Paper

EXPERIMENTAL AND THEORETICAL STUDY OF RADON DISTRIBUTION IN SOIL

M. Antonopoulos-Domis,* S. Xanthos,* A. Clouvas,* and D. Alifrangis†

Abstract—**Radon concentration as a function of the soil depth (0–2.6 m) was measured during the years 2002–2003 and 2003–2004 on the Aristotle University campus. Radium distribution in soil was found constant. On the contrary, as expected, radon concentration increased with soil depth. However, the radon concentration did not follow the well known monotonous increase, which levels off to a saturation value. In both radon distributions, radon concentration increased up to a soil depth of about 80 cm, seemed to remain constant at depths of 80–130 cm, and then increased again. The experimental distribution was reproduced by solving the general transport equation (diffusion and advection). The main finding of the numerical investigation is that the aforementioned, experimentally observed, profile of radon concentration can be explained theoretically by the existence of two soil layers with different diffusion-advection characteristics. Soil sample analysis verified the existence of two different soil layers. Different boundary conditions of the radon concentration at the soil surface were used for the solution of the diffusion-advection equation. It was found that the calculated radon concentration in the soil is, away from the soil surface, the same for the two boundary conditions used. However, from the (frequently used) boundary condition of zero radon concentration at the soil surface, the experimental profile of the radon concentration at the soil surface cannot be deduced. On the contrary, with more appropriate boundary conditions the radon concentration at the soil surface could be deduced from the experimental profile. The equivalent diffusion coefficient could be uncovered from the experimental profile, which can then be used to estimate the radon current, which is important, for example, for the estimation of radon entrance to dwellings.**
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Key words: diffusion; radium; radon; soil

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INTRODUCTION

It is well known that population exposure to high concentrations of radon and its decay products is a significant health risk, possibly associated with various malignancies and especially with lung cancer. At least 80% of the radon emitted into the atmosphere comes from the top few meters of the ground (Shweikami et al. 1995). Over the past few decades, significant research efforts (theoretical and experimental) have been devoted to the migration of radon in soil (Washington and Rose 1990; Nazaroff 1992; Asher-Bolinder et al. 1990; Schery et al. 1984; van der Spoel et al. 1999; Yakovleva 2005; Papachristodoulou et al. 2007). The practical interest is in the estimation of radon release in the atmosphere and entrance into dwellings. The model used, in most cases, is diffusion and the objective is to uncover, from measurements, the parameters controlling the migration of radon through soil.

In the present work radon concentration as a function of the soil depth (0–2.6 m) was measured twice, in a location of the Aristotle University campus, in Thessaloniki (northern Greece). Radon migration equations (diffusion-advection) are discussed and applied to simulate the measured radon profile and to uncover the parameters necessary to estimate radon current, hence its release in the atmosphere and its entrance into dwellings.

MATERIALS AND METHODS

Radon concentration as a function of the soil depth (0–2.6 m) was measured during the years 2002–2003 and 2003–2004, in a location of the Aristotle University campus in Thessaloniki in northern Greece. The measurements were performed with two continuous radon monitors (Barasol detectors; Algade, 1 Avenue du Brugeaud, BP 46, 87250 Bessines Sur Gartempe, France). The first one was located in a fixed depth (85 cm) since 2001, and the second one was located in different soil depths (with 10 cm step) from 10–260 cm depth. The use of the first detector (located in a fixed depth) was to give information about any temporal variation of the radon concentration during the total period of measurement. The second detector was positioned in each soil depth for a time period of about 5 d. The radon concentration as function of the soil depth was therefore not measured simultaneously but in different time periods. In order to reduce the uncertainties due to possible temporal variations, the radon concentration as a function of the soil depth was measured twice (during 2002–2003 and 2003–2004).

Barasol detectors perform static measurements (without disturbance) of radon gas (Papastefanou 2007). Measurement is provided by a silicon detector that records alpha particle emissions of the radon present in an optimized measurement cylindrical chamber (6 cm in diameter, 57 cm in length). The detector totalizes alpha particle emissions generated during pre-established time intervals of 15 to 240 min. A micro-processor is used to store the measured values. Readout is performed by a standard personal computer with associated software. The detector is a light tight implanted silicon junction (planar). It has protection against light by an aluminum layer and mechanical protection by a cellulose varnish. The useful area of the detector is 450 mm^2 and the depleted depth is 100 μm. Resolution with the detector placed in the air is 60 keV (full width at half maximum, FWHM) at 5.486 MeV (^{241}Am). The background count rate is below 1 event every 24 h and the detection limit for radon is 50 Bq m^{-3}. The unit also measures atmospheric parameters such as temperature and atmospheric pressure.

In order to study the horizontal variability of the radon in soil, the radon concentration was measured in a fixed depth of 50 cm in 7 points with an horizontal step of 50 cm. The detectors used for this purpose are Electret Ion Chambers (Rad Elec, Inc., 5716-A Industry Lane, Frederick, MD 21704). These are integrating ionization chambers wherein the electret (permanently charged Teflon disk) serves both as a source of electrostatic field and as a sensor. It consists of an electret mounted inside a small chamber of 50 mL made out of conducting plastic. The ions produced inside the chamber are collected onto the electret causing a reduction of the surface charge on the electret. The reduction in charge is a measure of the ionization integrated over a period of exposure to alpha particles emitted by the decay process of radon gas and its decay products. The exposure period was 4 d.

