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A theoretical method for estimating the characteristics of radon transport in homogeneous soil

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Abstract
A theoretical method for estimating the characteristics of radon transport in homogeneous soil is developed. The method allows the following characteristics to be estimated: depth distribution function of the soil gas radon concentration, equilibrium radon concentration in the soil air, depth at which the radon concentration reaches its equilibrium value, radon flux density from the Earth's surface, and convective radon transport velocity. The method is based on soil gas radon concentration measurements and is appropriate in the case of relatively uniform geology.

Key words *method – radon – soil – convective velocity – radon flux density*

1. Introduction

A knowledge of certain radon transport characteristics (depth distribution function $A(z)$ of the soil gas radon concentration, radon flux density $q(z)|_{z=0}$ from the Earth's surface, convective radon flux velocity υ in soil, etc.) is essential in solving a number of radioecological and geophysical problems. Radon transport in soil is described by the well-known diffusive-convective equation (Nazaroff and Nero, 1988). The solution to this equation is an exponential soil radon concentration distribution with depth. The exponential coefficient varies with the physical-geological soil parameters and weather conditions. The latter affect the convective radon flux velocity in soil.

It has been verified experimentally (Fleischer, 1997; Abumurad and Al-Tamimi, 2001; Jönsson, 2001) that the depth distribution of the soil gas radon concentration obeys the exponential law in the case of a relatively homogeneous geological structure and a great depth of occurrence of water-bearing horizons. Given the radon concentration distribution function we can readily determine the following parameters: equilibrium soil gas radon concentration A_∞, characterizing the radon potential of a given area, depth at which the equilibrium concentration is found, soil gas radon concentration gradient specifying the radon flux density according to Fick's law, and convective velocity.

The central problem is to find experimentally the function $A(z)$. Reconstruction of the vertical profile of the soil gas radon concentration requires that measurements be performed at different depths. The number of measurements varies with prescribed accuracy. The measurements can be very expensive and difficult to perform.

However, the number of radon concentration measurements can be reduced to two measurements, using the properties of the exponential law.

The measurements should be performed at shallow depths (≤ 1 m deep), because here the gradient is very step.

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In this work, a method for estimating the radon transport characteristics in soil is developed. The approach under review is based on the above-mentioned diffusive-convective radon transport model and *in situ* radon concentration measurements at two depths.

2. Methodology

Solving the stationary diffusive-convective radon transport equation in the *quasi*-homogeneous approximation, we will get a depth distribution of the radon concentration in the soil air (Jönsson, 1997) for the z-axis directed downward from the Earth's surface. Thus,

$$A(z) = A_{\infty}\left(1 - \exp^{-\left(\sqrt{\left(\frac{\upsilon}{2D_e}\right)^2 + \frac{\lambda}{D_e}} + \frac{\upsilon}{2D_e}\right)z}\right) \quad (2.1)$$

where $A(z)$ is the radon concentration per unit volume of the soil air (Bqm^{-3}), υ is the convective radon flux velocity (ms^{-1}), D_e is the effective radon diffusion coefficient (m^{2}s^{-1}), and λ is the radon decay constant (s^{-1}).

The equilibrium soil gas radon concentration depends solely on the physical-geological soil parameters, and we have

$$A_{\infty} = \frac{K_{em} A_{\mathrm{Ra}} \rho_s (1 - \eta)}{\eta} \quad (2.2)$$

where K_{em} is the radon emanation coefficient (rel. units), A_{Ra} is the specific activity of ^{226}Ra (Bqkg^{-1}), ρ_s is the solid soil particle density (kgm^{-3}), and η is the soil porosity (rel. units).

Let us denote the soil gas radon concentration measured at a depth h_1 by A_1 and that measured at a depth $h_2 = 2h_1$ by A_2. Substituting A_1 and A_2 into eq. (2.1), we will arrive at the following equation

$$A(z) = \frac{A_1}{2 - \frac{A_2}{A_1}}\left(1 - \exp^{-\left(\frac{1}{h_1}\ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right)\right)z}\right). \quad (2.3)$$

It is evident from eq. (2.3) that the equilibrium soil gas radon concentration generally found at a great depth and characterizing the soil radon potential (Yakovleva, 2002) can be estimated from as few as two measurements near the Earth's surface. Thus we obtain (Yakovleva and Ryzhakova, 2002)

$$A_{\infty} = \frac{A_1}{2 - \frac{A_2}{A_1}}. \quad (2.4)$$

The depth (z_{eq}) at which A_∞ is found is determined by introducing the parameter (rel. units) $X = A\left(z_{eq}\right)/A_{\infty}$. The parameter specifies the degree to which the soil gas radon concentration approaches its equilibrium value. For example, with $X = 0.95$, the soil gas radon concentration at the depth sought will be only 5% lower than its equilibrium value. Then we can find z_{eq} from the following equation

$$z_{eq} = h_1 \frac{\ln(1 - X)}{\ln\left(\frac{A_2}{A_1} - 1\right)}. \quad (2.5)$$

