1994_27

ACTIVE AND PASSIVE RADON CONTROL FEATURE EFFECTIVENESS ESTIMATED FOR THE FLORIDA RESIDENTIAL CONSTRUCTION STANDARD

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ABSTRACT

The radon resistance of different residential construction features was evaluated for the Florida residential construction standard to distinguish regions requiring active radon controls from those where passive controls suffice. Radon resistance, defined as the ratio of reference indoor radon levels to levels with a particular construction feature, was estimated individually for candidate features using model simulations and indoor radon measurements. Active radon control by sub-slab ventilation (suction pit or ventilation mat systems) was most effective, followed by sub-slab vapor barriers, increased house ventilation, improved slab-foundation design, improved concrete quality, sealed slab cracks and openings, and sealed pipe penetrations. Sealing cracks related to slab reinforcement and soil compaction made little difference. For Florida residences, passive features reduce indoor radon by more than a factor of two, and active features give further reductions to exceed a factor of ten. This work was funded by the Florida Department of Community Affairs.

INTRODUCTION

This paper estimates the effectiveness of selected active and passive radon control features proposed for new houses in areas of elevated and intermediate soil radon potential in Florida. The feature effectiveness is used with state-wide maps of soil radon potential (Nielson et al 1994a) to estimate where passive controls can adequately limit indoor radon levels and where active controls are required. The regional radon control requirements are part of a draft residential building standard (Rogers and Nielson, 1994a) developed under the Florida Radon Research Program (FRRP) under direction of the Florida Department of Community Affairs and the U.S. Environmental Protection Agency (Sanchez et al 1991).

The Florida residential construction standard aims to reduce indoor radon to concentrations as low as reasonably achievable, not to exceed 4 pCi L^{-1}. The standard requires radon-protective features where a significant fraction of houses would exceed 4 pCi L^{-1}. In this way, most houses in an area needing radon protection are controlled to levels below 4 pCi L^{-1} in order to limit the high end of their distribution to 4 pCi L^{-1}.

Active radon controls reduce indoor radon levels by mechanically altering pressures and/or ventilation rates in a house, beneath a slab, or within or under a crawl space. They generally reduce radon levels better than passive controls, but their ongoing operating costs make them cost more than passive controls. Passive radon controls reduce radon by design, material, or construction features that block radon entry. By avoiding mechanical operation, they eliminate ongoing operating costs or user attention beyond normal home maintenance (such as re-caulking, etc.). Although less effective, passive features provide cost-effective minimum radon protection that suffices for many areas with marginal radon potential.

METHODS FOR EVALUATING FEATURE EFFECTIVENESS

The effectiveness of different radon control features was evaluated using model simulations and indoor radon measurements. For both kinds of evaluations, the effectiveness of a radon control feature was defined as the ratio of indoor radon concentration without the feature to that with the feature. Reference cases were defined with no radon control features for comparing and ranking individual features. The interactions of multiple features were considered from model analyses of grouped features. The most detailed analyses focussed on passive features, since their effectiveness determined the radon potential above which active features are required. The effectiveness of active features, on the other hand, needs only to insure that adequate radon controls can be achieved for the highest range of mapped radon potentials.

Model Calculations

The effectiveness of different passive radon protection features was evaluated by numerical simulations with the RAdon Emanation and TRAnsport into Dwellings (RAETRAD) computer model. The multiphase RAETRAD calculations include soil moisture effects on radon entry (Rogers and Nielson 1991a; 1993), and have been validated with Florida research structures and houses (Nielson et al 1994b). The present simulations utilized reference house and soil conditions to compare indoor radon levels with and without the building feature being evaluated. Although building and soil properties are interactive and cannot always be separated to estimate their effectiveness, many properties are relatively independent, permitting direct estimation of their individual contributions to radon resistance. For interactive properties such as the slab-foundation design, multiple simulations were conducted to evaluate the interactions.