Soil samples were collected with 10 cm step up to a depth of 1.5 m. Standard soil analysis was performed in each sample (determination of organic matter, sand, clay, etc.). Particle size distribution of soil samples was determined according to pipette method (Gee and Bauder 1986). Soil organic matter was determined by means of wet oxidation method (Nelson and Sommers 1982). In addition the ^{226}Ra activity per unit mass (Bq kg^{-1}) was measured in soil samples (of about 0.3 kg mass) collected every 5 cm depth up to a depth of 60 cm and also in one sample at a depth of 160 cm. The measurements were performed by standard gamma spectroscopy with a 50% relative efficiency high pure germanium detector. The ^{226}Ra activity was determined from the 352 keV gamma line of ^{214}Bi and the 609 keV gamma line of ^{214}Pb. This indirect determination of the ^{226}Ra activity requires the secular equilibrium between ^{226}Ra and its progeny ^{222}Rn, which can only be accomplished by hermetically sealing the samples and waiting for a time period not less than 20 d before the measurement. The uncertainty of the ^{226}Ra activity is about 20%.

EXPERIMENTAL RESULTS

First we will focus our attention to the temporal variation of the radon concentration in the soil as measured by the Barasol detector located in 85 cm depth, from October 2001 up to September 2004. Fig. 1 presents the mean monthly values of the radon concentration in the soil gas (in Bq m^{-3}). The uncertainty of each measurement is less than 2%. The mean value of all measurements is presented with a dashed line. It is clear in Fig. 1 that maximum values occur in winter months and minimum values in summer months. The above statement is also supported by the fact that a negative correlation was found between radon concentration and temperature of the soil as measured simultaneously by the Barasol detector (Fig. 2).

In order to study the horizontal variability of radon concentration in soil gas, the radon concentration in 50 cm depth was measured in 7 points (holes) with an horizontal step of 50 cm (Fig. 3). The horizontal variability of the radon concentration is within $\pm$11%.

As the radon source term is the soil gas is due to the radium content in the soil, it is interesting to study the ^{226}Ra concentration (Bq kg^{-1}) as a function of the soil depth. The ^{226}Ra concentration (Bq kg^{-1}) as a function of the soil depth is shown in Fig. 4. Within the error bars, no big difference of the ^{226}Ra concentration (Bq kg^{-1}) at the different soil depths is observed.

The radon concentration as a function of the soil depth was measured in the same location twice. The first time was between 18 October 2002 to 10 May 2003 and the second time between 28 November 2003 to 20 September 2004. The radon concentration, as a function of the soil depth for these two time periods, is presented in Fig. 5. Despite the differences of the absolute values between the two curves, both curves have the same form. In both radon distributions, radon increases up to a soil

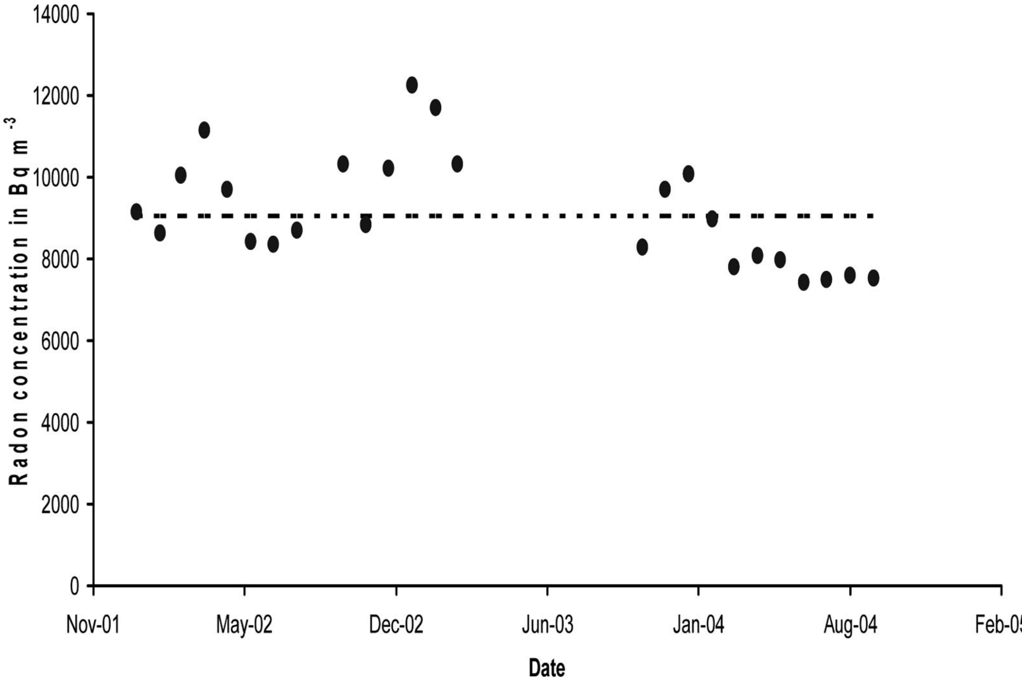

Fig. 1. Mean monthly values of the radon concentration in the soil gas (in Bq m^{-3}) as measured by the Barasol detector located at 85 cm depth, from October 2001 up to September 2004. The dashed line gives the mean value of all measurements.

