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Modeling Radon Entry into Houses with Basements: The Influence of Structural Factors

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MODELING RADON ENTRY INTO HOUSES WITH BASEMENTS: THE INFLUENCE OF STRUCTURAL FACTORS

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May, 1990

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Abstract

Where indoor concentrations are high, radon entry in houses with basements is usually due primarily to the convective transport of soil gas through openings in the subsurface part of the building shell. The factors determining the rate of entry may conveniently be divided into those associated with the undisturbed soil and those associated with the structure and its surroundings. This paper uses a numerical model to determine the influence of the latter factors on the soil gas and radon entry rates. The most important of these is the presence or absence of a gravel layer below the slab; the presence of the gravel can increase the radon entry rate through the perimeter gap between the foundation footer, slab, and wall by as much as a factor of 5 over that for homogeneous soil. The permeability of the gravel becomes important when the soil permeability is unusually high, i.e., greater than 10^{-10} m^2. Of lesser importance are the thickness of the gravel layer, the radium content of the gravel, and the presence of additional openings in the slab. If cracks in the basement walls are major radon entry paths, as in concrete-block construction, the permeability of the soil restored to the area adjacent to the walls after completion of construction (backfill) is the determining factor in convective radon entry through these openings; if the soil is packed loosely, so that there is a gap between wall and soil, radon entry through a wall crack may be further increased by as much as a factor of 7.5. Radon entry rates through the slab-footer gap and through openings in the slab are only weakly influenced by the permeability of the backfill area. The resistance of the perimeter gap to soil gas entry becomes significant if it is greater than that of an idealized crack of width 0.001 m, assuming a soil permeability of 10^{-11} m^2. In sum, modeling indicates that substructure and backfill characteristics can have an important influence on radon entry rates.

Introduction

For most houses with high indoor radon concentrations, soil is the principal source of radon (*1-3*). In houses with basements, experimental results and theoretical considerations (*4-5*) strongly indicate that soil-gas flow is the most important means of radon entry. Driven by the pressure difference between the house and the outside, air flows from the soil surface, through the soil surrounding the basement, including an area that may have been altered during the construction of the house, and into the basement through cracks, gaps, and other openings (hereinafter referred to generally as openings) in the walls and floor. If the pressure differences across the narrow openings can be estimated, so that the pressures at their interfaces with the soil are available as boundary conditions, the pressure and velocity fields in the soil can be determined from Darcy's law for permeable media and the continuity equation. Given the velocity field, the radon concentration in the soil is determined from the mass-transport equation, assuming that the radon production rate of the soil is known. The radon entry rate into the basement is the product of the normal velocity and concentration, integrated over all openings.

A complete understanding of the flow of soil gas into basements, then, requires the study of the factors influencing the depressurization of basements, the nature of the coupling between basement and soil, and the properties of the soil itself. Basement depressurization is dependent primarily on inside and outside temperatures and wind speed (*6-7*) and may therefore be assumed to be independent of the basement-soil coupling and the properties of the soil. The effects on radon entry of the openings in the basement shell, of the area of disturbed soil immediately surrounding the basement, and of the area of undisturbed soil cannot be completely isolated from one another. In order to focus on the influence of the disturbed area and on the placement and width of openings, this paper uses a simple expression due to Baker (*8*) to obtain the pressure drop across an opening and assumes the undisturbed soil to be completely homogeneous. We use a modified version of the numerical model of Loureiro (*9-10*), which is described in detail by Revzan (*11*), to evaluate radon entry through the perimeter shrinkage gap between basement floor, foundation footer, and walls, with emphasis on the influence of the high-permeability gravel that normally underlies the floor. We evaluate radon entry when openings in the walls are also present; in this case, the emphasis is on the permeability of the region of replaced soil adjacent to the walls ("backfill"). A separate paper (*12*) examines the influence of the characteristics of the undisturbed soil on radon entry.

Model Description

The major features of a basement shell and its surroundings are shown in vertical and horizontal cross-section in Figures 1 and 2, respectively. Soil gas flows through the soil, including the backfill, the layer of relatively high-permeability gravel underlying the slab, and the slab-footer and slab-wall gaps, which are shown greatly enlarged for clarity. The inaccessibility of the slab-footer gap prevents its width from being known. Mowris (*13*) estimates the width of the slab-wall gap as 0.001 to 0.007 m, based on concrete shrinkage; in special circumstances, the slab-wall gap may be as wide as 0.05 m to allow for drainage of water entering the basement through porous walls. Where the walls are of concrete-block construction, soil gas may pass through cracks in the mortar or through the relatively permeable blocks

themselves; since the blocks are hollow, the flow paths may be complex and difficult to simulate. Other major pathways for soil-gas entry are cracks and openings for drains and utilities, such as those shown in idealized form in Figure 1. The nature of the openings in a basement shell is considered in more detail by Scott (*14*).

The configuration of a basement and its surroundings is sufficiently complex that a numerical model is the appropriate analytical tool. We use a steady-state finite element model (*9-11*) that allows us to calculate the temperature, pressure, soil-gas velocity, and radon-concentration fields in the region of a heated and depressurized basement. However, in order to simplify the problem as much as possible for examination of the influence of structural factors, soil-gas transport caused by temperature differences among soil, basement, and outside is neglected and no temperature field is generated. There is no reason to expect interrelationships between buoyancy forces and the structural factors under consideration here. The rectangular coordinate system of Loureiro has been replaced by a cylindrical one to allow more rapid computation on small computing systems; the construction gap and other gaps and cracks in the basement walls and floor are then represented by cylindrically-symmetrical openings. For problems that are symmetrical in the horizontal plane, the use of a cylindrical coordinate system has no significant effect on results.

Only the briefest description of the equations, boundary conditions, and techniques of solution is given here; for a more complete discussion, see (*11*). The model comprises a cylindrical basement embedded in a cylindrical block of soil whose outer and lower boundaries are chosen distant enough from the basement that negligible increase in soil-gas entry results from their extension. (In actual situations, the water table may be closer to the basement than the lower boundary, but the effects of reducing the depth of the soil block will not be considered here.) The normal derivatives of the pressure and radon concentration fields are assumed to vanish at these boundaries and at all concrete surfaces shown in Figures 1 and 2, i.e., air enters the soil only at the surface. The model allows the region within the boundaries to be divided into any number of sub-regions of rectangular vertical cross-section, each of which is characterized by the coordinates of its vertices and its radon diffusivity, radium content, density, porosity, and fraction of radon produced that is entrained by the soil gas (''emanating fraction''). For the purposes of this paper, those sub-regions which are concrete (wall, slab, and footer) or air (cracks and gaps) are not considered to be part of the model, although in other applications diffusion through concrete and flow through openings may be treated numerically.