The features evaluated were chosen from those recommended in the 1991 version of the Florida Standard for Radon-Resistant Building Construction (Dixon 1991). The simulations focused on slab-on-grade houses, since they comprise nearly all new Florida residential construction (ICF and Camroden 1992). The simulations characterized the effects of fill soil compaction, sub-slab vapor barriers, wire-mesh slab reinforcement, bar reinforcement of re-entrant slab corners, sealing of slab penetrations, closure and sealing of large slab openings, reduction of concrete porosity (as estimated by reduced concrete slump), and use of different slab-foundation designs.

The simulations utilized a 8.6 x 16.5 m reference house with an interior height of 2.4 m, an indoor air pressure of -2.4 Pa, and an outdoor air exchange rate of 0.25 h^{-1}, consistent with previous analyses of Florida houses (Nielson et al 1993a). Underneath was a 4.3 m soil profile divided for calculation purposes into ten layers, as illustrated in Fig. 1 and as defined parametrically in Table 1. Soil density for layers three through ten was defined from an average of the soils listed in the Alachua County Soil Survey (Thomas et al 1985). The top two layers were considered disturbed, and their density was defined as 87% compaction for uncompacted soils and 92% compaction for compacted soils. The maximum dry density for sandy soils was defined from the same soils (Thomas et al 1985) as 1.80 g cm^{-3}. Soil porosity was calculated as:

$$p = 1 - \rho/\rho_g \tag{1}$$

where p = porosity (cm^3 pore space per cm^3 total space)
ρ = density (g cm^{-3})
ρ_g = specific gravity (2.7 g cm^{-3} assumed).

The depth of the water table was defined as 2.5 m, and soil water contents were defined from the position of each layer above the water table (Nielson and Rogers 1992). Water saturation fractions were calculated as:

$$S = \rho M/p \tag{2}$$

where S = soil water saturation fraction (cm^3 water per cm^3 pore space)
M = soil water content (dry weight percent).

Radon diffusion and air permeability coefficients were defined from soil moisture, porosity, and particle size (Rogers and Nielson 1991b), assuming a sandy soil textural classification (Soil Conservation Service 1975). Soil radium concentrations and radon emanation coefficients were defined uniformly as 4 pCi g^{-1} and 0.55, respectively.

TABLE 1. Soil Profile Properties for the Radon Entry Simulations

Layer No.	Depth to Water Table (cm)	Layer Height (cm)	Soil Density (g cm^{-3})	Soil Porosity	Soil Water (dry wt%)	Water Saturation Fraction	Radon Diffusion Coeff. (cm^2 s^{-1})	Air Permeability (cm^2)
1^u	265	30	1.57	0.419	23.3	0.354	1.87x10^{-2}	9.07x10^{-8}
1^c	265	30	1.66	0.385	24.6	0.385	1.68x10^{-2}	7.09x10^{-8}
2^u	235	30	1.57	0.419	24.0	0.365	1.81x10^{-2}	8.85x10^{-8}
2^c	235	30	1.66	0.385	25.4	0.397	1.62x10^{-2}	6.86x10^{-8}
3	204	30	1.59	0.411	25.0	0.383	1.72x10^{-2}	6.34x10^{-8}
4	174	30	1.59	0.411	25.9	0.396	1.65x10^{-2}	6.11x10^{-8}
5	143	30	1.59	0.411	27.0	0.413	1.57x10^{-2}	5.78x10^{-8}
6	113	30	1.59	0.411	28.8	0.441	1.44x10^{-2}	5.22x10^{-8}
7	82	30	1.59	0.411	31.9	0.489	1.23x10^{-2}	4.14x10^{-8}
8	52	30	1.59	0.411	41.3	0.631	6.23x10^{-3}	1.22x10^{-8}
9	18	37	1.59	0.411	56.3	0.862	4.20x10^{-4}	1.09x10^{-10}
10	0	152	1.59	0.411	65.4	0.995	1.14x10^{-5}	6.40x10^{-13}

^{u}Uncompacted fill soil.
^{c}Compacted fill soil.