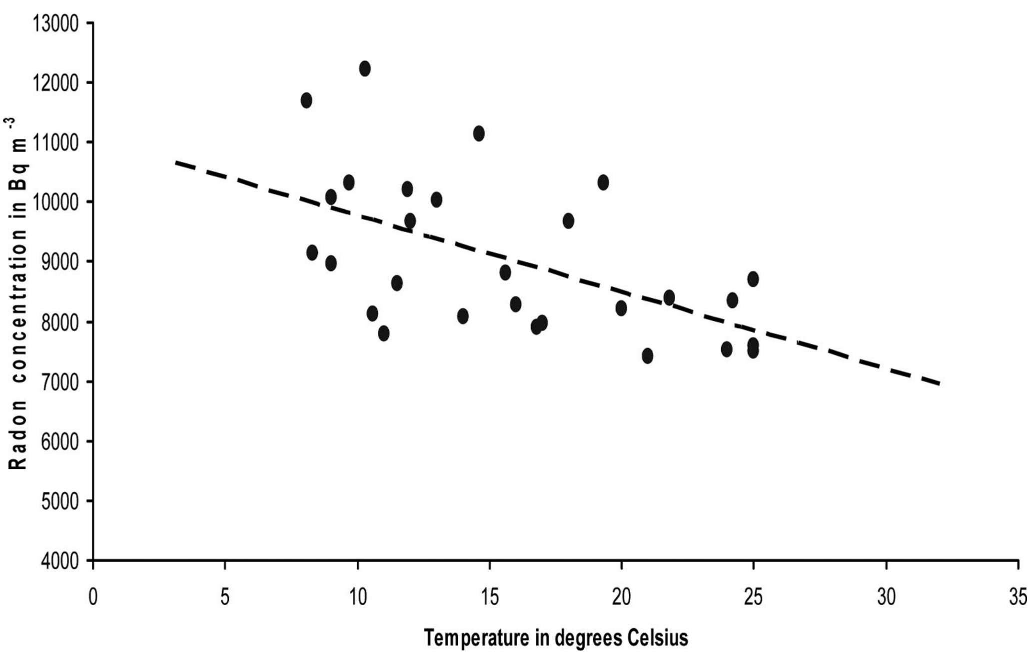

Fig. 2. Correlation between mean monthly values of radon concentration in the soil gas (in Bq m^{-3}) and the temperature, as measured simultaneously by the Barasol detector located in 85 cm depth, from October 2001 up to September 2004. The dashed line presents the best fit passing through the experimental points.

depth of about 80 cm, seems to remain constant at depths of 80–130 cm, and then increases again. This behavior is not commonly found. The expected behavior is a monotonous increase of the radon concentration with the soil depth, which levels off to a saturation value. In order to explain the experimental radon distribution, the general transport equation (diffusion and advection) was solved. The results obtained are presented in the following section.

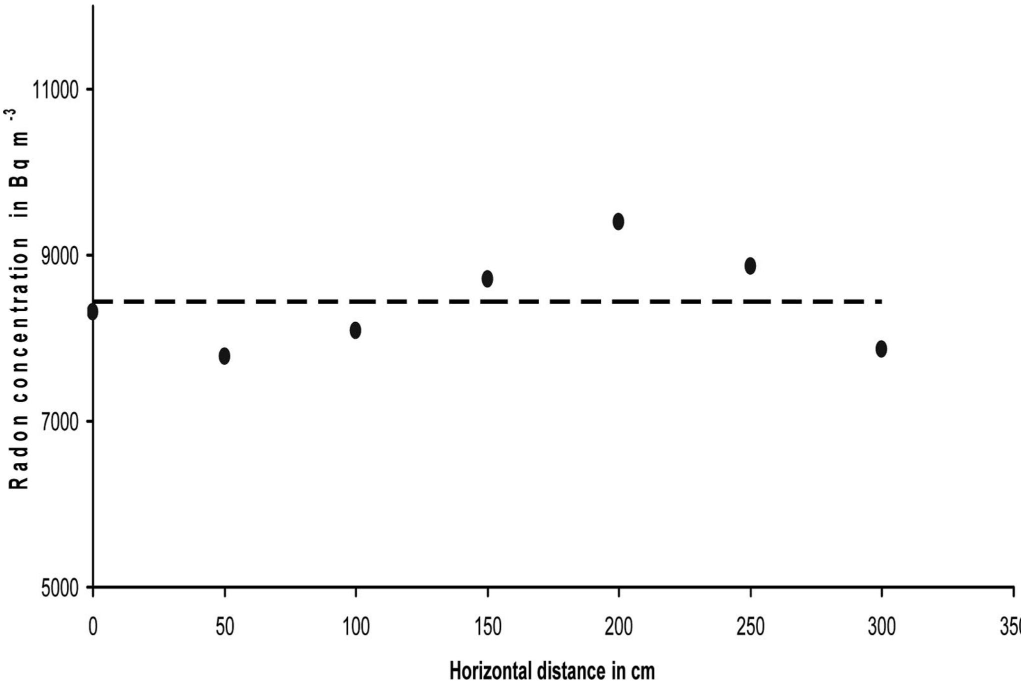

Fig. 3. Horizontal variability of radon concentration at 50 cm depth. The dashed line is the mean value of all measurements.

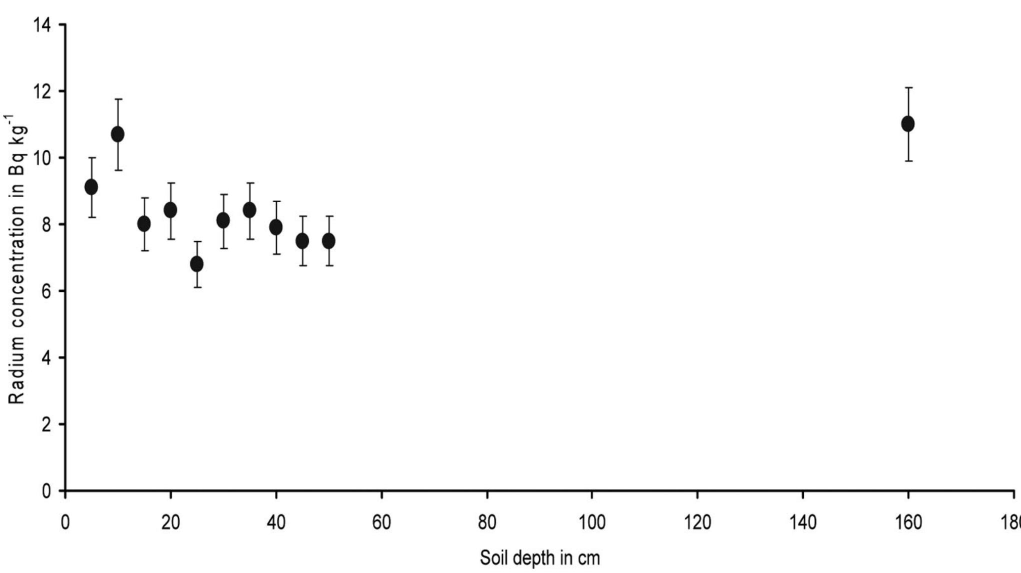

Fig. 4. ^{226}Ra concentration (in Bq kg^{-1}) as a function of the soil depth.

