RELATIONSHIP BETWEEN RADIUM CONCENTRATION LEVELS IN SOIL AND RADON TRANSPORT THROUGH SOILS INTO HOMES

Ben Hull
Office of Radiation Programs
U.S. Environmental Protection Agency
Kirk Nielson
Rogers and Associates Engineering Corporation

ABSTRACT

A number of sites currently listed on the Superfund National Priority List (NPL) are known or suspected to contain enhanced levels of naturally occurring radioactive materials (NORM). One of the radionuclides commonly encountered at these sites is Ra-226. The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) does not establish specific cleanup criteria for radionuclides. Instead, Section 121(d) of CERCLA requires that remedies for Superfund sites comply with Federal and state laws that are applicable or relevant and appropriate (ARAR). "CERCLA Compliance with Other Laws Manual" (EPA/540/G-89/006, August 1988) presents a list of potential ARARs as an aid to Remedial Project Managers (RPMs), State personnel at State-lead Superfund sites, On-Scene Coordinators (OSCs), and other persons responsible for planning response actions. For sites contaminated with Ra-226, the EPA standards set forth in 40 CFR 192 are often used as an ARAR.

Though 40 CFR 192 has served effectively as an ARAR for radium contaminated sites, questions have been raised regarding the required excavation depths of radium-contaminated soil adjacent to the foundations of private residences. In order to provide additional guidance regarding excavation depths, EPA is performing a series of analyses to determine those excavation depths that are required to meet current health based standards under a broad range of environmental settings regarding soil type and moisture conditions. This paper presents a brief summary of the current status of these computer analyses.

INTRODUCTION

The RAETRAN code, developed by Rogers & Associates Engineering Corporation, is being used to assess the relationship between Ra-226 concentration in soil, radon fluxes at the soil surface, and average radon concentrations in homes. These relationships are being modeled parametrically as a function of key parameters, including:

- Thickness of the contaminated soil layer,
- Proximity of the contaminated layer to the foundation of a home,
- Key properties of the soil, including moisture content (saturation), porosity, and permeability, and taking into consideration the coupled relationships between these parameters,
- The effects of intervening layers of "clean" fill between the foundation of a home and the contaminated layer of soil and the soil surface,
- the effects of localized "hot spots" of contaminated soil for a range of geometries and distances from the foundation of the home or the soil surface,
- the effects of the pressure gradient between the home and the subslab, and
- the effects of indoor air turnover rate as coupled to the pressure gradient and associated influx of radon into the home.

In addition to evaluating excavation depths, replacement fill material must have the appropriate properties to replace the contaminated soil which has been excavated. The placement of fill material at sites where radioactively contaminated soil has been excavated must meet two conditions; namely, the fill soil must minimize the release of radon and must be structurally sound to accomplish its intended purpose as structural fill at the site.

SOIL EXCAVATION DEPTHS

Calculations based on the RAETRAN (RAdon Emanation and TRANsport) model (1-2) were performed to estimate the depths of soil cleanup that would be required to remediate various concentrations of soil contamination.

The extent of soil cleanup needed to remediate a dwelling environment was calculated for various soil types, moisture contents, and Ra-226 contamination distributions. The cleanup needs were estimated in terms of the maximum quantity of residual radium contamination that could remain in the foundation soil without contributing to elevated indoor radon concentrations. The limiting residual radium contamination permissible in the foundation soil was calculated as the amount that would contribute 2 pCi liter^{-1} (74 Bq m^{-3}) to the indoor radon concentration. The 2 pCi liter^{-1} limit was based on the EPA indoor radon criterion of 4 pCi liter^{-1} which is the lowest action level for total radon resulting from all sources. (3) The present limit was set at half of the EPA criterion to allow for averaging over other levels in the house, for radon generated in uncontaminated soil regions that exceeded the assumed background level, and for radon from other sources such as water and building materials.

The RAETRAN model is based on the approximate separability of two main radon entry routes for independent radon entry calculations. The routes are (a) through discrete foundation cracks and (b) through the intact concrete floor slab. The separability is suggested to be a good approximation for typical slab perimeter shrinkage cracks by results of 2-dimensional finite-difference calculations of radon entry, (4) which indicate that radon depletion near the perimeter cracks has little interaction with the diffusion-dominated entry through most of the floor slab.

