Regularities research of radon transfer to underground enclosing buildings structures

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Abstract. Radon indoor build-up poses a serious health threat, increasing the risk of lung cancer in those exposed. Effective limitation of the radon intake from the soil is possible only through the modern building technologies and materials use with high radon-protective characteristics in the building underground part. The ensuring radiation safety complexity is that, depending on the instantaneous soil-atmosphere-building system state, both diffusion and convection can act as the radon intake dominant mechanism, and each of these transfer mechanisms requires its own radon protection measures set. In the article, the dominance areas of each transfer mechanisms are established on the theoretical researches, and an approach to determining the radon load on the building underground shell is proposed.

1. Introduction
The natural and artificial nature ionizing radiation continuously affects a person throughout his life. Nowadays, an almost completely individual annual effective radiation dose is formed by natural radiation sources, such as radon and its subsidiary decay products (SDP), cosmic radiation, external terrigenous radiation (natural background radiation), radionuclides in food and atmospheric air.

The greatest threat to public health is posed by exposure to radon and its SDP, which form more than half of the annual individual exposure dose to the population in most countries of the world. In this case, the negative radon effect and its decay products is manifested exclusively in buildings, in the atmospheric air the radon concentration is negligible.

2. Materials and methods
Nowadays, indoor exposure to subsidiary decay products is officially recognized as the second most severe (after smoking) death cause from lung cancer. Thus, according to the Environmental Protection Agency more than 7,000 people die annually in the United States due to lung diseases caused by the radon presence in buildings (for comparison, in car accidents – 23 000, in fires – 4 400 people) [1]. The national radon program in the UK has found that indoor radon is responsible for 2 000 lung cancer deaths per year [2]. Even in the Netherlands, the country with the lowest radon levels in buildings in Europe, about 400 people die annually from household exposure to radon [3].

Such statistics have led to the domestic exposure recognition to radon as a threat to the collective population health. Almost all countries in Europe and North America are implementing national radon programs, which purpose is to obtain reliable information on radon concentrations in homes and workplaces, with the subsequent measures development to reduce these concentrations to acceptable
values. A significant reduction in radon levels in housing was achieved due to building codes toughening in Finland and Ireland, whose territories are traditionally classified as radon-hazardous [4-5], the radon concentration determination is a mandatory element of the workplace certification procedure in Ireland. There is a two-level standard in the Russian Federation: the radon equivalent equilibrium volumetric activity (EEVA) should not exceed 200 Bq/m³ in existing buildings and 100 Bq/m³ in commissioned and reconstructed buildings [6-7].

Ensuring radon statutory levels is possible only if we understand the laws governing the radon environment formation in a building. It is known that for the implementation of an unfavorable radon situation in a building, it is simultaneously necessary to have a radon source in the immediate vicinity, driving forces that can transfer it towards underground structures, and ways for radon entry into the building.

Radon can be released from the enclosing structures materials, enter the room with water, gas and atmospheric air, but the only source that can lead to exceeding the established radon levels is the soil at the building base [8-10]. Effectively limiting the radon intake from the ground automatically ensures the building’s radon safety. The second most powerful source, the radon release from enclosing structures materials, is not able to increase the equivalent equilibrium volumetric activity (EEVA) of radon in an enclosed space by more than 15-20 Bq/m³ [11].

3. Results and discussion
Radon is formed in the soil pores from parent radium at a rate of G

\[ G = \rho_g \cdot \lambda \cdot \frac{E}{\varepsilon}, \] (1)

where \( \rho_g \) - soil density, kg/m³; \( \lambda = 2.09 \cdot 10^{-6} \) c⁻¹ – radon decay constant; \( E \) – radon emanation rate, Bq / kg; \( \varepsilon \) – soil sponginess

The radon emanation rate \( E \) is determined by the radium content in soil grains. However, not all of the formed radon atoms will fall into the pore space; some of them will end up inside other grains and will not take part in the transfer to the surface. The radon atoms fraction that is able to participate in the further activity transfer is described by the emanation coefficient \( k_{em} \). Thus, the radon emanation rate is

\[ E = C_{Ra} \cdot k_{em}, \] (2)

where \( C_{Ra} \) – specific activity of radium in soil, Bq / kg.

Since radium is contained only in soil grains, then in the calculation, the grain density can be used instead of the total density

\[ \rho_s = (1 - \varepsilon) \cdot \rho_{gr}, \] (3)

where \( \rho_s = 2 \, 650 \) kg/m³ – density of most grains [12].

The radon formation rate can be written in the form (4) taking into account (2) and (3)

\[ G = C_{Ra} \cdot \rho_{gr} \cdot k_{em} \cdot \lambda \cdot \frac{1 - \varepsilon}{\varepsilon}. \] (4)

The radon formed in the soil under the differences influence in concentrations and pressures is transferred towards the day surface, from which it enters the atmosphere. If underground horizontal enclosing buildings structures are on the transfer path, then they prevent the radon discharge into the atmosphere, as a result a drop in radon activities is formed at the outer structures boundaries \( \Delta A \)

\[ \Delta A = A_s(h) - A_s, \] (5)

where \( A_s \) – volumetric radon activity in indoor air, Bq/m³; \( A_s(h) \) –the radon volumetric activity in the soil at the foundation depth \( h \), Bq/m³.
It is this difference $\Delta A$ that is the main driving force behind the radon entry into the indoor air. But given that the radon activity in soil air is higher than its activity in indoor air, it can be considered

$$\Delta A \approx A_s(h)$$  \hspace{1cm} (6)

and then $A_s(h)$ is the radon load on the underground building envelope.

