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Application of numerical modelling for the better design of radon preventive and remedial measures

Martin Jiránek

Abstract. The main aim of the presented work was to verify, whether soil gas radon concentrations measured directly on building sites at a depth of 0.8 m below ground level and used in several countries for the design of protective measures against radon from the soil are in agreement with concentrations measured under houses after they had been built on a corresponding site. The correlation between sub-slab concentrations and concentrations measured at a depth of 0.8 m below the uncovered soil surface has been studied using a numerical simulation with the help of the computer program Radon2D. Numerical predictions showed that radon concentrations under the houses could be significantly different from concentrations measured on the building site and used for the assessment of radon risk categories. The highest differences were predicted for soil profiles with highly permeable upper layers. In the case of houses resting on the ground level the sub-slab radon concentration can be up to 3.4 times higher compared to the concentration measured at a depth of 0.8 m. An even higher increase was predicted for houses with the floor embedded 2 m below ground level. In this case the sub-floor concentrations increased up to 9.3 times. Numerical modelling can thus be considered as a powerful tool that can ensure the higher reliability of radon preventive and remedial measures.

Key words: radon • numerical modelling • radon concentration • radon prevention • radon remediation

M. Jiránek
Faculty of Civil Engineering,
Czech Technical University,
7 Thákurova Str., 166 29 Praha 6, Czech Republic,
Tel.: +420 224 354 806, Fax: +420 233 339 987,
E-mail: jiranek@fsv.cvut.cz

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Introduction

The risk of radon penetration from soils into buildings is in several countries (Czech Republic, Sweden, Germany, etc.) expressed by the radon index of the building site [5]. Its determination is based on the assessment of the soil permeability and soil gas radon concentration. Both parameters are measured directly on the particular building site at a depth of 0.8 m below ground level. The results of the radon index assessment are used for the design of protective measures against radon from the soil. It is usually assumed that the radon concentration under the house corresponds to the concentration measured at a depth of 0.8 m below the uncovered ground level. However, radon concentrations measured in the sub-floor layer under completed houses revealed that this assumption is mostly not true. We had found out that from 65 single family houses resting on the ground level radon concentrations measured in the sub-floor layer of 21 houses were up to 3.3 times higher than the concentrations measured in the soil around particular houses at a depth of 0.8 m.

Situations that could be especially dangerous are those, when the radon concentration under the real house is higher than the concentration measured during the assessment of the radon index of the building site. If the design of radon reduction techniques is based on values that are lower than concentrations corresponding to real conditions, the protection of buildings against radon from the soil can be seriously underestimated. In order to minimize the amount of ineffective measures the above-mentioned situations should be identified and responsible soil and house characteristics should be described. Numerical modelling can be very effective in predicting such situations, because it enables the analysis of various combinations of different parameters that could have an effect on the radon distribution in the soil and under the house. It would be almost impossible to formulate some general recommendations in this field without proper theoretical analysis.

Mathematical model

The effect of placing a house on the radon concentration field in the soil air under the house and in its vicinity was studied by numerical modelling with the help of the computer program Radon2D [2]. This program solves the well-known equation describing two dimensional (2D) steady state radon transport in a porous medium caused by diffusion and convection:

$$D_e \nabla^2 C - \frac{\vec{v}}{\varepsilon} \nabla C + G - \lambda_r C = 0 \tag{1}$$

with the radon generation rate defined as

$$G = \frac{a_{\mathrm{Ra}} \cdot \lambda_r \cdot \rho \cdot f}{\varepsilon} \tag{2}$$

where D_e is the effective radon diffusion coefficient [m^2/s]; C is the radon concentration in the soil gas [Bq/m^3]; G is the radon generation rate [$Bq/(m^3s)$]; $\vec{v}$ is the air flow velocity in a porous material [m/s]; λ_r is the radon decay constant [$2.1 \times 10^{-6}\ s^{-1}$]; ε is the porosity [dimensionless]; ρ is the bulk density of a material [kg/m^3]; f is the radon emanation coefficient [dimensionless] and a_{Ra} is the content of radium ^{226}Ra in the soil [Bq/kg].