For modeling and comparison purposes, a model slab-on-grade house *and related* soil conditions were defined. These are presented in Table I. The model house was analyzed for several different soil conditions and different radium concentration levels. The host soil conditions analyzed for included three types of soils (loamy sand, clay loam, and sandy clay loam, Fig. 1), which were intended to represent a common range of grain size distributions and permeabilities. The backfill soil was a sandy clay loam in all three cases. Three different water saturations at bar matric potentials of -0.1, -0.3 and -15.0 were also analyzed for each of the soil types (host and backfill) to examine the effects of moisture content. The moisture at -0.3 bar matric potential was chosen to represent typical moist but drained soil conditions, those at -0.1 bar to represent maximum drained soil moisture for sandy soils; and those at -15 bar to represent soils dried to the permanent plant wilting point. (11) The effects of varying the concentration of Ra-226 within the backfill for concentration levels of 1, and 3 pCi/g was also analyzed. The soils and their associated moisture saturations, air permeabilities, and radon diffusion coefficients are presented in Table II.

During the RAETRAN analyses soil properties including radium concentration were modeled through a total depth range of 15 meters. This depth range was considered adequate because it exceeded the combination of a surface soil excavation of 5 meters and the nominal "infinite depth" for the modeled diffusion and advection conditions of 4 to 5 meters.

Results of the calculations using the RAETRAN radon entry model are presented by plotting backfill depth (excavation depth) and soil radium concentration (pCi/g) for the host soil for various soil types with different radon diffusion coefficients, saturations, and Ra-226 concentration levels. Variations in the soil excavation depth for a host soil consisting of clay loam, sandy clay loam, and loamy sand are shown in Figs. 2, 3, and 4 respectively for a -0.3 bar matric potential for the host and the backfill soil. The backfill soil composition for all three cases is composed of sandy clay loam with Ra-226 concentration levels of 1, and 3 pCi/g. Variations observed in Figs. 2, 3, and 4 show an overall increase in the required excavation depths. This trend is due to the change in the clay and silt concentrations between a clay loam, sandy clay loam, and loamy sand which directly affects the water saturations, air permeabilities and radon diffusion coefficient values.

Furthermore for the coarsest soil (loamy sand, Fig. 4), approximately 6 pCi g^{-1} contamination may contribute 2 pCi liter^{-1} indoors, and soil contamination levels as low as 13 pCi g^{-1} may require excavation and replacement of about 2 m of surface soil. The intermediate soil (sandy clay loam, Fig. 3)

TABLE I

Model House and Soil Parameters Used in Radon Entry Calculations

House Area	143.5 m^2	Indoor ^{222}Rn Conc.	2.0 pCi lit^{-1}
House length/width	2.0 (ratio)	Background ^{226}Ra Conc.	1.0 pCi g^{-1}
House volume	350 m^3	^{222}Rn Emanation Coeff.	0.20
Indoor pressure	-2.4 Pa	Soil bulk density	1.6 g cm^{-3}
House ventilation rate	0.35 h^{-1}	Soil porosity	0.41
Crack width	5.9 cm	Radon water/air dist.,k_H	0.26 cm^3 cm^{-3}
Crack location	20 cm fr. ext.	Concrete slab thickness	10 cm
Crack area fraction	0.02	Concrete slab porosity	0.30

TABLE II

Soils and their Derived Parameters Used in Radon Entry Calculations

Soil Condition	Soil[a]	Matric Potential (bars)	Moisture Saturation (fraction)	Air Permeability (cm^2)	Rn Diffusion Coefficient (cm^2 s^{-1})
1	loamy sand	-0.1	0.408	1.4x10^{-7}	1.6x10^{-2}
2	loamy sand	-0.3	0.290	1.8x10^{-7}	2.2x10^{-2}
3	loamy sand	-15.0	0.106	2.0x10^{-7}	3.5x10^{-2}
4	clay loam	-0.1	0.780	6.9x10^{-10}	1.6x10^{-3}
5	clay loam	-0.3	0.712	2.7x10^{-9}	3.4x10^{-3}
6	clay loam	-15.0	0.483	3.1x10^{-8}	1.3x10^{-2}
7	sandy clay loam	-0.1	0.608	2.6x10^{-8}	7.3x10^{-3}
8	sandy clay loam	-0.3	0.472	7.3x10^{-8}	1.3x10^{-2}
9	sandy clay loam	-15.0	0.316	1.2x10^{-7}	2.1x10^{-2}