MATHEMATICAL DESCRIPTION

The migration equation

The general migration equation (diffusion and advection) reads:

$$\frac{\partial I}{\partial t} = \nabla(D\nabla I) - \upsilon\nabla I - \lambda I + P, \qquad (1)$$

where I is the radon volumetric activity in the gas phase (Bq m^{-3} of pore air), D is the effective diffusion coefficient (m^2 s^{-1}), υ is the effective advective velocity of radon in soil (m s^{-1}), λ is the radon decay constant (s^{-1}), and P is the radon production rate (Bq m^{-3} s^{-1}), as expressed in eqn (2a):

$$P = FA_{Ra}\lambda\rho, \qquad (2a)$$

where F is the effective emanation factor, A_{Ra} is the radium content of soil (Bq kg^{-1}), and ρ is the soil dry density. Effective coefficients are described in Nazaroff

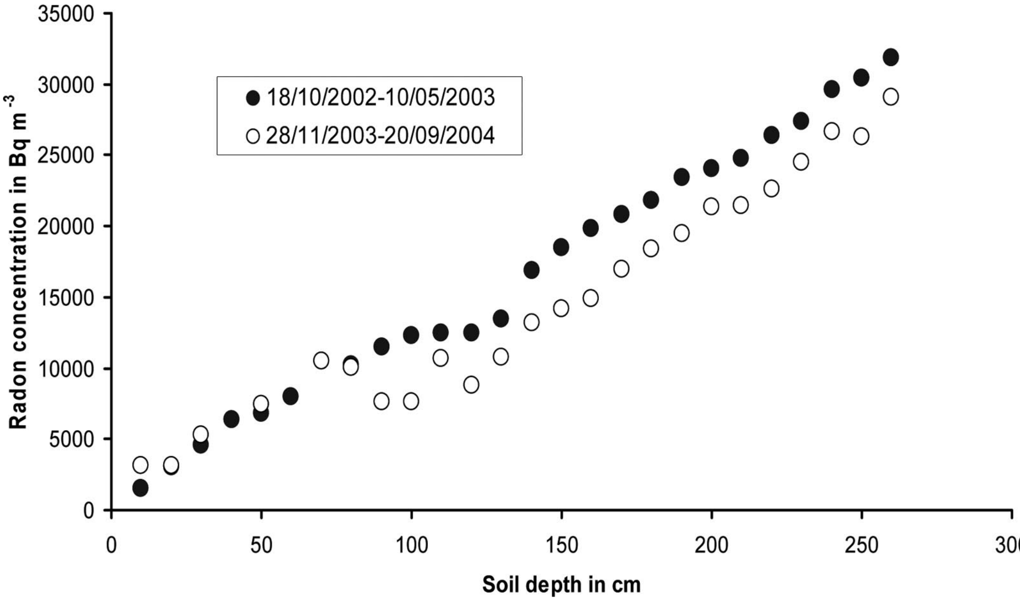

Fig. 5. Radon concentration (in Bq m^{-3}) as a function of the soil depth.

(1992). Following Nazaroff (1992) the effective emanation factor F is given by:

$$F = f/(\varepsilon_\alpha + k\varepsilon_w + K\rho), \qquad (2b)$$

where f is the well known emanation coefficient, ε_α is the air filled porosity, ε_w is the water filled porosity, k is the aqueous-gaseous partition coefficient, and K the sorbed-gaseous partition coefficient.

In eqn (1) it is assumed that the velocity υ is constant, independent of the position in the soil. Let us consider the one dimensional problem in homogeneous soil:

$$\frac{\partial I}{\partial t} = D\frac{\partial^2 I}{\partial z^2} - \upsilon\frac{\partial I}{\partial z} - \lambda I + \lambda I_\infty. \qquad (3)$$

In eqn (3) it is $I_\infty = F A_{Ra} \rho$. The soil surface is at $z = 0$ and increasing positive z corresponds to increasing depth in the soil. The general solution of eqn (3) at steady state, i.e., for $\partial I/\partial t = 0$, reads,

$$I(z) = \mathrm{A}e^{-az} + \mathrm{B}e^{(\upsilon/D + a)z} + I_\infty, \qquad (4)$$

where constants A and B are determined by the boundary conditions and a is the positive root of the equation:

$$Da^2 + \upsilon a - \lambda = 0 \qquad (5)$$

i.e.,

$$a = -\upsilon/2D + [(\upsilon/2D)^2 + \lambda/D]^{1/2}. \qquad (6)$$

Single homogeneous soil layer

Let us apply the (almost universally used in the literature) boundary condition at $z = 0$:

$$I(0) = 0 \qquad (7)$$

and

$$\left.\frac{dI}{dz}\right|_{z=\infty} = 0, \qquad (8)$$

which is equivalent to the requirement of finite $I(\infty)$. Applying these boundary equations to eqn (4), $I(z)$ reads

$$I(z) = I_\infty(1 - e^{-az}) \qquad (9)$$

where $I_\infty = FA_{Ra}\rho$ is I at $z = \infty$.