The first term on the left-hand side of Eq. (1) represents radon transport due to diffusion, the second term describes convective transport, the third term expresses the increase of radon concentration in the soil pores due to the radon generation rate and the last term represents the drop in radon concentration due to its radioactive decay. The radon transport caused by water flow is neglected in Eq. (1) due to its minor importance. The validity of Eq. (1) is conditioned by the assumptions that the convection of air through the soil is caused only by the pressure difference, the air is incompressible and the airflow is laminar, i.e. the velocity of the airflow can be described by Darcy's law:

$$\vec{v} = -\frac{k}{\mu} \bar{\nabla} p \tag{3}$$

where μ is the dynamic viscosity of air [1.7×10^{-5} kg/(ms)]; p is the air pressure [Pa] and k is the soil permeability [m^2] characterizing the potential for radon and other gases to migrate through the soil. Permeability can be determined by direct measurements or by an expert evaluation of the soil [5]. In the case of soils with permeability usually lower than 10^{-8} m^2 and a pressure difference not higher than 50 Pa, the above-mentioned requirements are met.

The solution of Eq. (1) has been derived by means of the finite element method using the Petrov-Galerkin approach, which is based on the special selection of the weighting functions different from the interpolation functions [7]. The computer program Radon2D calculates the pressure field within the porous medium, the airflow velocity field and the radon concentration field. The reliability of the applied computer program Radon2D was verified on several soil profiles and also on six houses with different types of sub-slab depressurization systems [4]. The verification was based on the comparison of the calculated and measured values of underpressure and radon concentration in the soil gas. The accuracy of the model has been proved by the international comparison [1] and the sensitivity of the numerical solution to changes of particular parameters has been presented in [3].

Simulation of real conditions

Soil profiles

The distribution of the radon concentration in the soil air has been studied on nine soil profiles corresponding to real geological conditions. The width of the modelled soil blocks was 1 m and they reached to a depth of 5 m below the unbuilt soil surface. In order to be able to describe geological changes in the vertical direction, every soil profile consisted of six horizontal layers resting one above the other. Each layer was characterized by different thickness from 0.2 m to 1.0 m and different values of soil permeability, radon diffusion coefficient, radon generation rate and porosity. The values of these crucial parameters were chosen in such a way so that they reflected typical ranges, which can be measured in particular geological formations or which can be found in the literature [6]. Descriptions of all modelled soil profiles can be found in Table 1.

The boundary conditions used in the calculations were defined as close to typical values as was possible. Radon concentration in the deep soil gas was assumed to be under the constant value 145 kBq/m^3 (corresponding to the ratio between the radon generation rate G and radon decay constant λ) with the only exception for soil profile no. 7 where the concentration 23 kBq/m^3 was considered (this value corresponds again to the ratio G/λ). Radon concentration in the outdoor air was set to 20 Bq/m^3. The relative air pressure pe on the exterior surface of soil profile no. 9 was supposed to be 1 Pa and in the case of other soil profiles pe was 0 Pa. At the bottom of all soil profiles the relative air pressure ps was assumed to be 0 Pa.

Understructure of houses

Radon concentration fields in the soil under the houses have been studied by placing the understructure of a typical single-family house into each soil profile. Three positions of the house with respect to the ground level were considered – a house resting on the ground level, a house with the floor embedded 2 m below the

Table 1. Description of modelled soil profiles. Symbols: k – soil permeability [m^2]; D – radon diffusion coefficient [m^2/s]; G – radon generation rate [kBq/(m^{3}s)]

Soil profile	Soil layers arranged from the surface to the depth					
	1	2	3	4	5	6
1	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$
2	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$
3	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$
4	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$
5	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$
6	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 3 \times 10^{-4}$
7	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 5 \times 10^{-5}$
8	$k = 1 \times 10^{-14}$ $D = 3 \times 10^{-8}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$
9	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 1 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$	$k = 1 \times 10^{-10}$ $D = 3 \times 10^{-6}$ $G = 3 \times 10^{-4}$

ground level and a house with the floor raised 0.6 m above the ground level. Numerical models of each of the above-mentioned positions of the house in the soil used for simulation are shown in Figs. 1, 2 and 3. Due to symmetry, only the left-hand side of the houses was considered. Footers as well as the 100 mm thick slab placed between them and the basement walls were made of concrete. In some calculations a wall-floor joint of a