A significant interaction was noted, in preliminary simulations, between radon transport through the slab and the slab-footing design. Therefore three reference designs were used for the feature effectiveness evaluations: floating slab, slab poured into stem wall (SSW), and thickened-edge monolithic slab. The other house features were analyzed for each of these reference designs.

Foundation footings extended to 61 cm below grade for the floating-slab and SSW houses, and to 30 cm below grade for the monolithic-slab house. The foundation concretes were defined to have a radon source term (product of radium concentration and radon emanation coefficient) of 0.07 pCi g^{-1}, consistent with previous measurements on Florida residential concretes (Rogers et al 1993). The porosity, radon diffusion coefficient, and air permeability of poured concrete (with 20-cm slump) were defined respectively as 0.22, 1.3x10^{-3} cm^2 s^{-1}, and 1.1x10^{-12} cm^2, and corresponding values for solid concrete block were defined as 0.26, 2.9x10^{-3} cm^2 s^{-1}, and 1.3x10^{-8} cm^2. The radon diffusion and air permeability of 0.015-cm (6-mil) polyethylene vapor barrier sheets were measured respectively as 3.4x10^{-7} cm^2 s^{-1} and 4.3x10^{-13} cm^2.

The floating-slab design was simulated with a 30-cm poured-concrete footing beneath a 60-cm hollow concrete block stem wall with a 10-cm solid concrete block cap. It had a 0.5-cm perimeter shrinkage crack between the slab and stem wall. The SSW design had an identical stem wall, except its solid block cap was replaced by a chair block (hollow block with the top inside quadrant removed) into which the slab was cast. The SSW design similarly had a crack at the slab perimeter (where the chair block forms the slab edge). Although this crack ideally does not exist in SSW designs, it is included for two reasons. It commonly occurs unless precautions are taken to avoid it, and the chair block walls are sufficiently porous to constitute an effective crack unless the entire chair block is filled with concrete. The thickened-edge monolithic slab design was simulated with no perimeter cracks or openings, and consisted of a continuum of poured concrete. Its footing extended only 30 cm below the fill soil into the native terrain. Vapor barrier membranes, when used, extended beneath the slab and, for monolithic designs, beneath the footing.

Variations in concrete slump were simulated by varied radon diffusion coefficients for the concrete. Thus the diffusion coefficient for concrete with a 10-cm slump was estimated as 6.7x10^{-4} cm^2 s^{-1}, and that for 15-cm slump as 9.3×10^{-4} cm^2 s^{-1}, based on empirical diffusion-density relations (Rogers et al 1993).

Simulations of slab reinforcement represented three conditions: cracking of non-reinforced slabs, reduced cracking of reinforced slabs, and no cracking. The non-reinforced slab was simulated with a single crack through its midpoint, based on a shrinkage fraction of 6×10^{-4}, which produces a crack about every 8.5 m (Ytterberg 1987). Slabs reinforced with 15 x 15 cm 10-gauge wire mesh were simulated with smaller cracks spaced at approximately 3 m (Acres International 1990). Simulations of re-entrant slab corners assumed no cracking if the corner was reinforced, and a single 2.1 m x 0.019 cm crack if the corner was not reinforced. The crack size is based on measured crack sizes typical for mesh-reinforced slabs. The sub-slab vapor barrier was considered intact under all slab cracks because of the relatively small crack sizes.

Slab penetrations by pipes were simulated with a total area corresponding to all plumbing, gas, and electrical penetrations through a slab. However the area was distributed equally for the simulations among three separated interior slab locations. Larger slab openings were 30 cm x 30 cm, typical of plumbing access areas beneath bath tubs or showers (Henschel 1993). The sub-slab vapor barrier was assumed to be open beneath unsealed penetrations, and closed beneath sealed penetrations. The simulations assumed compacted fill soil, and seal effectiveness equivalent to that of concrete.