In case of a pure diffusion model, i.e., setting $\upsilon = 0$ in eqn (3), it can be seen from eqn (5) that

$$I(z) = I_\infty(1 - e^{-z/L_D}) \qquad (10)$$

$$L_D = (D/\lambda)^{1/2}, \qquad (11)$$

which is the well known solution of the diffusion model and L_D is the diffusion length. In the case of a pure advection model, i.e., setting $D = 0$ in eqn (3), it follows from eqn (5) that

$$I(z) = I_\infty(1 - e^{-z/L_A}) \qquad (12)$$

$$L_A = \upsilon/\lambda, \qquad (13)$$

which is of exactly the same form with eqns (10) and (9), but now the characteristic "migration length" is L_A

of eqn (13). In the case of the diffusion-advection model, the migration length is $L_{DA} = 1/a$, with a that of eqn (6) and

$$I(z) = I_\infty(1 - e^{-z/L_{DA}}). \qquad (14)$$

Usually the experimental data are fitted with the model solution and the corresponding characteristic length is determined. In the case of the diffusion-advection model, the data would determine a. It is clear from eqn (6) that given a value of a there is a set of infinite pairs (D, υ) that satisfy eqn (6), including the pairs ($D = \lambda/\alpha^2$, $\upsilon = 0$) corresponding to pure diffusion and ($D = 0$, $\upsilon = \lambda/\alpha$) corresponding to pure advection. In other words, it is not possible to deduce the actual pair (D, υ) from a measured profile. The only parameter that can be determined from a measured $I(z)$ is a, and this should be sufficient. The fact that all three models (pure diffusion model, pure advection model, diffusion-advection model) provide the same form of $I(z)$ (eqns 10, 12, and 14) suggests that the diffusion advection model can be substituted by a pure diffusion model, with an equivalent diffusion coefficient D_e, defined as:

$$\sqrt{\frac{\lambda}{D_e}} = a = -\frac{\upsilon}{2D} + \sqrt{\left(\frac{\upsilon}{2D}\right)^2 + \frac{\lambda}{D}}. \qquad (15)$$

The form of $I(z)$ given by the three models describes a monotonous increase of the radon concentration as a function of the soil depth, which levels off to a saturation value. This behavior is not the one observed experimentally (Fig. 5); therefore, the single homogeneous soil layer model cannot explain the experimental results.

Two soil layers

The experimental profile $I(z)$ of radon concentration in the soil (Fig. 5), in particular the change of curvatures and the fact that the profile does not lead to saturation, indicates the existence of two or three soil layers with different soil matrices. Following this observation soil samples were analyzed. The moisture content at different soil depths was not measured, as this changes strongly with time and the radon measurements were done over a period of about a year. However, moisture content strongly affects radon migration. Soil particle distribution (in %) is presented in Fig. 6, where it can be seen that at the soil depth of about 60–70 cm there is an inversion of the curves (clay concentration becomes higher than sand) and, for depths higher than 100 cm, sand and clay concentrations remain practically constant. The change of curvatures of the radon concentration profile has been observed (Fig. 5) at about the same depth. This is a strong indication that there are at least two soil layers.

Following these observations we considered a two-layer soil model (Fig. 7). Let the soil consist of two layers, with significantly different soil matrices, with respect to radon migration, and with interface at

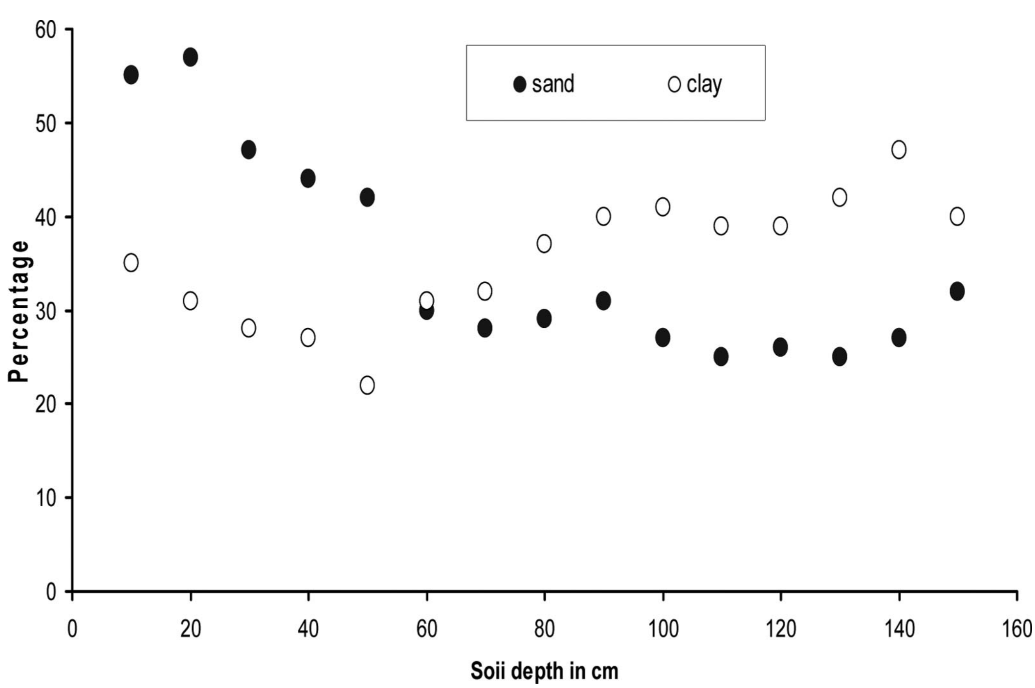

Fig. 6. Soil particle distribution (sand and clay) as function of the soil depth.

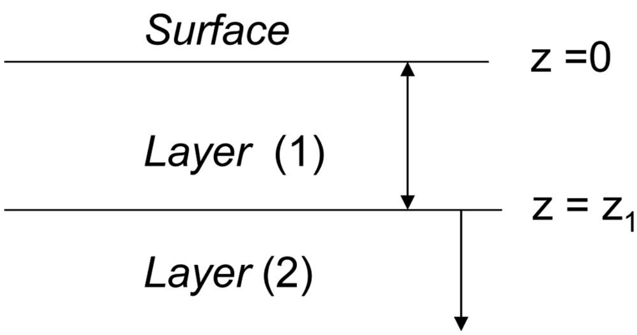

Fig. 7. Two soil layers with different soil matrices.