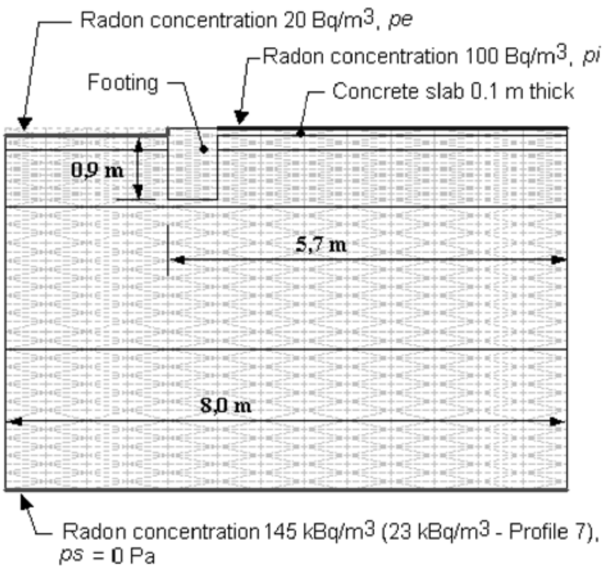

Fig. 1. Model of the house resting on the ground with applied boundary conditions and finite elements.

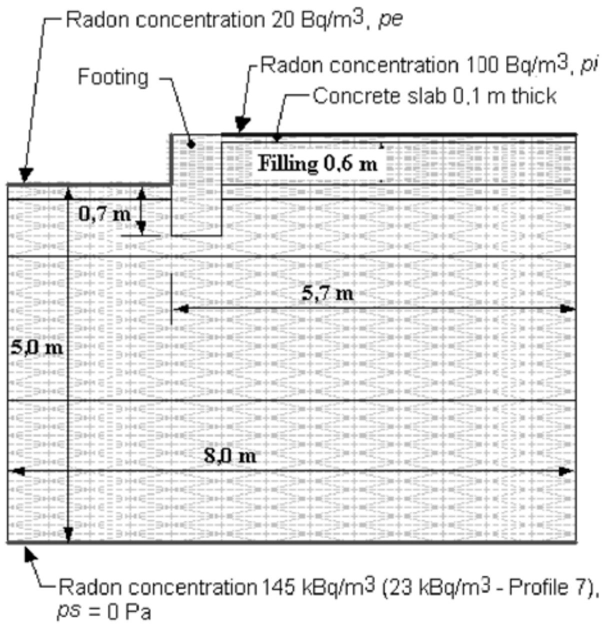

Fig. 2. Model of the house placed 0.6 m above the ground with applied boundary conditions and finite elements.

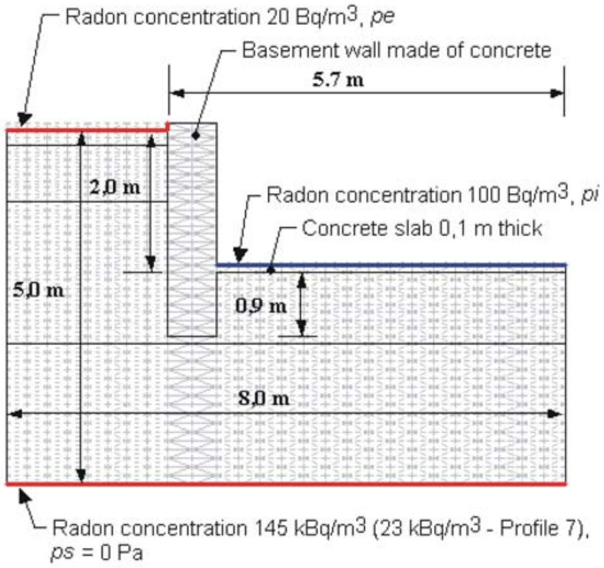

Fig. 3. Model of the house placed 2 m below the ground with applied boundary conditions and finite elements.

width of 1 up to 3 mm through which a convective flow of soil air into the house could occur was considered. Radon concentration inside the house was assumed to be under the constant value 100 Bq/m^3. Interior surfaces of the house substructure were gradually subjected to relative pressures *pi* 0 Pa, –2 Pa or –4 Pa, corresponding to typical values of underpressure generated indoors due to temperature differences and wind effects. The surface of the ground around the house was exposed to the relative pressure *pe* –2 Pa (lee-side of the house) or +2 Pa (windward side of the house).