Indoor Radon Measurements

Indoor radon measurements are insufficiently precise to estimate radon reductions smaller than a few percent, but are better for radon reductions approaching a factor of two. Radon precision was improved by normalizing indoor measurements by sub-slab radon concentrations to reduce inter-site variations (Nielson et al 1993a). The effectiveness of radon-resistance features was thus compared by changes in the net indoor/subslab radon concentration ratios (C_{net}/C_{sub}) from two empirical studies and on-going measurements.

The effectiveness of different slab-foundation designs and of active control systems in reducing radon levels was studied in several FRRP building demonstration projects. These include two test cells and 20 houses studied by Geomet Technologies, Inc., 27 houses studied by Florida Solar Energy Center, 30 houses studied by Southern Research Institute, and 14 houses studied by University of Florida. Other houses are still being studied by University of Florida and by Southern Research Institute. Measured C_{net}/C_{sub} ratios from these studies were compared to estimate the effectiveness of selected radon-protective building features. FRRP data also characterized existing house ventilation rates, and helped estimate the potential for reducing radon by increased ventilation.

RESULTS

The results of the model simulations were summarized for each radon-protective feature by the ratio of indoor radon for the reference case (without the feature) to indoor radon with the feature ($C_{ref}/C_{feature}$). The ratios were then used to rank the various features according to their effectiveness in reducing indoor radon concentrations. The results of these feature rankings are presented along with the $C_{ref}/C_{feature}$ ratios in Table 2. Where the feature effectiveness depends strongly on the slab-foundation design, individual $C_{ref}/C_{feature}$ ratios are reported for each case. However for ranking purposes, the individual values are summarized by a single representative value in the last column of Table 2. For predicting effects of the proposed residential building standard, beneficial features already used in present building practice or codes were retained as the reference case. Their effectiveness is shown in Table 2 as a reciprocal for consistency and convenience in ranking with other building features.

The most effective passive radon control feature was the sub-slab vapor barrier. Its effectiveness correlated strongly with the slab-foundation design, ranging from 1.75 to 2.53. The average effectiveness of the three individual ratios is 2.13. If only SSW and monolithic designs are considered, the vapor barrier effectiveness averages 2.32. The next most effective passive radon control feature is the slab-foundation design itself. Comparing the monolithic and SSW designs to the reference floating-slab design gives individual effectiveness ratios of 1.76 and 1.47, which average 1.62.

The next most effective passive radon control is reduced slab porosity. Concrete porosity is reduced by lower initial water content, which is represented by the slump of the wet mix. Compared to a reference case with 20-cm slump, mix designs for 10 cm and 15 cm slump give effectiveness ratios ranging from 1.17 to 1.40 for 10-cm slump, and from 1.08 to 1.17 for 15-cm slump. These respectively average 1.28 and 1.12 if all three slab-foundation designs are considered, or 1.33 and 1.15 if only SSW and monolithic designs are considered.

Sealing of the large slab openings and all cracks wider than 0.08 cm reduced indoor radon by 1.09 to 1.17, averaging 2.13 if all three slab-foundation designs are considered, or 1.15 if only SSW and monolithic designs are considered. However if the slab openings and only the cracks wider than 0.16 cm are sealed, the indoor radon is reduced by only 1.10 for the SSW and monolithic designs. Sealing of slab penetration joints reduced indoor radon levels by 1.08 to 1.15, averaging 1.12 if all three slab-foundation designs are considered, or 1.14 if only SSW and monolithic designs are considered.

