-4}$	$5. \times 10^{-4}$	$5. \times 10^{-4}$	$5. \times 10^{-4}$
d. filled stem wall	0.16	1.2	3.8	5.1
e. soil layer 0 to 1 m deep*	0.64	1.6	4.2	7.9
f. soil layer 0.5 to 1.5 m deep*	0.74	1.6	2.5	3.3
g. slab opening only	0.14	0.55	1.1	1.2
Fill air permeability (m^2):	10^{-15}	10^{-13}	10^{-11}	10^{-9}
a. all other parameters = base case	5.3×10^{-4}	$5. \times 10^{-2}$	1.1	2.1
b. filled stem wall	$6. \times 10^{-4}$	4.8×10^{-2}	0.8	1.6
c. slab opening only	$3. \times 10^{-5}$	$3. \times 10^{-3}$	0.2	1.6
Radium content (relative to base case):	0.1	1	5	10
a. fill	1.3	1.6	2.6	4
b. soil below 0.6 m*	0.75	1.6	5.1	9.3
c. soil below 4.6 m*	1.5	1.6	1.7	2.0
Width of slab edge opening (cm):	0.1	0.2	1	5
a. all other parameters = base case:	0.88	1.5	1.6	1.6

* Depth with respect to grade level

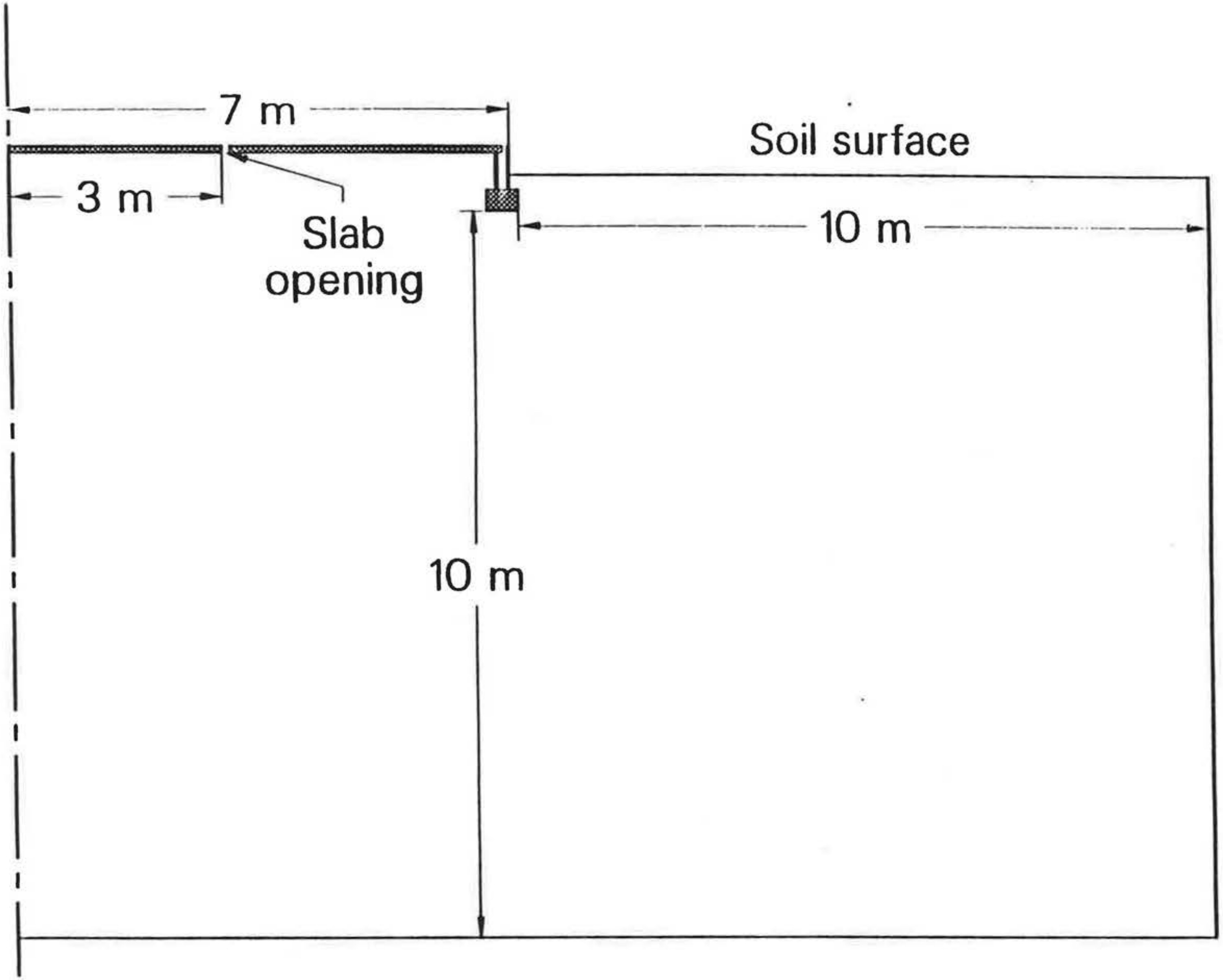

Figure 1: Vertical cross-section of the region modeled showing the dimensions of the soil block and the location of the slab gap for the base case. Greater detail for the stem wall is presented in Figure 2.