The pressure boundary condition at an interface between the soil and an opening in the basement shell is determined iteratively. Initially, we set the pressure at the soil side of the opening to the basement pressure. After the pressure field in the soil is determined from Darcy's law and the continuity equation, the soil-gas flow rate through the opening is calculated from Darcy's law. The pressure drop across the opening is then determined from an algorithm due to Baker (*8*), which is quadratic in the soil-gas flow rate. By equating the flow rate in Darcy's law to that in the Baker algorithm, the pressure at the soil-opening interface is found as a function of the basement pressure and the pressure in the soil immediately outside the opening. With this pressure as a boundary condition, a new pressure field is calculated. The process continues until the relative difference between pressures obtained at successive iterations is less than the specified tolerance (in this paper, 10^{-6}) for all control volumes.

When the soil permeability is less than 10^{-12} m^2, the soil-gas velocity at openings in the basement shell is low and diffusion is the principal means of radon entry (*10-11*). In this case, the radon entry rate will be strongly dependent on the concentration in the gap, which in turn will be dependent on the assumed concentration at the basement side of the gap. In situations of practical interest, however, the velocity will be relatively high and the entry rate primarily convective, so that diffusion through the gap may be neglected. (The neglect of diffusive transport through openings does not, however, imply that diffusion is ignored in the calculation of the radon concentration field within the soil.) The radon concentration in the gap is therefore assumed constant, i.e., the normal derivative of the radon concentration at any soil-opening interface vanishes. The normal derivative at all concrete surfaces is also zero, and the boundary conditions are completed by assuming that the concentration vanishes at the soil surface, i.e., that the outdoor concentration is small enough to be neglected.

The radon production rate of the soil is not relevant to the discussion of this paper and is therefore arbitrary. The radon concentration far from the basement, which is determined by the production rate, may therefore be assumed to be unity, i.e., the radon concentration field is normalized. After the concentration field is determined from the mass-transport equation by an iterative process, with tolerance 10^{-6}, the normalized convective radon entry rate through an opening, E_r, is found by summing the product of the concentration, the normal velocity, and the control-volume area over the opening area. In this paper, the term "radon entry rate" should everywhere be taken to mean "normalized convective radon entry rate".

Results

The structural factors influencing radon entry may be divided into the following four groups: 1) the thickness, permeability, and radium content of the gravel layer; 2) the width and thickness of the gap between the footer, slab, and wall; 3) the number, location, and size of the openings in the walls and slab; 4) the thickness and permeability of wall-soil gap and the backfill region. In order to make the subject manageable, we select a base configuration whose parameters are typical of modern construction and vary each of the parameters of interest in turn. In this base configuration, the footer is 0.45 m (18 in) wide and 0.30 m (12 in) high; the wall and slab are 0.15 m (6 in) and 0.10 m (4 in) thick, respectively; the slab-footer and slab-wall gaps are 0.003 m in width and 0.25 m in thickness; the gravel has a permeability of 5×10^{-9} m^2, a thickness of 0.15 m, and a radium content identical to that of the soil; the backfill region has a permeability equal to that of the surrounding soil, which is assumed to be homogeneous and to extend 10 m beyond the outside of the basement wall and 10 m below the bottom of the slab. The diffusivity of radon in the undisturbed soil and the gravel is 10^{-6} m^2 s^{-1}; the permeability of the undisturbed soil is 10^{-11} m^2, except where noted; the other characteristics of the soil do not enter into the discussion, since the radon entry rate is normalized. The basement is represented as a cylinder 10 m in diameter with a floor 2 m below the soil surface. The pressure inside the basement is assumed to be 5 Pa below that of the surface of the soil. (The radon entry rate, unlike the soil-gas-entry rate, does not vary linearly with the basement-outside pressure difference, but the departure from linearity is relatively unimportant in realistic situations (*10*)).

The effect on radon entry of the footer, which is invariably present, has not heretofore been considered. Using the base configuration except for a soil permeability of 10^{-12} m^2, E_r in the absence of a footer, assuming a 0.003 m gap between slab and wall, is $8.6 \times 10^{-3} m^3 s^{-1}$; the introduction of the footer reduces E_r to 8.1×10^{-3} m^3 s^{-1}. When the soil permeability is 10^{-10} m^2, the corresponding entry rates are 6.2×10^{-1} and 6.8×10^{-1} m^3 s^{-1}, so that the presence of the footer actually increases the entry rate; the increase is due to higher soil-gas-radon concentration at the gap. The streamlines for the latter case are shown in Figure 3.

The effect of the gravel layer is shown in Figures 4 and 5, in which the normalized radon entry rate and the mean soil-gas-radon concentration at the slab-footer gap, respectively, are plotted against soil permeabilities from 10^{-12} to 10^{-8} m^2 with the gravel permeability as a parameter. (Soils with permeabilities greater than 10^{-10} m^2 are highly unusual; soils of higher permeability are included for completeness and in order to illustrate the nature of the entry process.) The entry rates and concentrations in the absence of the gravel layer are shown as references. For soil permeabilities below 10^{-12} m^2, the entry rate varies nearly linearly with permeability and the normalized concentration at the soil side of the gap is greater than 0.95. The entry rate of soil gas is not shown, but may be estimated by dividing the radon entry rate by the corresponding concentration; for the case of no gravel layer, this rate varies linearly with soil permeability.

It may be seen from Figure 4 that the the presence of an gravel layer increases the convective radon entry rate by approximately a factor of 5 when the soil permeability is less than 10^{-11} m^2; the size of the factor diminishes as the soil permeability increases. For a soil whose permeability is 10^{-11} m^2 and whose pore-space radon concentration far from the surface is 3.5×10^4 Bq m^{-3}, the radon concentration due to convective soil-gas entry in a house of volume 500 m^3 and air exchange rate 0.5 h^{-1} is 7 Bq m^{-3} in the absence of gravel and 33 Bq m^{-3} when a 0.15 m thick gravel layer of permeability greater than 10^{-9} m^2 is present.