$z = z_1$. Following the discussion of the previous section we will use a diffusion model on the understanding that the diffusion coefficient D is the equivalent coefficient D_e defined by eqn (15). Indices 1, 2 will refer to layers 1, 2, respectively. The boundary conditions used here are:

$$I_1(0) = 0 \tag{16}$$

$$\left.\frac{dI_2}{dz}\right|_{z=\infty} = 0 \tag{17}$$

$$I_1(z_1) = I_2(z_1) \tag{18}$$

$$D_1\frac{dI_1(z_1)}{dz} = D_2\frac{dI_2(z)}{dz}. \tag{19}$$

Conditions in eqns (16) and (17) are the same as in the single soil layer approach (eqns 7 and 8, respectively). In addition, we have also the conditions in eqns (18) and (19), which enforce continuity of I and of the current $D\ dI/dz$ at the layers interface $z = z_1$. With these boundary conditions $I_1(z)$ and $I_2(z)$ read

$$I_1 = A_1(e^{-a_1z} - e^{a_1z}) - b_1(e^{a_1z} - 1) \tag{20}$$

$$I_2(z) = A_2e^{-a_2z} + I_{2\infty} \tag{21}$$

$$I_{1\infty} = b_1 = F_1A_{Ra1}\rho_1 \qquad I_{2\infty} = b_2 = F_2A_{Ra2}\rho_2 \tag{22}$$

$$A_1 = \frac{a_2D_2(b_1 - I_{2\infty}) - (a_2D_2 + a_1D_1)b_1e^{a_1z_1}}{(a_1D_1 - a_2D_2)e^{-a_1z_1} + (a_2D_2 + a_1D_1)e^{a_1z_1}} \tag{23}$$

$$A_2 = A_1[e^{(a_2 - a_1)z_1} - e^{(a_1 + a_2)z_1}] - b_1e^{(a_1 + a_2)z_1} + (b_1 - I_{2\infty})e^{a_2z_1}, \tag{24}$$

where a_1 and a_2 are given by eqn (15) and F, A_{Ra}, and ρ are the effective emanation factor, activity (Bq kg^{-1}) of radium, and soil density, respectively. In case layer 2 is identical to layer 1, eqns (20) and (21) reduce to eqn (9), as they should.

The parameters controlling eqns (20) and (21) are a_1, a_2, D_1, D_2, b_1 and $I_{2\infty}$. For a qualitative understanding of eqns (20) and (21) let us proceed with the following approximations. For z_1 large enough, $\exp(a_1z_1)$ is at least one order of magnitude larger than $\exp(-a_1z_1)$ and, in addition, $\exp(-a_1z_1)$ is much smaller than 1. Taking also into account that $D = \lambda/a^2$ (eqn 15) it follows that

$$A_1 \approx -b_1 + [a_1/(a_1 + a_2)](b_1 - I_{2\infty}) \times e^{-a_1z_1} \approx -b_1 \tag{25}$$

$$A_2 \approx (b_1 - I_{2\infty})e^{a_2z_1}. \tag{26}$$

With these approximations $I_1(z)$ and $I_2(z)$ read

$$I_1(z) \cong I_{1\infty}(1 - e^{-a_1z}) \qquad 0 \leq z \leq z_1 \tag{27}$$

$$I_2(z) \cong I_{2\infty} - (I_{2\infty} - I_{1\infty})e^{-a_2(z - z_1)} \qquad z_1 < z. \tag{28}$$

From the experimental profile we assume that $z_1 = 130$ cm. For $0 \leq z \leq 130$ cm we fit the experimental profile with eqn (27) and for $z > 130$ cm with eqn (28). For the first soil layer the parameters which best fit the experimental data are $a_1 = 0.009$ cm^{-1} and $I_{1\infty} = 20{,}000$ Bq m^{-3}. But as $I_{1\infty}$ is taken also into account in eqn (28) (second layer), we found that the best set of parameters which fit the whole experimental profile is $a_1 = 0.014$ cm^{-1}, $I_{1\infty} = 16{,}000$ Bq m^{-3}, $a_2 = 0.0055$ cm^{-1}, and $I_{2\infty} = 41{,}000$ Bq m^{-3}. The results are presented in Fig. 8. The experimental points refer to the first series of measurements (18 October 2002 to 10 May 2003). It can be seen from Fig. 8 that the model fits satisfactorily the measured profile up to a depth of about 230 cm. The change of curvature at 240 cm, and the fact that the profile does not lead to saturation, indicate perhaps the existence of a 3rd soil matrix, starting at depth of about 2.4 m.

The same procedure was also applied to the experimental measurements of the second period (28 November 2003 to 20 September 2004). The results are presented in Fig. 9. The parameters used in the model in order to fit the experimental profile are $a_1 = 0.02$ cm^{-1}, $I_{1\infty} = 11{,}000$ Bq m^{-3}, $a_2 = 0.0055$ cm^{-1}, and $I_{2\infty} = 41{,}000$ Bq m^{-3}. The values of a_2 and $I_{2\infty}$ are identical with those reported previously and used in the model in order to fit the first experimental profile (Fig. 8). However, for the values of a_1 and $I_{1\infty}$ there is