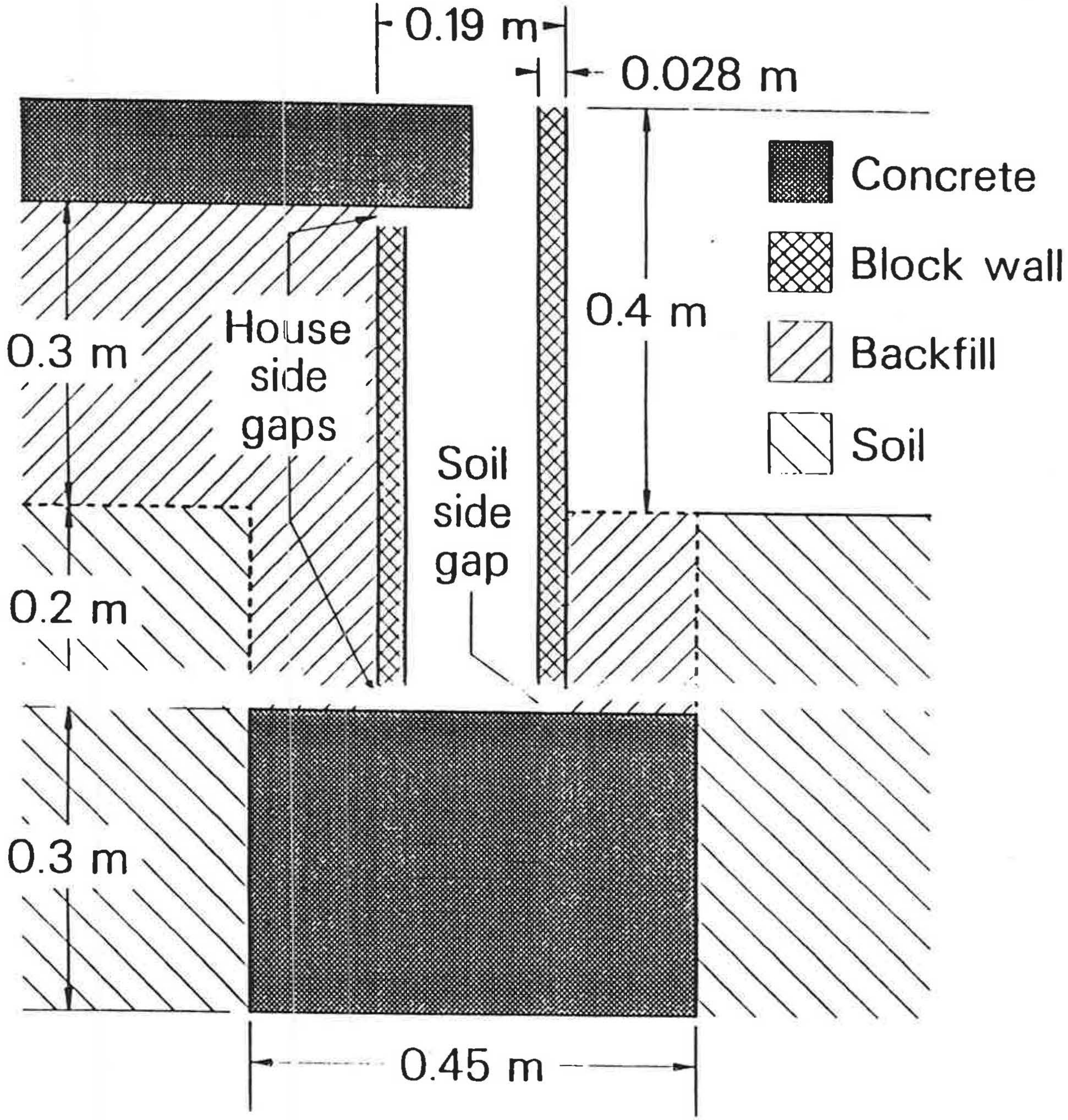

Figure 2: Detail of the

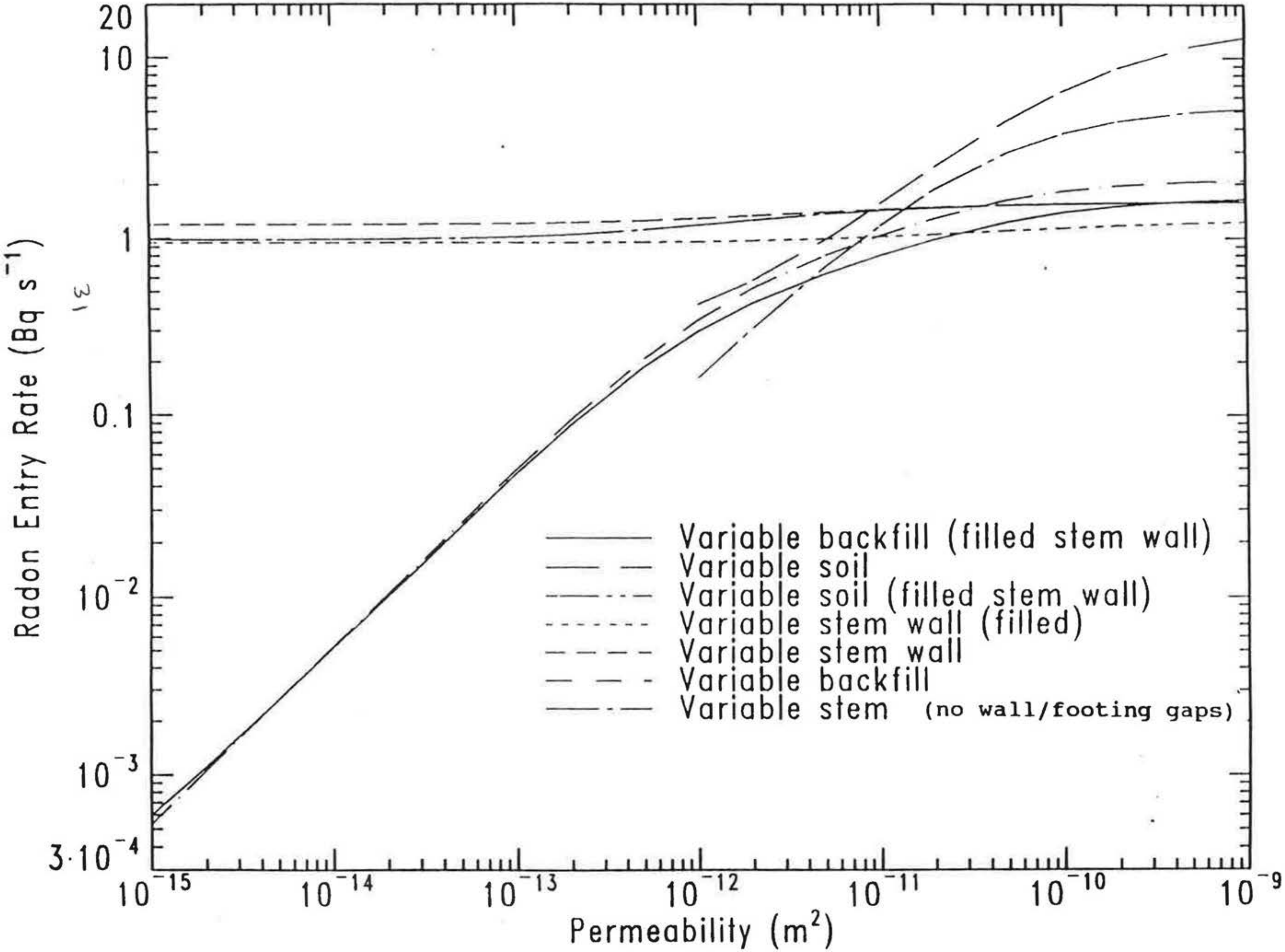

Figure 3: **Range of radon entry rates produced by variations in the soil, backfill, and stem wall permeabilities for open and concrete-filled stem walls. Also shown are entry rates when the stem wall/footing gap is eliminated. In each case, all other parameters have the base case value.**