[a] SCS classification

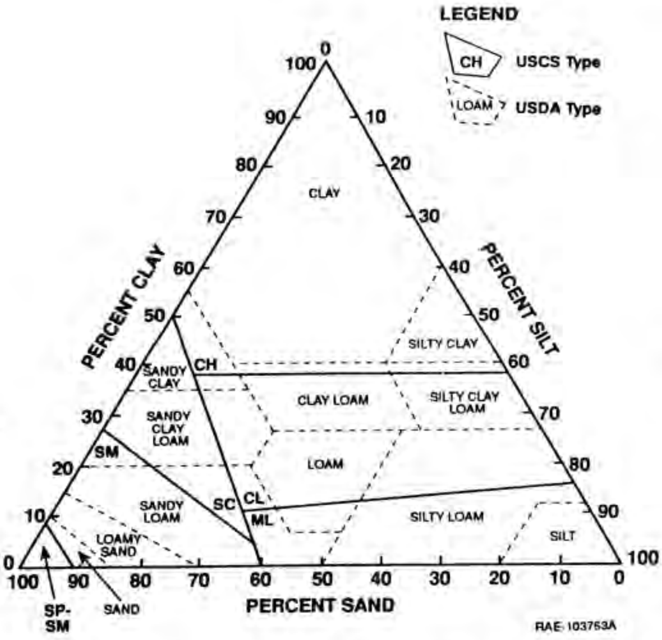

Fig. 1. Comparison of the USGS soil classification with USDA textural classification. (15)

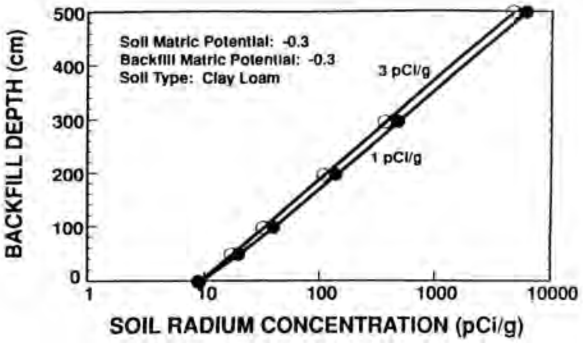

Fig. 2. Depths of sandy clay loam backfill over clay loam soil, both at -0.3 bar matric potential, to reduce indoor radon to 2 pCi^{L-1}.

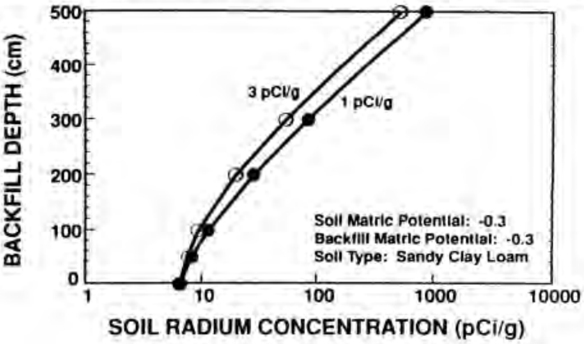

Fig. 3. Depths of sandy clay loam backfill over sandy clayloam soil, both at -0.3 bar matric potential to reduce indoor radon to 2 pCi^{L-1}.

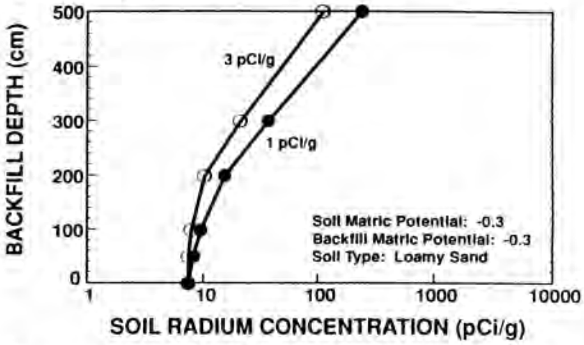

Fig. 4. Depths of sandy clay loam backfill over loamy sand soil, both at -0.3 bar matric potential, to reduce indoor radon to 2 pCi^{L-1}.

similarly may have only about 6 pCi g^{-1} before exceeding the indoor radon criterion. Approximately 2 m excavation and replacement of this soil is sufficient for 27 pCi g^{-1} contamination in the host soil. The finest soil (clay loam, Fig. 2) may exceed 9 pCi g^{-1} radium contamination before exceeding the indoor radon criterion, and with approximately 1 m of excavation and replacement, this soil could contain up to 40 pCi g^{-1} contamination. The above calculations assume a sandy clay loam backfill directly against the floor slab with a Ra-226 concentration of 1 pCi/g and at a -0.3 bar matric potential.