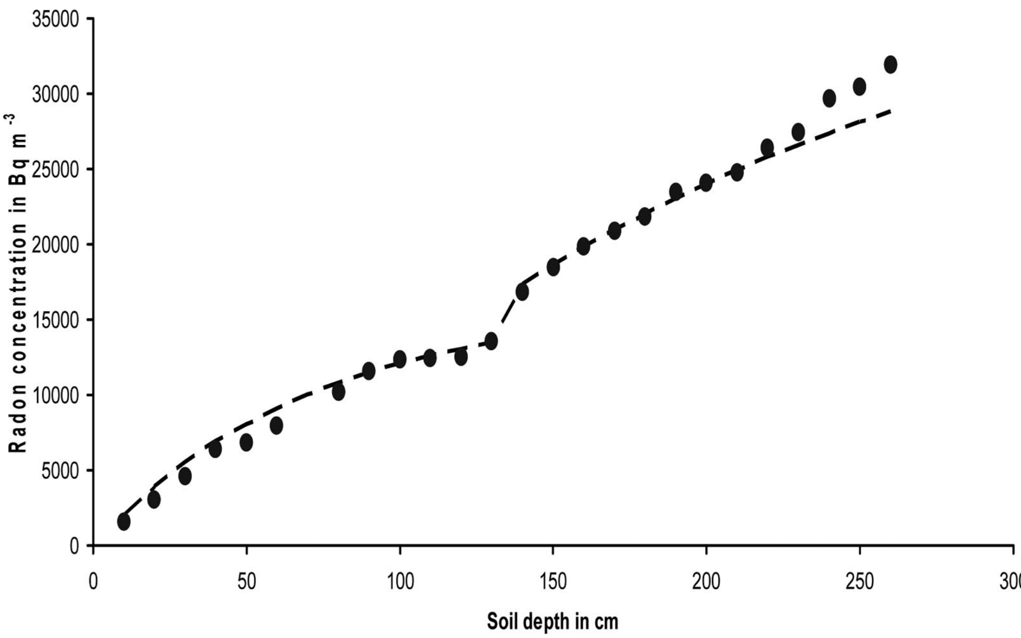

Fig. 8. First experimental profile (points) measured during 18 October 2002 to 10 May 2003 and two soil layers model (dashed line).

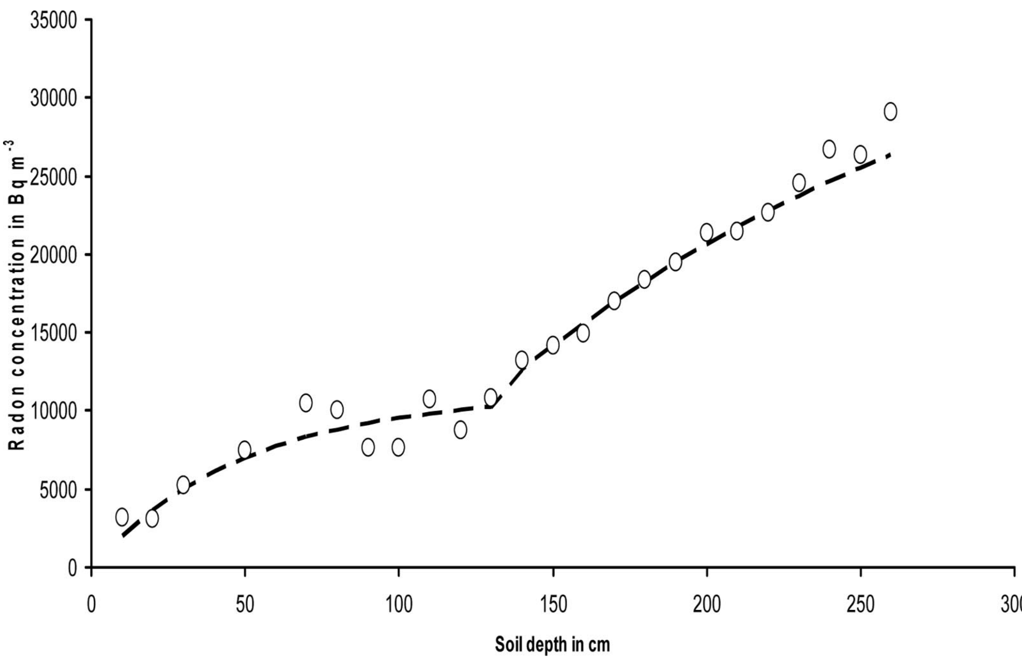

Fig. 9. Second experimental profile (points) measured during 28 November 2003 to 20 September 2004 and two soil layers model (dashed line).

a difference of about 30%. As a conclusion, the two soil layers model can reproduce satisfactorily both experimental profiles.

Discussion about the boundary conditions—radon concentration at the soil surface

The simple two soil layers model used (eqns 27 and 28), supported by the soil analysis, could satisfactorily fit the measured profile. However, if the interest is in the radon concentration at the soil surface, it is clear that the usually used boundary condition $I(0) = 0$ (eqn 7) not only gives zero radon concentration at the soil surface, but also neglects the contribution of advection to the radon current at the surface of the soil. Therefore, the boundary condition $I(0) = 0$ is conceptually not appropriate.

A boundary condition relating the rate of transfer of a passive scalar across the surface of soil to the air depends on the relative concentration of the scalar on the surface of the soil and in the bulk of the air. Consider a stream of air passing over the surface of the soil and let S_o be the concentration of the scalar on the soil surface and S_b the concentration of the scalar over the boundary layer of the flow of the air. The simplest reasonable assumption is that the rate of exchange is proportional to the difference $S_o - S_b$ (Crank 1975). Applying this to the case of radon transfer from soil to air, the corresponding boundary condition would read

$$\left.\frac{dI}{dz}\right|_{z=0} = k(I_o - I_b), \tag{29}$$

where k is a proportionality constant, I_o is the concentration (Bq m^{-3}) of radon at the soil surface ($z = 0$), and I_b the concentration in the bulk of air over the soil surface. Applying the boundary conditions in eqns (29) and (8) to eqn (4), $I(z)$ reads

$$I(z) = I_\infty - \frac{1}{1 + a/k}(I_\infty - I_b)e^{-az}. \tag{30}$$

Constants a and k can be deduced from the measured profile $I(z)$. It is certain that

$$I_b \ll I_o \ll I_\infty. \tag{31}$$

Therefore, I_b can in practice be neglected with respect to I_∞, hence eqn (30) can be practically approximated with

