

# A versatile method for estimating the characteristics of radon transport in soil

V. S. Yakovleva

Tomsk Polytechnic University, Tomsk, 634050, pr. Lenin, 30, Russia

**Abstract.** A versatile method for estimating the characteristics of radon transport in 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.

## 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  $v$  in soil, etc.) is essential in solving a number of radioecological and geophysical problems. The radon transport in soil is described by the well-known diffusive-convective equation (Nazaroff, 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; Jönsson, 2001; Abumurad and Al-Tamimi, 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  $A_\infty$ , 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 down to two measurements, using the properties of the exponential law. The measurements should be performed at shallow depths ( $\leq 70$  cm deep).

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

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

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

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

$$A_\infty = \frac{K_{em} A_{Ra} \rho_s (1 - \eta)}{\eta}, \quad (2)$$

where  $K_{em}$  is the radon emanation coefficient (rel. units),  $A_{Ra}$  is the specific activity of  $^{226}\text{Ra}$  ( $\text{Bq kg}^{-1}$ ),  $\rho_s$  is the solid soil particle density ( $\text{kg m}^{-3}$ ), and  $\eta$  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. (1), we will arrive at the following formula

$$A(z) = \frac{A_1}{2 - \frac{A_2}{A_1}} \left( 1 - \exp^{-\left(\frac{1}{h_1} \ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right)\right)z} \right). \quad (3)$$

It is evident from Eq. (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

$$A_\infty = \frac{A_1}{2 - \frac{A_2}{A_1}} \quad (\text{Yakovleva and Ryzhakova, 2002}). \quad (4)$$

The depth ( $Z_{eq}$ ) at which  $A_\infty$  is found is determined by introducing the parameter  $X = \frac{A(z_{eq})}{A_\infty}$  (rel. units). 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

$$z_{eq} = h_1 \frac{\ln(1 - X)}{\ln\left(\frac{A_2}{A_1} - 1\right)}, \quad (5)$$

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

$$\begin{aligned} q(z)|_{z=0} &= -D_e \frac{\partial(\eta A(z))}{\partial z} \\ &= D_e \eta \cdot \frac{A_1}{2 - \frac{A_2}{A_1}} \cdot \frac{1}{h_1} \cdot \ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right), \end{aligned} \quad (6)$$

and the convective radon flux velocity is expressible as

$$v = \frac{D_e}{h_1} \ln\left(\frac{1}{\frac{A_2}{A_1} - 1}\right) + \frac{\lambda h_1}{\ln\left(\frac{A_2}{A_1} - 1\right)}. \quad (7)$$

The radon flux density and convective velocity can be determined by Eqs. (6) and (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,  $0.03 \text{ cm}^2 \text{ s}^{-1}$  (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 ( $\sim 1 \text{ m}$ ). 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 be performed at depths between 0.2 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 0.2 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 require further development.

### 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  $\alpha$ -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  $\text{kBq m}^{-3}$ . The equilibrium radon concentration  $A_\infty$  calculated by Eq. (4) was 21.0  $\text{kBq m}^{-3}$ . This value is twice as high as that measured value  $A_2$  at a depth of 70 cm, which is usually recommended for the radon concentration measurements.

We have also estimated  $A_\infty$  by formula (2) to get 20  $\text{kBq m}^{-3}$ . To this end, soil samples were taken, and their density, porosity and  $^{226}\text{Ra}$  specific activity were determined (Karataev et al., 2000; Yakovleva, 2002). The radon emanation coefficient was taken to be 0.2. The values of  $A_\infty$  calculated by Eqs. (2) and (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  $\text{kBq m}^{-2} \text{ s}^{-1}$ , and the convective flux velocity is  $1.7 \cdot 10^{-4} \text{ cm s}^{-1}$ .

#### 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:

1. versatility since only two measurements of the soil gas radon concentration are needed to determine a number of radon transport characteristics;
2. validity for any conventional devices and techniques used for measuring the soil gas radon concentration; and
3. 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:

- seismology, for improving the earthquake prediction accuracy, i.e. reducing the weather conditions effect on results of soil radon concentration monitoring;
- radioecology, for improving the reliability of potential soil radon risk estimates; and
- geophysics, for studying the convective gas flow velocity; etc.

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