Results

The numerical model described above was used to find out in which geological profiles placing a house will have a substantial influence on the soil gas radon concentration and on the other hand which profiles are not sensitive. Vertical distribution of radon concentration calculated for all soil profiles can be seen in Fig. 4, from which it is obvious that great differences exist between particular profiles. At a depth of 0.3 m below the soil surface concentrations vary from 10 to 70 kBq/m^3 and at a depth of 0.8 m (sampling depth for the assessment of the radon index of the building site) the dispersion is nearly the same – concentrations are within the range 15–75 kBq/m^3. The most significant differences (20–140 kBq/m^3) were predicted for a depth of 1.5 m. This can be attributed to the different permeability of the upper layers. Upper layers of low permeability reduce radon transport from deep soil towards the soil

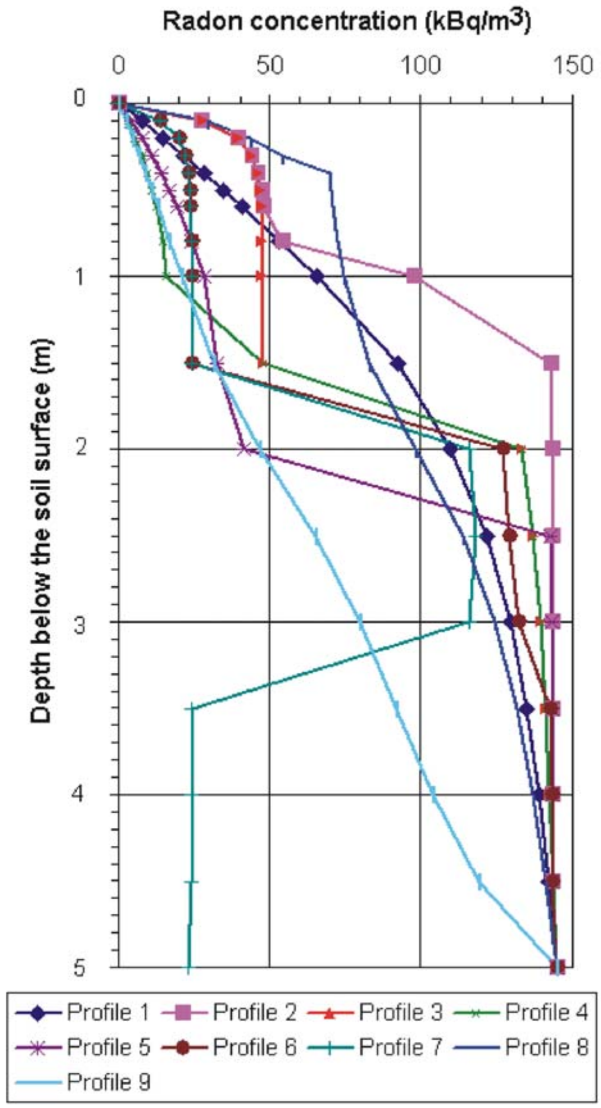

Fig. 4. Vertical distribution of radon concentrations calculated for all soil profiles.

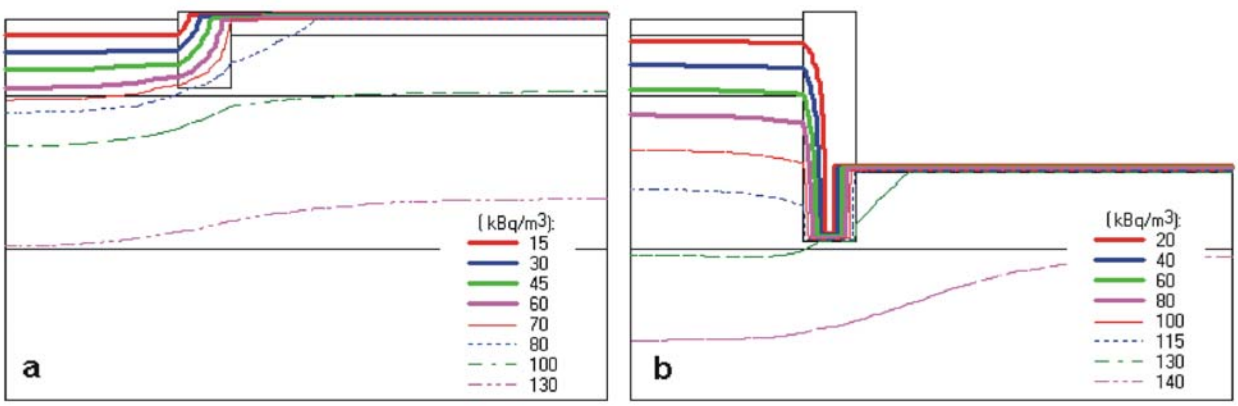

Fig. 5. Radon concentration fields predicted by the numerical simulation in highly permeable soils (profile no. 1) under the houses resting on the ground (a) and embedded 2 m below the ground level (b).