$$I(z) = I_\infty\left(1 - \frac{1}{1 + a/k}e^{-az}\right). \tag{32}$$

This gives

$$I(0) = I_\infty\left(1 - \frac{1}{1 + a/k}\right). \tag{33}$$

Least squares fitting of eqn (32) to the measured data (first experimental profile), up to a depth of $z_1 = 130$ cm (first soil layer), gave $a = 0.905$ m^{-1}, $k = 186$ m^{-1}, and $I_\infty = 20{,}000$ Bq m^{-3} (represented with a dashed line in Fig. 10). The $I(z)$ values, calculated by eqn (27) with $a = 0.9$ m^{-1} and $I_\infty = 20{,}000$ Bq m^{-3}, are presented (straight line) in the same figure for comparison reasons. The two curves almost coincide. Although eqn (27) is deduced with the non appropriate boundary condition $I(0) = 0$, the results of $I(z)$ obtained with this equation are identical with those obtained with eqn (32), away from the soil surface. However, eqn (27) gives at the soil surface a zero radon concentration (which of course is wrong). On the contrary, eqn (32) gives a radon concentration at the soil surface ($z = 0$), for the present experimental profile, $I(0) = 97$ Bq m^{-3}.

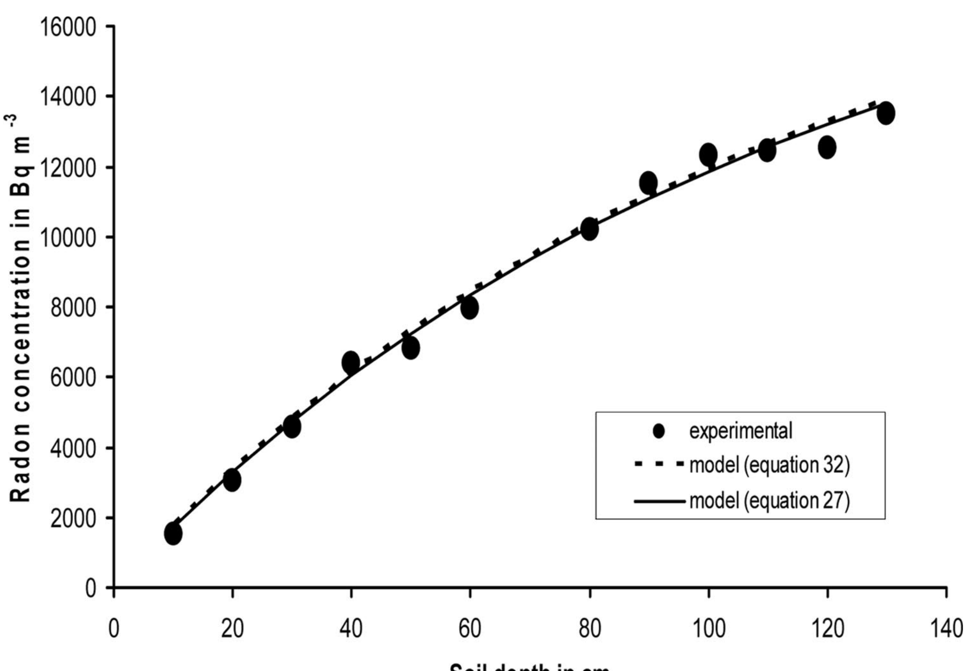

Fig. 10. Homogeneous soil models with different boundary conditions.

The determination of a from the radon profile gives the equivalent diffusion coefficient $D_e = \lambda / a^2$, which can then be used to estimate the radon current $J(z)$, which is important, for example for the estimation of radon entrance to dwellings:

$$J(z) = -D_e \frac{dI(z)}{dz}. \quad (34)$$

CONCLUSION

The main conclusions of the present work are as follows:

- Radon concentration in soil (fixed depth 85 cm) was measured from October 2001 up to September 2004. Maximum values occur in winter months and minimum values in summer months. Negative correlation was found between radon concentration and temperature of the soil;
- Radon concentration in 50 cm depth was measured in 7 points (holes) with a horizontal step of 50 cm. The horizontal variability of the radon concentration was found within $\pm 11\%$;
- ^{226}Ra concentration (Bq kg^{-1}) as function of the soil depth (0–160 cm) was found practically the same for all soil depths;
- Radon concentration as a function of the soil depth (0–260 cm) was measured in the same location twice. Despite the differences of the absolute values of the radon concentration between the two profiles, both profiles have the same form. In both radon distributions, radon concentration increases up to a soil depth of about 80 cm, seems to remain constant for a depth 80–130 cm, and then increases again. This behavior is not commonly found. The usually observed behavior is a monotonous increase of the radon concentration with the soil depth, which levels off to a saturation value;
- The experimental distribution was reproduced by solving the general transport equation (diffusion and advection). The diffusion and advection migration mechanism can be modeled by a diffusion only model with an appropriate equivalent diffusion coefficient. The main finding of the numerical investigation is that the aforementioned, experimentally observed, profile of radon concentration can be explained theoretically by the existence of two soil layers with different diffusion-advection characteristics. Soil sample analysis verified the existence of the two different type of soil layers;
- Particular attention was given to the first soil layer (0–130 cm). Different boundary conditions of the radon concentration at the soil surface were used for the solution of the diffusion-advection equation. It was found that the calculated radon concentration in the soil, away from the soil surface, is the same for the two boundary conditions used. However, the usually used boundary condition of zero radon concentration at the soil surface, $I(0) = 0$, cannot deduce from the experimental profile the radon concentration at the soil surface. On the contrary, with the use of a more appropriate boundary condition (eqn 29), the radon concentration at the soil surface could be deduced from the experimental profile; and
- From the experimental profile (radon concentration as a function of the soil depth for the first soil layer) the equivalent diffusion coefficient could be uncovered, which can then be used to estimate the radon current $J(z)$, which is important, for example for the estimation of radon entrance to dwellings.

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