The thickness of the gravel layer is a relatively minor factor in radon entry. The physical effect of the layer is to provide a high-permeability region that couples the narrow opening in the basement shell to the low-permeability soil; even a very thin layer serves to provide this coupling. For the base configuration, we find that the normalized radon entry rate in the absence of gravel is 1.4×10^{-5} m^3 s^{-1}. A layer 0.01 m thick increases the rate to 5.7×10^{-5} m^3 s^{-1}, while the rate at the standard thickness of 0.15 m is 6.5×10^{-5} m^3 s^{-1}. Increasing the thickness to 0.3 m, i.e., to the height of the footer, results in an entry rate of 6.9×10^{-5} m^3 s^{-1}. In practice, the gravel layer thickness is unlikely to be as low as 0.01 m or as great as the footer height; it is likely that the radon entry rate will differ from that of the base configuration by no more than 20% as a result of varying thickness.

The radium content and radon emanation rate of the gravel may be lower than that of the soil. When the soil and gravel permeabilities are both high, the speed of the soil gas through the gravel is so great that there is little opportunity for the entrainment of additional radon atoms as soil gas passes through the gravel. At soil and gravel permeabilities of 10^{-10} and 5×10^{-9} m^2, respectively, reducing the radium content of the gravel to zero results in a reduction of the radon entry rate by only 2%. For soil permeabilities of 10^{-11} and 10^{-12} m^2 and the same gravel permeability, the entry rates are reduced by 8% and 11%, respectively. In cases of very low soil-gas velocity, the radium content of the gravel may be the determining factor in the radon entry rate, but the entry rate is so low that the situation is of no practical importance.

The effect of a crack in the slab is simulated by adding a cylindrically-symmetrical opening to the model. If the new opening is of the same width as the slab-footer gap and is of radius 2.5 m, the soil gas is divided between the two openings, with a fraction of approximately 0.4 passing through the inner opening; the total soil-gas entry rate is almost identical to the rate when the slab-footer gap alone is present. For soil permeabilities below about 10^{-10} m^2, E_r is also divided on a 0.4/0.6 basis, with the total again nearly unchanged. At higher, but uncommon, soil permeabilities, the radon concentration at the outer opening becomes significantly lower than that at the inner, so that a larger fraction of the radon enters through the inner gap; at a soil permeability of 10^{-9} m^2, this fraction becomes 0.65. The total radon entry rate also begins to rise above the single-gap rate; at a permeability of 10^{-9} m^2, the ratio of the two is 1.25. If the widths of the two openings differ, the flow distribution will vary, but there is unlikely to be a marked change in the total entry rate.

The effect of variations in the gap width on convective radon entry is almost entirely due to the effect of the width on the pressure difference between basement and soil. When this pressure difference is negligible, the increase in entry due to a larger opening area is offset by the diminished soil-gas speed caused by a reduced pressure gradient near the gap. Figure 6, which displays E_r as a function of soil permeability for five gap widths between 0.0005 and 0.01 m, shows that E_r is nearly independent of gap width for soil permeability less than 10^{-11} m^2. For higher soil permeabilities, the effect of the pressure drop across the gap on radon entry is significant for gap widths of 0.001 m or less.

Openings in a basement wall are simulated in the model by narrow peripheral gaps. Such gaps cannot accurately represent actual cracks or gaps, which are not generally cylindrically symmetrical, but their use can enable us to gain a qualitative understanding of the soil-gas velocity and radon concentration fields that may occur. Table I gives the soil gas and radon entry rates and the soil gas radon concentrations at the soil-gap interface for 0.003 m wide gaps at the soil surface (''upper''), 1 m below the surface (''central''), and at the level of the top of the slab (''lower'') for the base configuration. (We assume that the pressure responsible for soil-gas entry is independent of height for the subsurface part of a basement. This may not be the case, and results should be considered in this light. A discussion of basement depressurization is outside the scope of this paper; see Feustel (*15*).) The table also gives results for the combination of the upper and lower wall gaps and for the several wall gap configurations with the slab-footer gap also present. The radon entry rate through the upper gap is very low, as would be expected from its proximity to the zero-concentration soil surface. The entry rates through the other two gaps are higher and similar in magnitude; that through the lower is nearly identical to to the entry rate through the slab-footer gap in the absence of gravel (see Figure 4). When the slab-footer gap is present, the entry rates through the wall gaps are reduced by about a factor of two. The entry rate through the slab-footer gap is changed only slightly from its base value by the presence of any of the wall openings; consequently, the presence of these gaps leads to an increase in the total E_r of less than 20%. The influence of wall gaps on the flow through the slab-footer gap is somewhat greater when no gravel is present beneath the slab.

When excavated soil is replaced after construction, shrinkage and poor compaction may leave a gap between the outside of the wall and the soil. Such wall-soil gaps may be simulated by very narrow, very high permeability areas of rectangular cross-section or, when a wall

opening is present, by an area of infinite permeability and infinitesimal thickness. The latter simulation is accomplished in the model by making the basement wall a boundary whose pressure is equal to the difference between the basement pressure and the pressure drop across the wall opening. The results for this "constant-pressure" configuration are shown in Table I. The soil-gas and radon entry rates through the wall gap are considerably increased over the corresponding rates in the absence of the wall-soil gap, the latter rate by a factor of 7.5. The radon entry rate through the slab-footer gap is reduced by a factor of 0.75, so the total radon entry rate is increased by a factor of 1.75. As the width of the wall-soil gap is increased, air is allowed to flow directly from the surface into the gap, so that the soil-gas flow rate into the wall opening is greatly increased, and the radon concentration in the gap is diminished. The radon entry rates lie between those occurring without the gap and those for the constant-pressure wall.

The permeability of the replaced soil, which is usually not compacted, may be greater than that of the undisturbed soil. This "backfill" is simulated by an area of rectangular cross-section extending 0.75 m beyond the basement, although the actual region may slope inward toward the footer. The soil in this area is assumed to have a radium concentration, emanating fraction, and density identical to those of the undisturbed soil. For the base configuration with an additional perimeter wall gap 1 m below the surface, entry rates for backfill permeabilities ranging from 10^{-11} m^2 (the soil permeability) to 10^{-8} m^2 are shown in Table I. The radon entry rates through the wall gap and the slab-footer gap are of a similar magnitude when the backfill and soil permeabilities are in the ratio of 10:1. Because of the presence of the footer and a section of undisturbed soil between the backfill and sub-slab areas, the characteristics of the backfill soil have a negligible influence on the radon entry rates through the slab-footer gap and any openings in the slab itself.