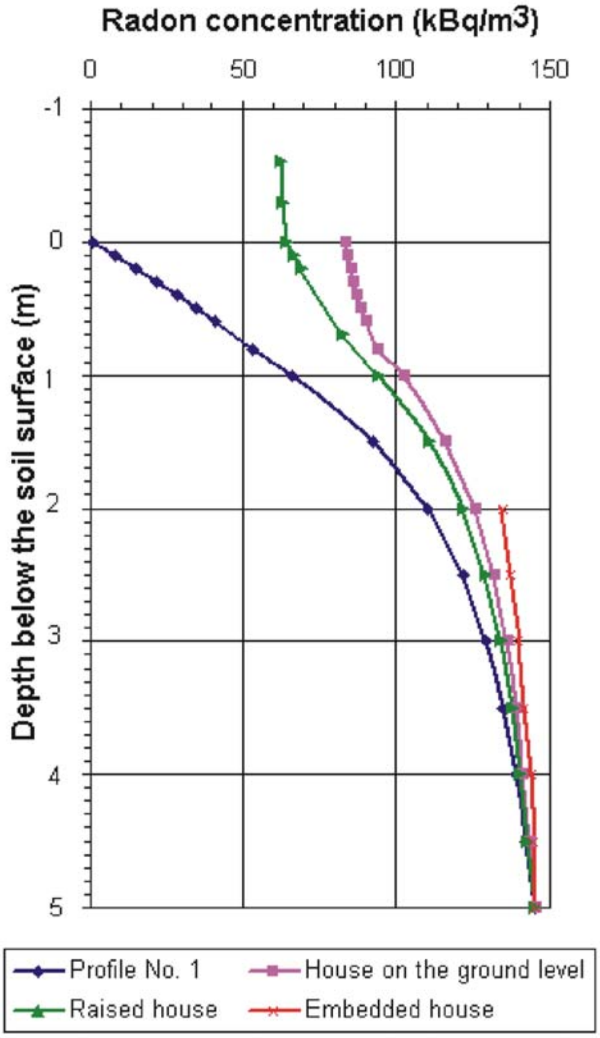

Fig. 6. Differences between the radon distributions within highly permeable soils caused by the placement of a house into different positions.

surface, which leads to higher radon concentration in deeper layers. On the other hand, highly permeable layers enable ventilation of the soil, which results in lower concentrations within the whole profile.

If a house is placed on the soil surface, its understructure eliminates the air exchange between the atmospheric air and soil air, and thus higher concentrations in the soil within the sub-house region should be achieved. The increase of the sub-floor concentrations will in a particular case depend on the air-tightness of the house understructure and permeability of upper layers. Even higher differences between the radon concentrations measured 0.8 m below the soil surface and sub-floor concentrations can be found for houses embedded several meters below the ground level, where completely different geological conditions can exist. The effect of placing a house into highly permeable soils (profile no. 1) can be seen from Figs. 5 and 6. Figure 5 shows quite clearly the deformation of the concentration fields caused by the understructure of houses, and from Fig. 6, the differences between sub-slab concentrations and concentrations measured 0.8 m below the soil surface can be identified. These differences are not apparent in the case of houses resting on soils of low permeability (Fig. 7), because as regards the ventilation of upper soil layers, low permeable soils function nearly in the same way as the house understructure. Numerical simulation comprising soil profiles with a different position of low permeable layers revealed that the distribution of the radon concentration in the soil is not affected by the placement of a building in all cases when the building rests on the layer of low permeability, no matter whether the deeper layers have low or high permeability. Analogically, it was confirmed that in all cases when the building is placed on the layer of high permeability the distribution of soil gas radon concentration would change (Fig. 8).

Differences between predicted sub-slab concentrations and predicted concentrations at a depth of 0.8 m below the unbuilt soil surface are for all soil profiles and all positions of the house in the soil presented in Figs. 9, 10 and 11.

In the case of houses with floors resting on the ground or raised 0.6 m above the ground higher sub-slab concentrations, compared to concentrations at a depth of 80 cm below the soil surface, are predicted for only 4 soil profiles – no. 1, 4, 5 and 9 (Figs. 9 and 11). In the remaining soil profiles sub-slab concentrations were from 0.3 up to 0.9 times lower. On the other hand, under the houses with floors embedded 2 m below the ground level sub-slab concentrations should be higher, according to numerical simulation in all soil profiles (Fig. 10).