TABLE 2. Ranking of Residential Construction Features by Average Radon Resistance Effectiveness

	Construction Feature	Reference Feature	Feature Effectiveness $C_{ref}/C_{feature}$	Summary Ranked Effectiveness
1.	Active SSV system[a]	no SSV	4.45	4.45
2.a	No vapor barrier - floating slab	vapor barrier	1.75^{-1}	2.13^{-1}
2.b	No vapor barrier - SSW	vapor barrier	2.11^{-1}	"
2.c	No vapor barrier - monolithic	vapor barrier	2.53^{-1}	"
3.	Enhanced ventilation[b]	0.25 ach	2.	2.
4.a	Monolithic slab & stem wall	floating slab	1.76	1.62
4.b	Slab poured into stem wall (SSW)	floating slab	1.47	"
5.a	10-cm concr. slump - floating slab	20-cm slump	1.17	1.33
5.b	10-cm concr. slump - SSW	20-cm slump	1.26	"
5.c	10-cm concr. slump - monolithic	20-cm slump	1.40	"
6.a	15-cm concr. slump - floating slab	20-cm slump	1.08	1.15
6.b	15-cm concr. slump - SSW	20-cm slump	1.12	"
6.c	15-cm concr. slump - monolithic	20-cm slump	1.17	"
7.	Seal slab openings & cracks[c]	unsealed	1.15	1.15
8.	Seal slab penetrations[d]	unsealed	1.14	1.14
9.	Seal slab openings & large cracks[e]	unsealed	1.10	1.10
10.	Passive SSV system	no SSV	1.07	1.07
11.	Compacted fill soil[f]	uncompacted	1.02^{-1}	1.02^{-1}
12.	Non-reinforced slab	reinforced[g]	1.01	1.01
13.	Reinforced re-entrant corners	non-reinforced	1.001	1.001
	Passive Groups (4, 6, 8, 9), (4, 5, 7, 8)			2.3, 2.8
	Active plus Passive Groups			10.3, 12.6

[a]Active sub-slab soil ventilation system.
[b]Indoor air exchange rate of 0.5 air changes per hour.
[c]Includes cracks >0.08 cm and two 30 cm x 30 cm openings.
[d]Includes all pipe penetrations.
[e]Includes cracks >0.16 cm and two 30 cm x 30 cm openings.
[f]Compacted to 92% compared to 87% if uncompacted.
[g]Using 15x15cm 10-gauge wire mesh in slab; bars at re-entrant corners.

The effects of compacting the fill soil are relatively small and nearly independent of slab edge detail. Although compaction may serve other useful purposes (such as minimizing long-term settlement cracking, etc.), it may actually increase indoor radon levels by an average factor of 1.02, suggesting it not be required for the present standard. The effects of slab reinforcement by wire mesh similarly may have little effect. Despite reducing overall crack areas, it may increase the total crack length, and thereby increase average indoor radon by a factor of about 1.01. Reinforcement of re-entrant slab corners gave a calculated reduction of indoor radon, but the reduction factor of 1.001 is considered negligible.

The most effective active radon control features were the active soil depressurization systems. Measured C_{net}/C_{sub} ratios from the first empirical study (Nielson et al 1993a) for both SSW houses and monolithic slab houses were highest for houses with no SSV system, were slightly lower for houses with a passive SSV system, and were significantly lower for houses with active SSV systems. Houses with capped SSV systems were erratic. Measured C_{net}/C_{sub} ratios for SSW houses averaged 2.7×10^{-3} for houses without SSV systems, 4.9×10^{-3} for houses with capped SSV systems, 1.7×10^{-3} for houses with passive SSV systems, and 4.3×10^{-4} for houses with fan-activated SSV systems. Measured C_{net}/C_{sub} ratios for monolithic-slab houses averaged 2.3×10^{-3} for houses without SSV systems, 6.2×10^{-4} for houses with capped SSV systems, 2.2×10^{-3} for houses with passive SSV systems, and 4.4×10^{-4} for houses with fan-activated SSV systems.