When the backfill and soil are equally permeable and the slab-footer gap is the only opening in the basement shell, a fraction of 0.7 of the soil gas flows through the area within 0.75 m of the wall; when the backfill permeability is a factor of 10^3 greater than that of the soil, the fraction increases to 0.99. Let us compare two soil-backfill configurations: in the first, the permeability of the backfill is 10^3 times that of the soil; in the second, the soil and backfill both have permeabilities equal to that of the backfill in the first case. Despite the very large fraction of the soil gas that flows through the backfill region in the first case, the radon entry rate does not attain the same value as in the second case, due to the diminution of the radon concentration caused by the shortened flow path. When the permeabilities are low, the two radon entry rates are more nearly similar due to the generally low soil-gas speed. Consequently, the influence of a relatively high-permeability backfill region is greatest when the permeability of the bulk of the soil is low.

Conclusions

The factors determining radon entry into basements may be divided into two groups: first, those factors associated with the undisturbed soil and second, those associated with the structure itself and with changes to the building site made by the builders. Of the latter group, the most important factor, in the general case, is the presence or absence of a layer of relatively high-permeability gravel under the basement slab. For low permeability soils, the radon entry

rate through the gap between the slab and the footer increases by a factor of 5 when the gravel layer is added. As the soil permeability approaches that of gravel, the importance of the latter is greatly reduced. The radium content and thickness of the gravel layer are relatively unimportant in those situations where the entry rate is sufficient to produce high indoor concentrations.

The sizes and numbers of cracks or other openings in the slab appear to be relatively unimportant so long as the overall area of penetration is small compared to the area of the slab and so long as the flow resistance of the openings remains small compared to that of the soil; the soil gas merely distributes itself according to the positions and widths of the openings. The flow resistance has been incorporated into the finite element model by using an expression developed from the theory of laminar flow between parallel plates. The predictions of the model indicate that gap resistance begins to become important for soil gas transport when the opening is 0.001 m wide and the soil permeability is 10^{-10} m^2. The resistance of wider openings becomes important at higher soil permeabilities, but such permeabilities occur rarely.

Openings in basement walls may be important points of radon entry. Where there is no gap between wall and soil and where the backfill is of identical permeability to the undisturbed (homogeneous) soil, the entry rate through a wall opening is similar to that through the slab-footer gap when no gravel is present. A wall-soil gap increases the flow of soil gas through a wall opening, while reducing the radon concentration at the mouth; the radon entry rate through wall openings increases by as much as a factor of 7.5, but the total radon entry rate increases by at most a factor of 1.75. When the backfill is of different permeability from the soil, the radon entry rate through wall openings is strongly influenced by the permeability of the backfill; if the ratio of backfill to soil permeability is a 10^3, 99% of the soil-gas flow occurs in the backfill region, so that the permeability of the backfill entirely determines the entry rate. Neither wall-soil gaps nor low-permeability backfills have a significant effect on radon entry through openings in the slab, which are isolated by a region of undisturbed soil and by the concrete footer.

In sum, the results of modeling indicate that the permeability of the material immediately adjacent to an opening in a basement shell, which may differ markedly from the permeability of the undisturbed soil, has an important—in some cases, determining—influence on the rate of radon entry through that opening.