The radon flux density from the Earth's surface is defined by the following relation (Ryzhakova and Yakovleva, 2002)

$$q(z)\big|_{z=0} = -D_e \frac{\partial(\eta A(z))}{\partial z} =$$

$$= D_e \eta \cdot \frac{A_1}{2 - \frac{A_2}{A_1}} \cdot \frac{1}{h_1} \cdot \ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right) \quad (2.6)$$

and the convective radon flux velocity is expressible as

$$\upsilon = \frac{D_e}{h_1}\ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right) + \frac{\lambda h_1}{\ln\left(\frac{A_2}{A_1} - 1\right)}. \quad (2.7)$$

The radon flux density and convective velocity can be determined by eqs. (2.6) and (2.7). To this end, we need to know the radon diffusion coefficient in addition to two measured values of the soil gas radon concentration. The choice of the diffusion coefficient presents no special problems. For the majority of sedimentary rocks constituting the surface layer, the diffusion coefficient varies within a small range and is, on average, 0.03 cm^2s^{-1} (Durrani and Ilić, 1997).

The measurements of A_1 and A_2 should be performed concurrently (by means of any conventional devices and techniques) at two points spaced 0.5 – 1 m apart. There is a limitation on the maximum separation between the two measuring points (~1 m). This is due to the fact that the soil properties at the measuring points should be the same. A minimum point separation of 0.5 is needed to avoid a possible influence on the results of the two measurements. Moreover, measurements for a smaller point separation present some technical problems.

It is recommended that both of the measurements should be performed at depths between 0.3 and 1 m for the following reasons: i) the soil gas radon concentration varies comparatively rapidly at these depths, which enables us to reduce the error in determination of the function $A(z)$, ii) the depth h_1 should not be smaller than 0.3 m because of a great influence of atmospheric conditions, which reduces the reliability of the results obtained, and iii) an increase in the measurement depth above 1 m would not be economically attractive.

The method under review is applicable for areas with a relatively homogeneous geological structure. In the case of radon anomalies (rocks with a high content of uranium, large fractures in the Earth's crust, etc.), the method will be not suitable.

3. Preliminary results of practical evaluation of the method under review

The method was tested in a small survey area with a homogeneous geological structure (surface soil layer is loam). The area is located in Lagernii sad (camp garden) in Tomsk (West Siberia, Russia). Two holes spaced 0.5 m apart were drilled by a customized soil auger. One hole was 35 cm deep (h_1), and the other was 70 cm deep ($2h_1$). The hole diameter was 5.5 cm.

Radon radiometers with track etch detectors of LR-115 type III-b (Nikolaev and Ilić, 1999) were placed in the holes. Then the holes were covered to provide air-tightness and allowed to stay for 72 h. The soil gas radon concentration (A_1 and A_2) was determined as directed by operating instructions for the AIST–TRAL complex. The etching and track counting methodology are described in Nikolaev *et al.* (1993).

The measured soil gas radon concentrations A_1 and A_2 were 6.8 and 11.4 $kBqm^{-3}$. The equilibrium radon concentration A_∞ calculated by eq. (2.4) was 21.0 $kBqm^{-3}$. This value is twice as high as the measured value A_2 at a depth of 70 cm, which is usually recommended for radon concentration measurements.

We have also estimated A_∞ by eq. (2.2) to get 20 $kBqm^{-3}$. To this end, soil samples were taken, and their density, porosity and ^{226}Ra specific activity were determined (Karataev *et al.*, 2000; Yakovleva, 2002). The radon emanation coefficient was taken to be 0.2. The values of A_∞ calculated by eqs. (2.2) and (2.4) agree very closely.

The depth at which the soil gas radon concentration accounts for 95% of its equilibrium value is 2.7 m. The radon flux density from the Earth's surface is 33.8 $kBqm^{-2}s^{-1}$, and the convective flux velocity is $1.7 \cdot 10^{-4}$ cms^{-1}.

4. Concluding remarks

We have developed a method for estimating the radon transport characteristics in soil. The approach under review has the following practical benefits: i) versatility since only two measurements of the soil gas radon concentration are needed to determine a number of radon transport characteristics; ii) validity for any conventional devices and techniques used for measuring the soil gas radon concentration; and iii) low cost since it requires neither a large number of measurements to determine the function $A(z)$ nor detailed information on the physical-geological soil parameters.

This method is useful in different fields of applied research such as: radioecology, for improving the reliability of potential soil radon risk estimates and for reducing the weather conditions effect on results of soil radon concentration monitoring; geophysics, for studying the convective gas flow velocity; etc.

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