Measured C_{net}/C_{sub} ratios from the second empirical study (Nielson et al 1993b) suggested that SSW construction according to the FRRP standard reduces indoor radon to about 9×10^{-4} of the sub-slab concentration (with an uncertainty of a factor of 2.2). Capped SSV systems did not differ significantly from passive SSV systems. Monolithic slab construction may improve radon resistance by approximately 33%, reducing indoor radon levels by a factor of 0.67 compared to SSW construction. Activation of SSV systems with exhaust fans reduces the C_{net}/C_{sub} ratio by approximately 70%, reducing indoor radon levels to about 0.3 times the levels that occur when the SSV system is in the passive or capped mode. The measurements on active SSV systems are sparse and uncertain, however, due to the small number of houses where the SSV systems were activated.

Preliminary data from on-going studies show similar trends. Measured C_{net}/C_{sub} ratios from eight monolithic slab houses averaged 7×10^{-4}, and those from the four houses where the sub-slab radon exceed 1000 pCi L^{-1} averaged 3×10^{-4} (geometric standard deviation = 2.2). Measured C_{net}/C_{sub} ratios from two SSW houses averaged 1.5×10^{-3} (geometric standard deviation = 5.3). Only one of the SSW houses had sub-slab radon exceeding 1000 pCi L^{-1}, and its C_{net}/C_{sub} ratio was 5×10^{-4}.

DISCUSSION AND CONCLUSIONS

Using the feature effectiveness factors in Table 2, separate active and passive radon controls were proposed for the Florida residential construction standard. Cost/benefit analyses indicated that the active SSV system was the only cost-effective approach for active radon control. Its effectiveness factor of approximately 4.45 may be a minimum, since active SSV systems nationwide are usually found to reduce radon by a factor of ten or more (sometimes approaching a factor of 100) (Henschel 1993). The number in Table 2 represents an average of the few cases where an FRRP study house had the SSV fan activated, however, and is used conservatively until additional Florida data become available. This conservative approach allows for possible inefficiency due to low-permeability foundation soils in Florida. Although suction pit and ventilation mat designs were both studied, the present data cannot distinguish their effectiveness.

Enhanced ventilation, while potentially effective, incurs an operating cost that generally is unacceptable except in temporary situations. The effectiveness of enhanced ventilation was estimated by comparing 0.25 air change per hour (ach) infiltration rates estimated by the FRRP with more common infiltration rates of about 0.5 ach. The higher ventilation rates are readily attainable with air-to-air heat exchangers or even with existing leakage rates common to many houses. Therefore enhanced ventilation could reduce indoor radon levels by about a factor of two. Enhanced ventilation is an active control feature because ventilation is dominated by fan-driven air handlers,

handlers, and has an operational energy cost. Although not generally cost-effective, enhanced ventilation can significantly lower radon levels where operating costs are not an important consideration.

Passive SSV system effectiveness was evaluated along with active SSV systems because FRRP radon levels were often measured with and without operating exhaust fans. Despite the potential for well-controlled measurements, the observed seven percent radon reduction was highly uncertain. Model simulations of passive SSV systems can give results in the same range, but are also highly uncertain because they depend strongly on uncertain meteorological and occupant variables. Because of its significant cost and marginal effectiveness, passive SSV systems are not advocated except as a contingency where there is a potential need for an active SSV system that can be built less expensively during initial construction.

A group of four passive radon control features was also selected for the Florida residential construction standard. These include features 4, 6 (or 5), 8, and 9 (or 7). The alternative slumps and crack widths were chosen during standard development for slightly improved passive group effectiveness. The vapor barrier also qualifies for the passive group, but its effectiveness is excluded because it is already required by existing building codes.

Slab-foundation design is the dominant passive feature selected, and is recommended as the prime radon control feature for new construction. The second passive feature, lower slump concrete, is also recommended because of its minimal cost and significant effectiveness. Although 15-cm slump (feature 6) is more easily attainable with present practices, 10-cm slump (feature 5) was later advocated because of its greater effectiveness and reasonable attainment. Sealing slab penetrations also gives significant benefit despite some initial cost and possible maintenance costs. Sealing of large floor openings and cracks also is recommended, since these can be readily identified, are likely to be completed successfully, and have significant radon reduction benefit. Together these four features, identified at the bottom of Table 2, give a passive radon resistance effectiveness of a factor of 2.3 if features 4, 6, 8, and 9 are selected, and a factor of 2.8 if features 4, 5, 7, and 8 are selected. The remaining features contribute little to further radon reduction, and in some cases (such as passive SSV systems) are associated with significant initial construction costs.