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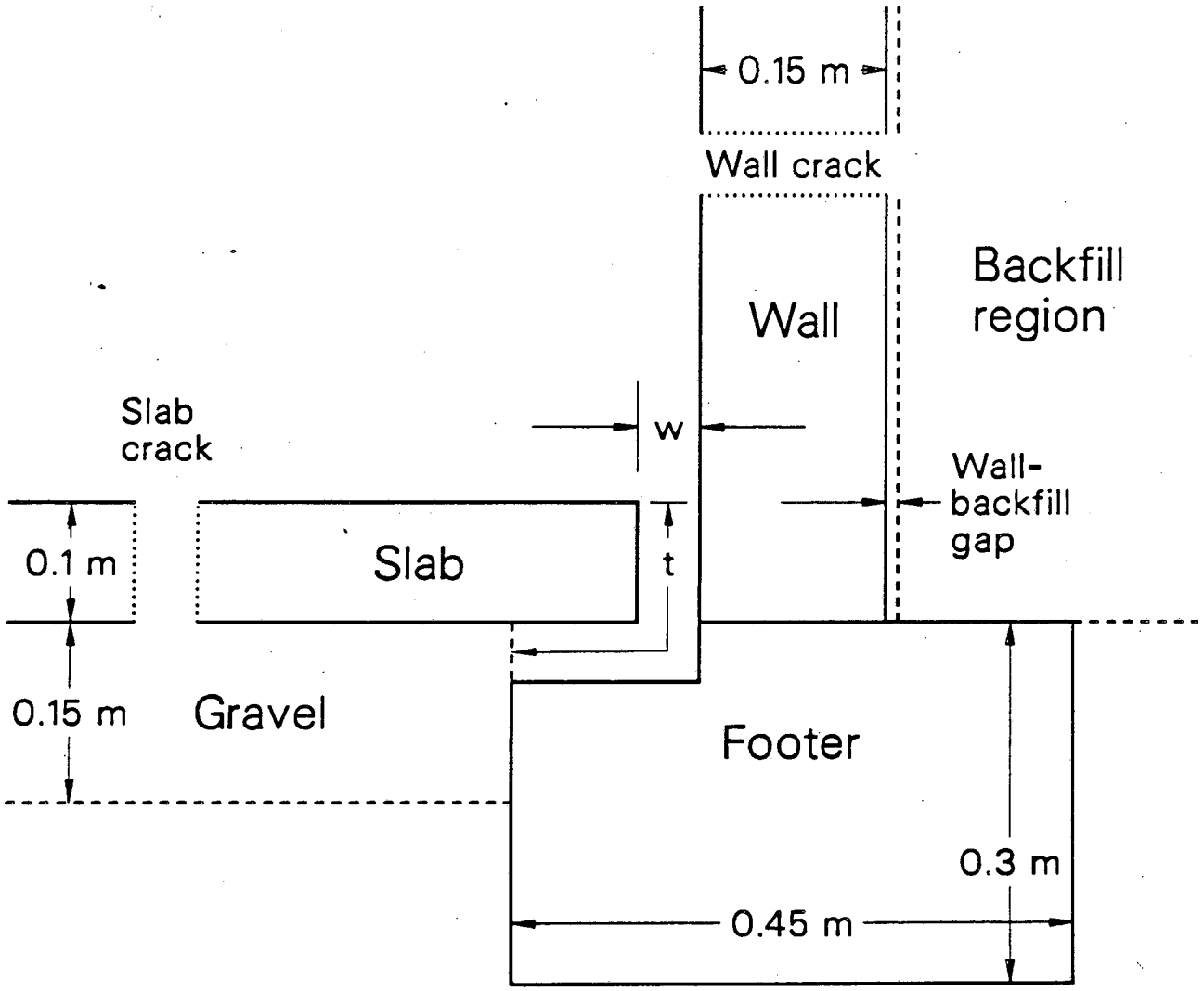
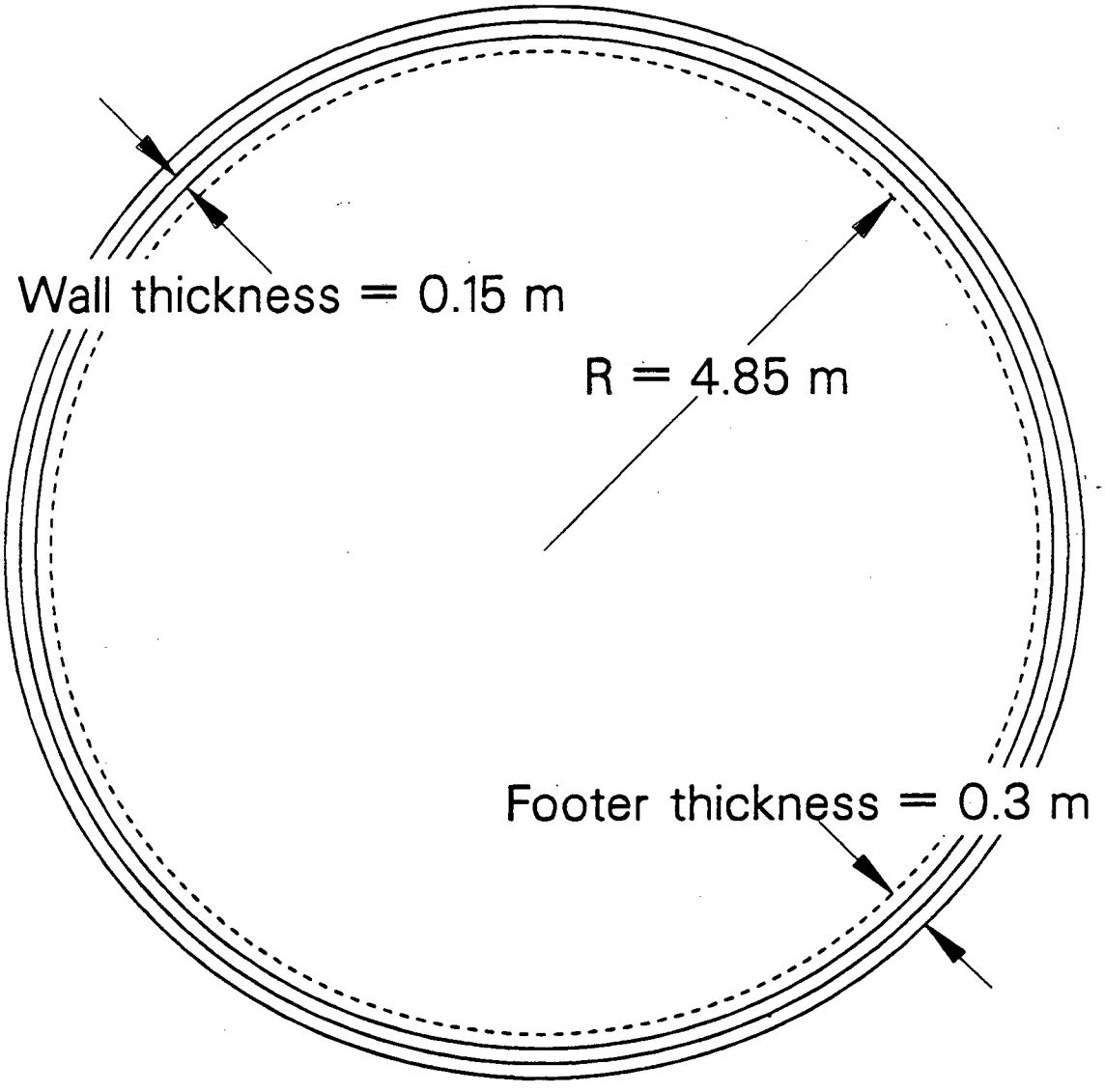
Gap positions	Wall gap(s)			Slab-footer gap			Total	
	E_s ($m^3 s^{-1}$)	C_g	E_r ($m^3 s^{-1}$)	E_s ($m^3 s^{-1}$)	C_g	E_r ($m^3 s^{-1}$)	E_s ($m^3 s^{-1}$)	E_r ($m^3 s^{-1}$)
(No wall-soil gap):								
Slab-footer				7.1×10^{-5}	9.8×10^{-1}	6.5×10^{-5}	6.5×10^{-5}	7.0×10^{-5}
Upper wall	5.1×10^{-5}	1.5×10^{-3}	7.6×10^{-8}				5.1×10^{-5}	7.6×10^{-8}
Central wall	2.2×10^{-5}	6.2×10^{-1}	1.4×10^{-5}				2.2×10^{-5}	1.4×10^{-5}
Lower wall	1.6×10^{-5}	8.5×10^{-1}	1.4×10^{-5}				1.6×10^{-5}	1.4×10^{-5}
Lower & upper wall	6.7×10^{-5}	4.3×10^{-1}	1.4×10^{-5}				6.7×10^{-5}	1.4×10^{-5}
Upper wall, slab-footer	5.1×10^{-5}	1.3×10^{-3}	6.6×10^{-8}	6.8×10^{-5}	9.8×10^{-1}	6.7×10^{-5}	1.2×10^{-4}	6.7×10^{-5}
Central wall, slab-footer	2.0×10^{-5}	5.7×10^{-1}	1.1×10^{-5}	6.6×10^{-5}	9.8×10^{-1}	6.5×10^{-5}	8.6×10^{-5}	7.6×10^{-5}
Lower wall, slab-footer	1.3×10^{-5}	8.1×10^{-1}	1.0×10^{-5}	6.6×10^{-5}	9.8×10^{-1}	6.4×10^{-5}	7.9×10^{-5}	7.4×10^{-5}
Lower & upper wall, slab-footer	6.3×10^{-5}	4.1×10^{-1}	1.0×10^{-5}	6.6×10^{-5}	9.8×10^{-1}	6.4×10^{-5}	1.3×10^{-4}	7.4×10^{-5}
(Infinitesimal wall-soil gap):								
Central wall, slab-footer	3.7×10^{-5}	5.1×10^{-1}	8.3×10^{-5}	5.1×10^{-5}	9.8×10^{-1}	5.0×10^{-5}	8.8×10^{-5}	1.3×10^{-4}
(No backfill):								
Central wall, slab-footer	2.0×10^{-5}	5.7×10^{-1}	1.1×10^{-5}	6.6×10^{-5}	9.8×10^{-1}	6.5×10^{-5}	8.6×10^{-5}	7.6×10^{-5}
(Backfill permeability 10^{-10} m^2):								
Central wall, slab-footer	1.9×10^{-4}	2.9×10^{-1}	5.6×10^{-5}	6.7×10^{-5}	9.7×10^{-1}	6.5×10^{-5}	2.6×10^{-4}	1.2×10^{-4}
(Backfill permeability 10^{-9} m^2):								
Central wall, slab-footer	1.9×10^{-3}	5.3×10^{-2}	1.0×10^{-4}	6.7×10^{-5}	9.5×10^{-1}	6.3×10^{-5}	1.9×10^{-3}	1.6×10^{-4}
(Backfill permeability 10^{-8} m^2):								
Central wall, slab-footer	1.7×10^{-2}	7.9×10^{-3}	1.3×10^{-4}	6.8×10^{-5}	9.1×10^{-1}	6.2×10^{-5}	1.7×10^{-2}	1.9×10^{-4}