Buildings under construction should comply with the requirements [6] for radon levels in indoor air, which is achieved by designing underground enclosing structures with the required radon protection characteristics. The radon load $A_s(h)$ is the initial data when calculating the sufficient resistance to floor structure radon penetration. Its accurate calculation will avoid the buildings commissioning with insufficient or significantly excessive radon protection properties since it cannot be measured directly [6].

The radon load $A_s(h)$, first of all, depends on the radium content in the soil and the mechanism by which radon is transferred in the soil mass: diffusion or convective [2]. The radium content in soils is not constant; it depends on the underlying rock radiochemical composition, climatic, landscape, geophysical and other features. The radium specific activity is in the range of 25-50 Bq/kg for most soils.

A gamma-spectrometric soil analysis widely represented in Moscow (moraine loam) was carried out in the radiation safety in construction laboratory of the Research Institute of Building Physics. According to its results, the radium specific activity value of was

$$C_{Ra} = 32.3 \pm 3.9 \text{ Bq/kg.}$$

The radon emanation coefficient for a given soil was determined on the same sample using the gamma method: an unsealed sample is placed in the spectrometer and at the initial moment the radium specific activity $C_{Ra,1}$ is recorded. The final value of the radium specific activity $C_{Ra,2}$ is fixed, and the emanation coefficient is calculated by the formula

$$k_{em} = \frac{C_{Ra,2} - C_{Ra,1}}{C_{Ra,2}}$$ \hspace{1cm} (7)

The loam radon emanation coefficient was

$$K_{em} = (32.3 - 23.7)/32.3 = 0.27.$$

![Figure 1. The radon emanation coefficient determination.](image)

It is possible to estimate the changes range in the radon volumetric activity in soils knowing the changes range in the radium specific activity in soils and the emanation coefficient approximate value.

$$A_{max} = \frac{G}{\rho} = C_{Ra} \cdot \rho \cdot k_{em} \cdot \frac{1 - \varepsilon}{\varepsilon} = (20...50) \cdot 2650 \cdot 0.27 \cdot \frac{1 - 0.4}{0.4} = 21.4...53.7 \text{ Bq/m}^3.$$
Thus, the most typical range of radon activities in the soil air is from 20 to 50 Bq/m$^3$, although the radon volumetric activity can reach hundreds of Bq/m$^3$ for uranium-rich soils.

Along with the assessment of the volumetric activity of radon in the soil air, the dominant mechanism of radon transfer determination is extremely important for the accurate calculation of the radon protection underground building envelope characteristics.

Convective (or advective) radon transfer is caused by a temperature-induced pressure gradient (0.5 ... 2 Pa) along the soil depth and the convective flow is determined from Darcy's law

$$q_{con} = \frac{k}{\mu} \cdot \frac{\partial p}{\partial z} \cdot A,$$

where $k$ – soil air permeability, m$^2$; $\mu = 1.7 \cdot 10^{-5}$ Pa·s – dynamic air viscosity (at 10°C), Pa·s. The soil air permeability is also quite variable and its measurement presents certain difficulties. Table 1 shows typical values for air permeability for the most common soil types.

Table 1. Air permeability of some soils types [3].

| Soil type                     | Air permeability, m$^2$ |
|-------------------------------|-------------------------|
| Fine gravel                   | $10^{-8}$               |
| Coarse sand                   | $10^{-9}$               |
| Homogeneous medium sand       | $10^{-10}$              |
| Clean sand with gravel        | $10^{-11}$              |
| Clean fine sand               | $10^{-12}$              |
| Silty sand                    | $10^{-13}$              |
| Homogeneous sludge            | $10^{-14}$              |
| Sandy clay                    | $10^{-15}$              |

The pressure gradient in the soil is caused by the surface layers lower temperature; its value does not exceed 2 Pa/m [1]. The soils permeability lie in the range from $10^{-9}$ m$^2$ for fine gravel to $10^{-15}$ m$^2$ for dense clays as seen from the table 1, while all soils containing clay have a permeability below $10^{-12}$ m$^2$ [3]. Figure 2 shows a change graph in the convective flux according to (8); the volumetric radon activity in the soil air was taken equal to 30 000 Bq/m$^3$.

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Figure 2. The convective flow density dependence the on the soil permeability and the pressure gradient in it.

Diffusion transfer is caused by the radon concentration gradient $A$ along the soil depth, its value is described by Fick's law.
The diffusion flux remains practically constant, since the radon transfer to the day surface is compensated by its formation in the soil mass, and the changes in the radon concentration in the room are negligible compared to the radon concentration in the soil. The main difference between diffusion and convective intake is that no air gaps in the underground building envelope are required for its flow.