For Florida areas with marginally-elevated radon, passive radon controls reduce radon by a factor of 2.3 to 2.8, depending on feature definition. In areas of elevated radon potential, active SSV systems along with passive controls increase radon protection to combined factors of about 10 to nearly 13 or more. Significantly greater radon protection may be attained with a well-performing active SSV system.

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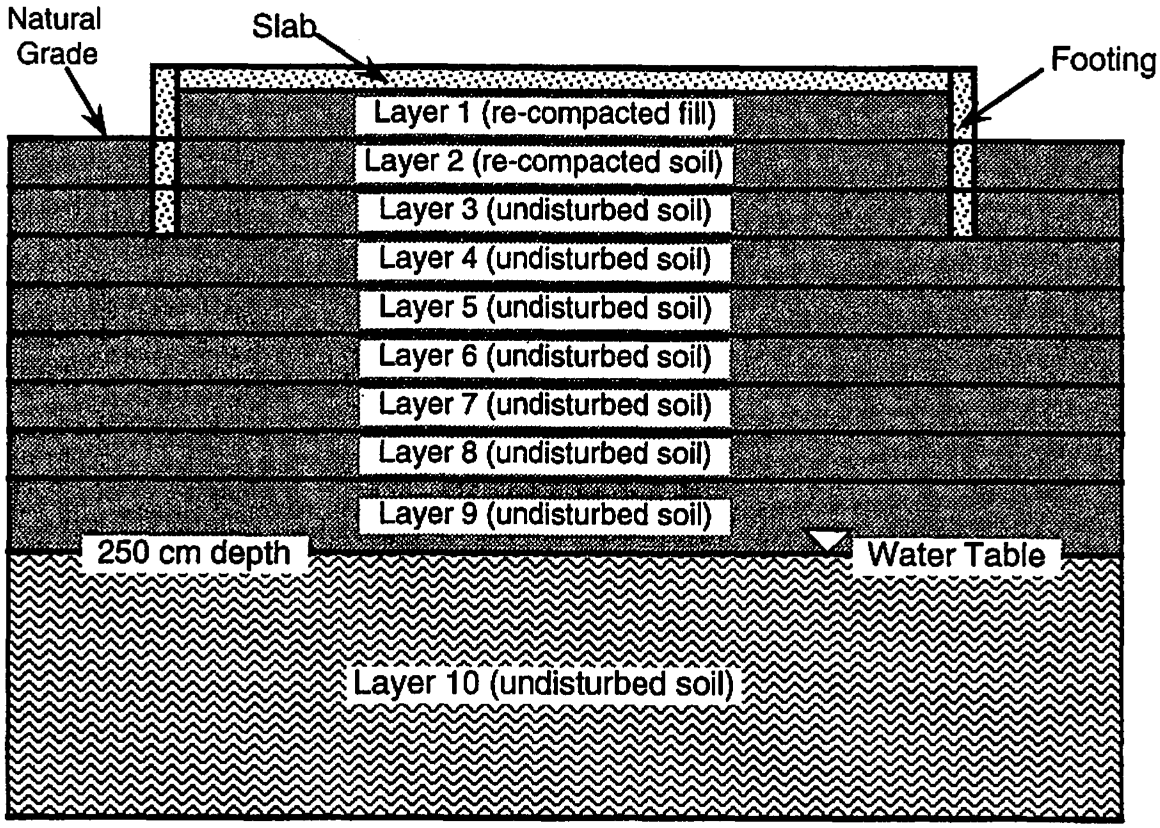

Fig. 1. Soil profiles defined for radon entry simulations.