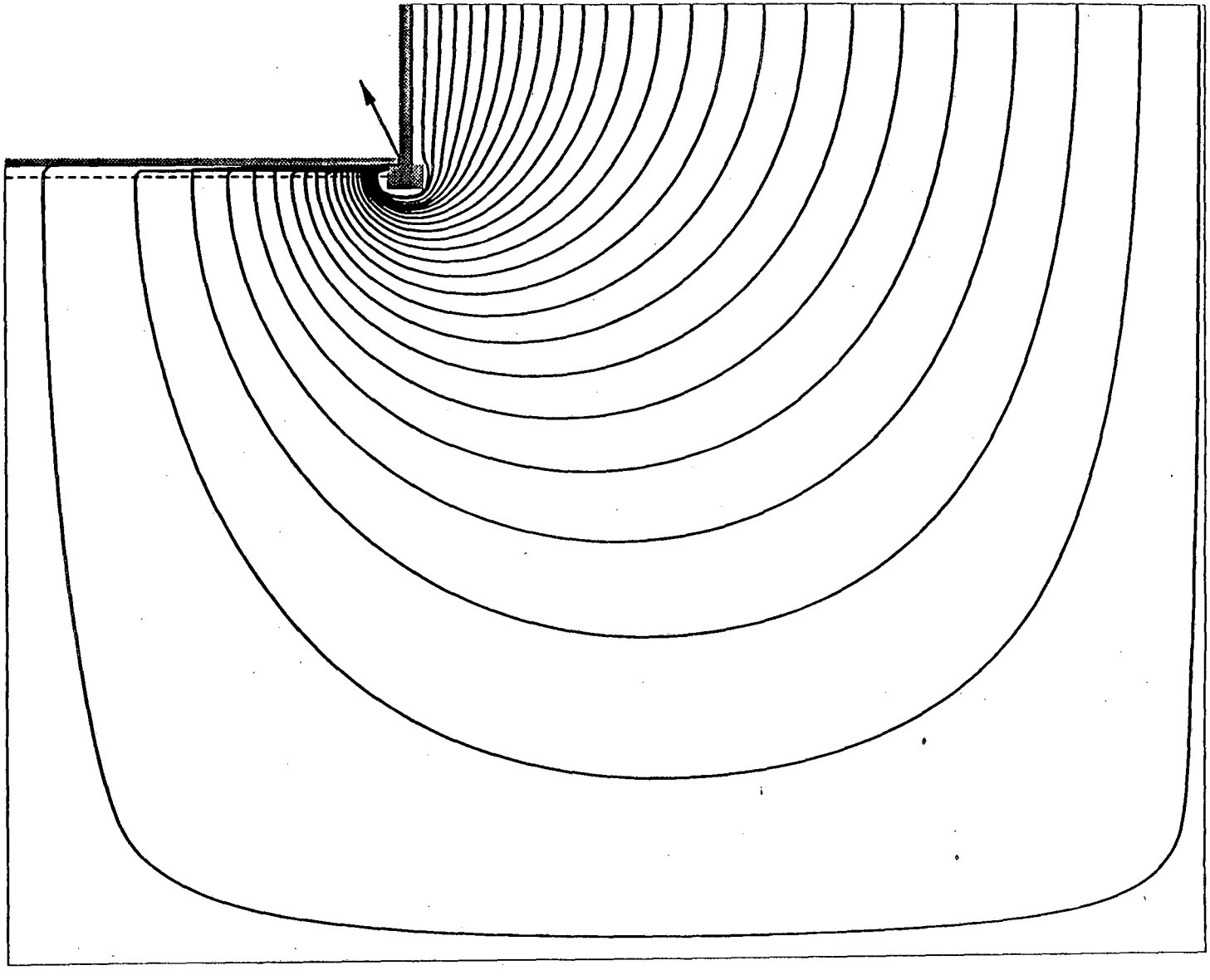
I. Soil gas entry rate, E_s, normalized radon concentrations at the gap, C_g, and normalized radon entry rate, E_r, for several combinations of entry pathways through the basement wall and the construction gap at the slab-wall-footer junction, with and without a gap between the wall and the restored soil, and for several backfill permeabilities. The soil is homogeneous of permeability 10^{-11} m^2 except for a gravel layer of permeability 5×10^{-9} m^2 and thickness 0.15 m beneath the slab.