Figure 3 shows the dependence expressed (9) for a typical range of the radon diffusion coefficient in soils \((0,5\pm5)\cdot10^{-6} \text{ m}^2/\text{s}\) with radon activity in the soil from 20 to 60 Bq/m³ [7].

![Figure 3](image)

**Figure 3.** The density dependence of the diffusion flow on the physical and mechanical characteristics of the soil.

The convective flow becomes comparable to the diffusion flow at soil permeabilities of more than \(5\cdot10^{-12} \text{ m}^2\) as can be seen from a comparison in Figures 2 and 3, and at permeabilities of \(10^{-11} \text{ m}^2\) it is dominant. On the contrary, at permeability below \(10^{-12} \text{ m}^2\), radon transfer occurs through diffusion, the convection contribution is negligible and does not need to be taken into account. Thus, in all clay-containing soils, the radon load on the underground building envelope determination can be based on the diffusion transfer model.

The equation for one-dimensional diffusion transfer of radon in the soil has the form

\[
\frac{\partial A}{\partial t} = \frac{\partial}{\partial z} \left( D \cdot \frac{\partial A}{\partial z} \right) - \lambda A + G. \tag{10}
\]

The radon activities gradient practically does not change in magnitude as already noted above, that is, the diffusion transfer proceeds under quasi-stationary conditions, that is

\[
\frac{\partial A}{\partial t} \approx 0.
\]

Thus, equation (10) takes the form

\[
D \cdot \frac{\partial^2 A}{\partial z^2} - \lambda A + G = 0. \tag{11}
\]

The solution to this equation is given in [12]

\[
A(z) = A_{\text{max}} \cdot \left( 1 - e^{-\frac{z}{L_d}} \right) = A_{\text{max}} \cdot \left( 1 - e^{-\frac{z}{\sqrt{D_{\text{ef}}}}} \right), \tag{12}
\]

where \(L_d\) – radon diffusion length, m; \(D_{\text{ef}}\) – effective diffusion coefficient of radon associated with the volumetric coefficient by the ratio
\[ D = \varepsilon \cdot D_{ef}. \]  

(13)

For solving equation (11) the initial conditions were

\[ A(0) = 0 \text{ Bq/m}^3, \quad A(\infty) = \Lambda_{\max} \text{ Bq/m}^3. \]

Table 2 shows the effective diffusion coefficient and the radon diffusion length for the most common soil types.

**Table 2.** Diffusion length and effective radon diffusion coefficient in various soils [2].

| Soil type                                      | Effective diffusion coefficient \(D_{ef}\), \(\text{m}^2/\text{s}\) | Diffusion length \(L_{ed}\), \(\text{m}\) |
|-----------------------------------------------|--------------------------------------------------|----------------------------------|
| Seasonal banded clays in nature               | \((0,65...0,75) \cdot 10^{-6}\)                  | 0,56...0,60                      |
| Loams in natural conditions                   | \((1,0...3,0) \cdot 10^{-6}\)                    | 0,69...1,20                      |
| Clay sand, compacted                          | \(2,6 \cdot 10^{-6}\)                           | 1,11                             |
| Loam (moisture 5.7%, porosity 0.408)          | \(2,7 \cdot 10^{-6}\)                           | 1,13                             |
| Crushed eluvial-deluvial deposits in natural conditions | \(4,5 \cdot 10^{-6}\)                           | 1,46                             |
| Deluvial, slightly moist deposits in natural conditions | \(7,0 \cdot 10^{-6}\)                           | 1,83                             |

Substituting in (12) the foundation depth \(z=h\) and the soil characteristics at the building base \((D_{ef} \text{ or } L_d)\), it is possible to determine the volumetric activity on the outer horizontal underground enclosing structure boundary \(A\) (h), equal to the radon load on the foundation \(\Delta A\). The task is reduced to determining the required resistance to radon penetration of the floor structure in the future [4-8]

\[ R_{tot} = \frac{\Delta A}{q_{dif}}, \]  

(14)

The total resistance to floor structure radon penetration is determined by the number and physical layers characteristics. The total resistance to radon penetration between individual layers is broken down at the last stage according to the formula

\[ R_{tot} = \sum_{i=1}^{n} R_i = \sum_{i=1}^{n} \frac{1}{\sqrt{2D_{i,ef}}} \cdot sh \left( H_i \frac{\lambda}{\sqrt{D_{i,ef}}} \right), \]  

(15)

where \(n\) – layers number in the floor structure; \(H_i\) – layer thickness, \(m\); \(D_{i,ef}\) – effective diffusion radon coefficients in layer materials, \(\text{m}^2/\text{s}\).

They are most often limited to two layers with the highest radon protection characteristics (reinforced concrete and polymer films) in practice.

4. Conclusions

The proposed approach makes it possible to determine the required radon protection capacity of the underground building envelope by assessing the building site potential radon hazard without measuring the variable and uninformative radon flux density from the soil surface, which is currently legally enshrined as a criterion for the territory radon hazard.

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