STRUCTURAL FILL AND RADON CONTAINMENT

Fine-grained soils such as silts and clays retain more water than sandy or gravelly soils, and thus exhibit lower radon

TABLE III

Equivalent Soil Textural Classifications and Their Derived Parameters Used in Radon Entry Calculations

Structural Fill Soil	USCS Class	Approx. USDA Class	Moisture Saturation[a]	Air Permeability	RnDiffusion Coefficient[b]
Group 1	SC, GC	sandy clay loam	0.472	6.9×10^{-8}	1.3×10^{-2}
Group 2	GM	gravelly sandy loam	0.461	7.5×10^{-8}	1.4×10^{-2}
Group 3	SM	loamy sand	0.290	1.7×10^{-7}	2.2×10^{-2}
Group 4	SW, SP, GW, GP	sand	0.213	2.1×10^{-7}	2.7×10^{-2}

[a] Fraction of pore space filled with water, based on soil water content at -0.3 bar matric potential, and 1.6 g cm^{-3} density.
[b] Computed, cm^2 s^{-1}.

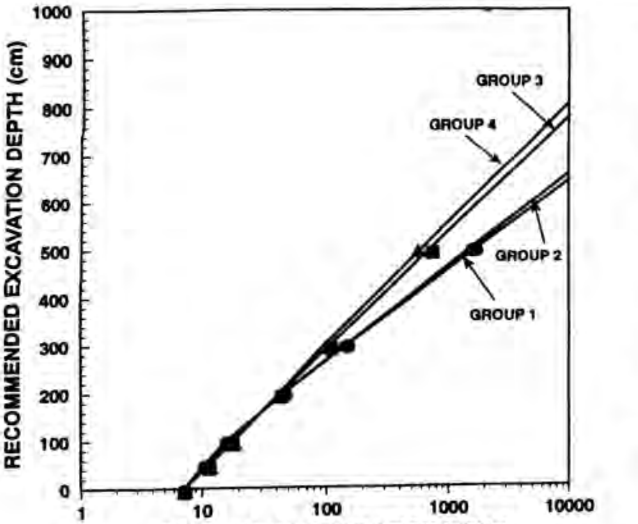

Fig. 5. Recommended soil excavation depths for varying levels of uniform Ra-226 contamination for the four soil structural stability groups identified in Table III.

diffusion and gas permeability coefficients under corresponding conditions. Although this may suggest use of fine-grained soils as fill material for replacing excavated soils near house foundations, structural considerations indicate a sometimes opposing trend with particle size. Analyses of soil properties needed for structural fill indicate that soil grain size distribution, moisture content, density, plasticity, and shear resistance primarily determine the suitability of a soil. (12) Other parameters such as compressibility, consolidation, elasticity, water permeability, and shrinkage also are significant.

Four soil groups (sandy clay loam, gravelly sandy loam, loamy sand, and sand) were identified with mechanical properties of soil suitable for structural fill around house foundations. Soil types according to the Unified Soil Classification System and the USDA textural classification system are listed in Table III along with their corresponding water saturations fractions, permeabilities, and radon diffusion coefficient values.

Radon entry calculations were performed using the methods and parameters described above for each of the soil groups listed in Table III. Corresponding soil excavation depths also were computed to estimate the quantity of clean replacement fill for each of the four groups that would be required over the uniformly contaminated soil to reduce indoor radon concentrations in the overlying model house to 2 pCi liter^{-1}. The resulting soil excavation depths for various concentrations of uniform radium contamination are presented in Fig. 5.

The Group 2 soil illustrated in Fig. 5 has similar moisture and radon transport properties to the Group 1 soil, and thus requires excavation depths that are only slightly deeper. For both the Group 1 and the Group 2 soil types excavation and replacement of approximately .5 m is sufficient if the host soil has less than 10 pCi g^{-1} contamination. The Group 4 soil has a lower moisture retention than the Group 3 soil, and accordingly has higher radon diffusion and air permeability coefficients. Overall of the four selected soil types displayed in Fig. 5, there is little difference in the recommended excavation depths if the Ra-226 concentration in the host soil is less than 40 pCi/g.

Based on the value ranking of the four structural stability groups for use as foundation materials, the Group 1 sandy clay loam and the Group 2 gravelly sandy loam appear to represent the best compromise for general applications. The sandy clay loam soil is uniformly graded from coarse to fine material with the fines acting as an effective binder.

CONCLUSIONS

Radon entry calculations were performed using the RAETRAN model to determine depths of soil cleanup required for slab on grade houses. Various soil conditions, moisture levels, and concentrations of Ra-226 were modeled for host and backfill soils. The limiting radium contamination permissible in the host and the backfill soil was calculated as the amount that would contribute 2 pCi/liter to the indoor radon concentration. Results indicate that for the slab on grade house with the backfill soil directly adjacent to the house approximately 6 to 9 pCi/g of Ra-226 contamination will contribute 2 pCi/liter indoors. Additional studies on evaluating the effects of a high permeable gravel layer beneath the slab are in progress.

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