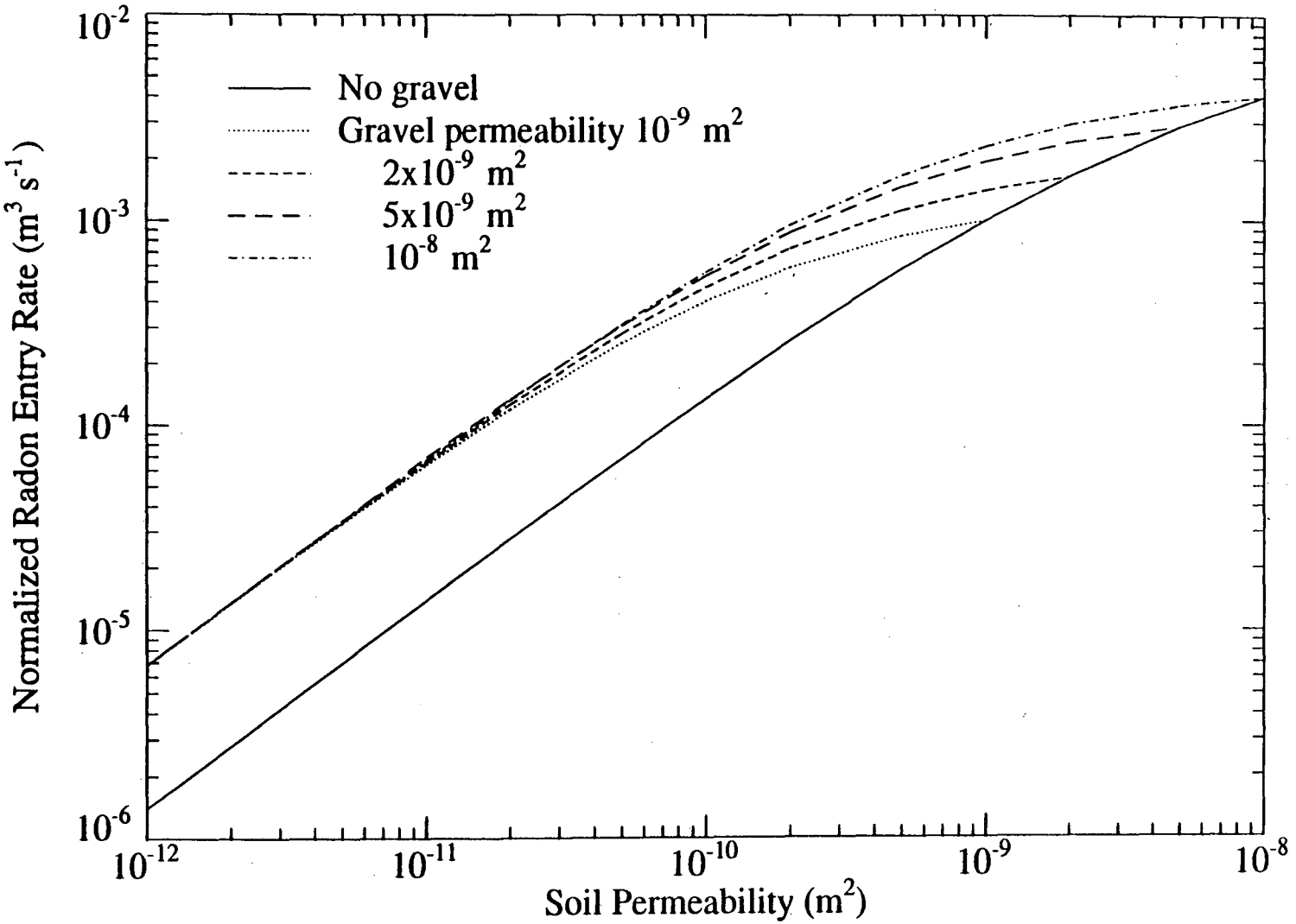
1. Vertical cross-section of a portion of a basement and its surroundings, as modeled; the gaps are shown greatly exaggerated. The dimensions shown are those of the base configuration. The variables w and t are, respectively, the width and thickness of the gap produced by concrete shrinkage.



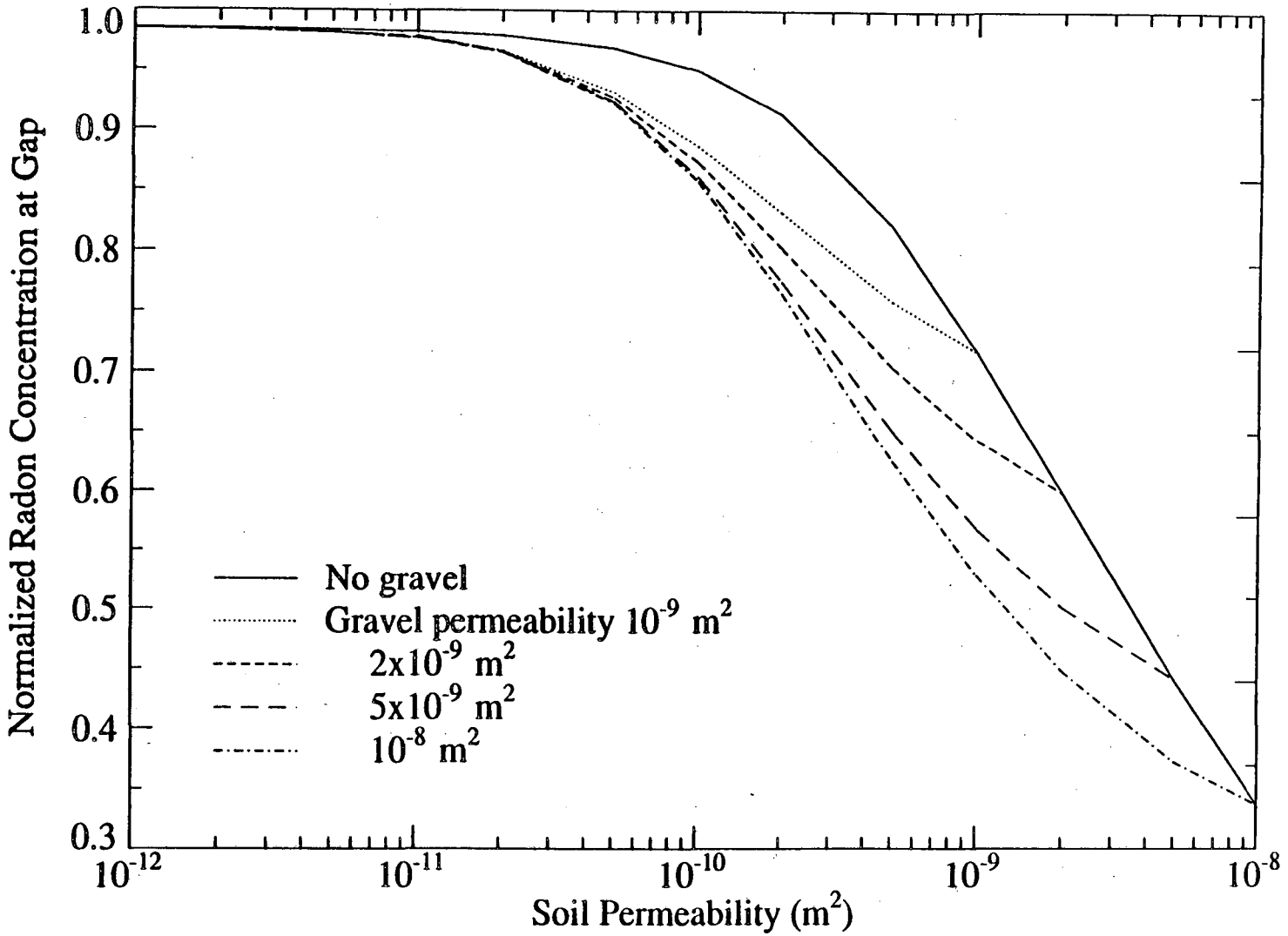
2. Horizontal cross-section of a basement, as modeled, with the dimensions of the base configuration. The area of the shrinkage gap is $2\pi Rw$, where w is the gap width shown on Figure 1.



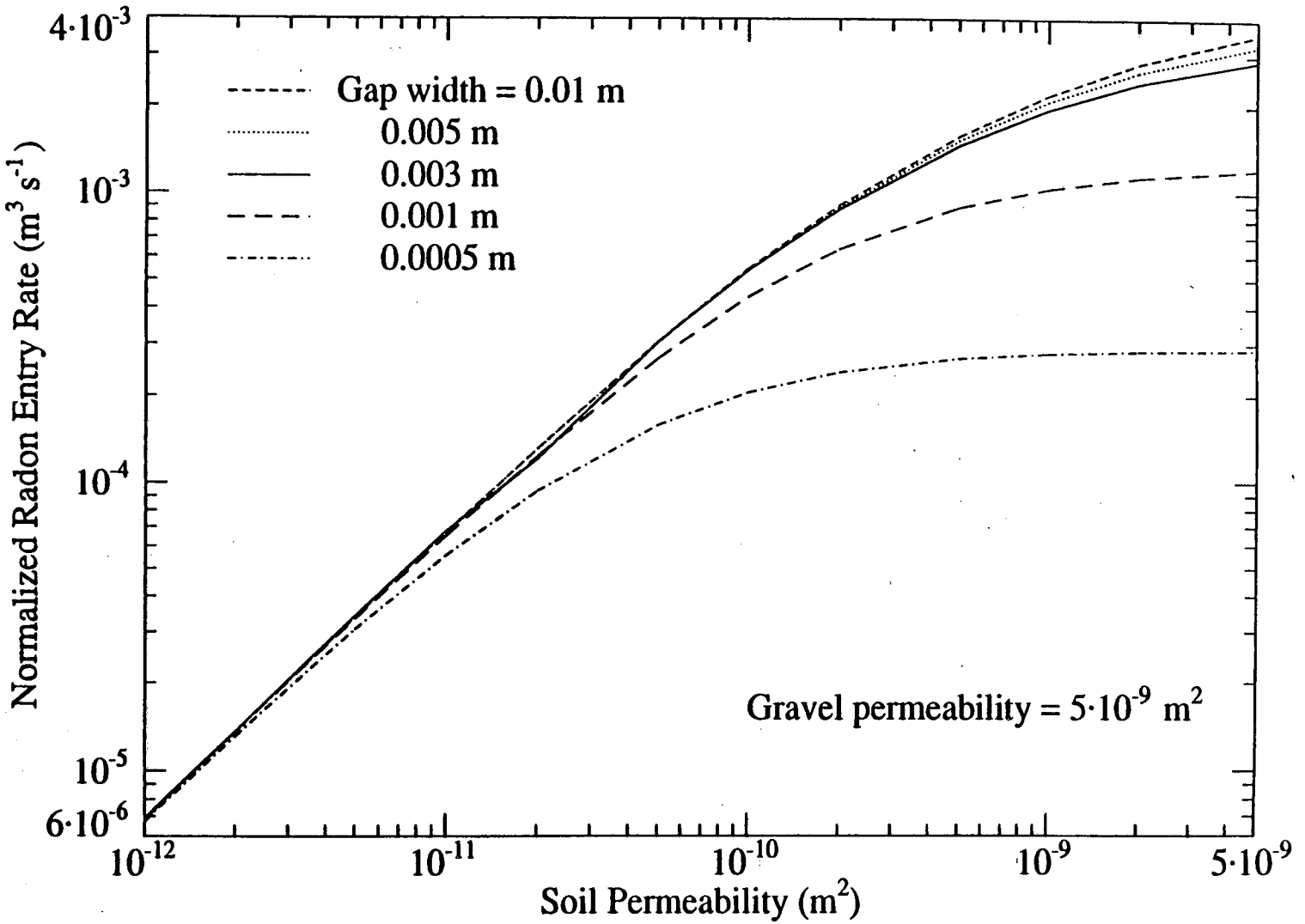
3. Streamlines of soil-gas flow into a 0.003 m slab-footer gap. The basement side of the gap is 5 Pa below atmospheric pressure. The dashed line represents the limit of the sub-slab gravel, whose permeability is 5×10^{-9} m^2. The bulk of the soil is homogeneous and of permeability 10^{-10} m^2.



4. Normalized convective radon entry rates into a typical basement through a 0.003 m slab-footer gap as a function of soil permeability. The permeability of the 0.15 m thick layer of gravel beneath the basement slab is the parameter. The basement is at -5 Pa pressure with respect to the atmosphere.



5. The concentration of radon in the soil gas entering a typical basement through a 0.003 m slab-footer gap as a function of soil permeability. The permeability of the 0.15 m thick layer of gravel beneath of basement slab is the parameter. The basement is at -5 Pa pressure with respect to the atmosphere.



6. Normalized convective radon entry rate into a typical basement through the slab-footer gap as a function of soil permeability for several gap widths. A gravel layer of thickness 0.15 m and permeability 5×10^{-9} m^2 underlies the basement slab. The basement is at -5 Pa pressure with respect to the atmosphere.

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