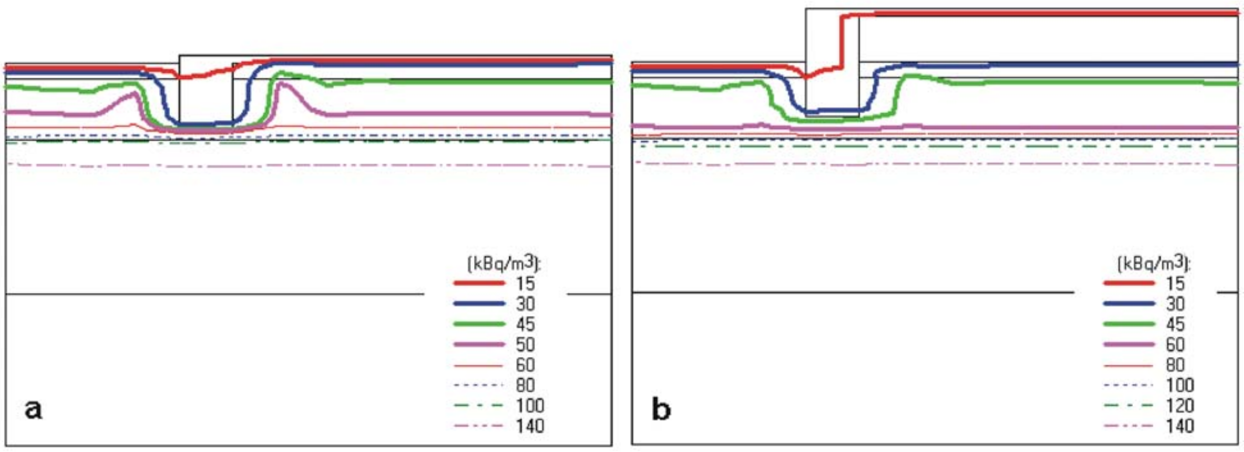

Fig. 7. Radon concentration fields predicted by the numerical simulation in soils of low permeability (profile no. 2) under the houses resting on the ground (a) and raised 0.6 m above the ground level (b).

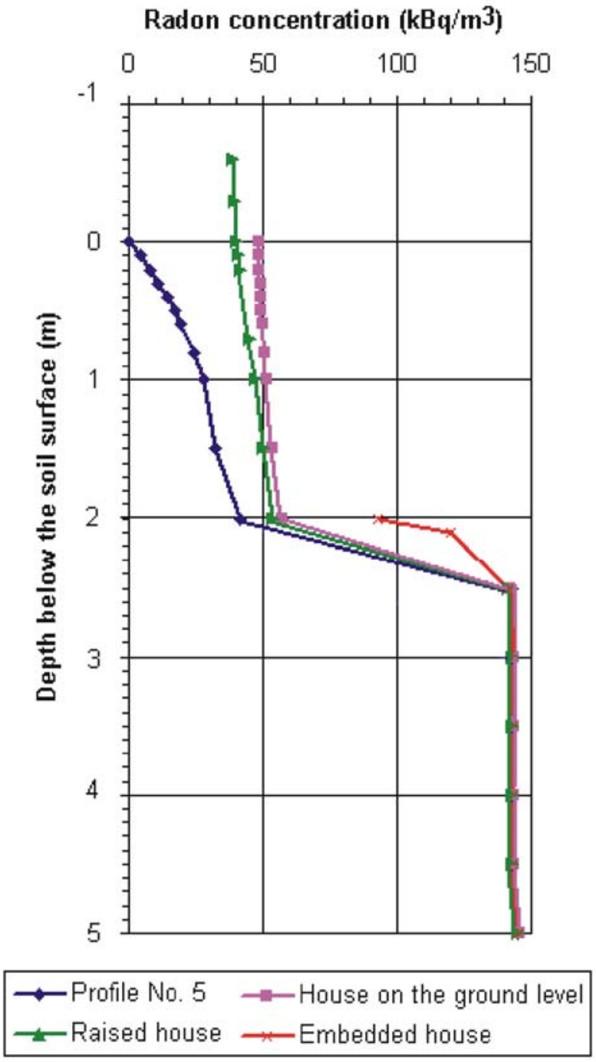

Fig. 8. Differences between the radon distributions within the soil profile no. 5 caused by the placement of a house into different positions.

Numerical simulation also revealed that the distribution of radon concentration in highly permeable soils under the house and in its vicinity is significantly influenced by indoor/outdoor and indoor/soil pressure

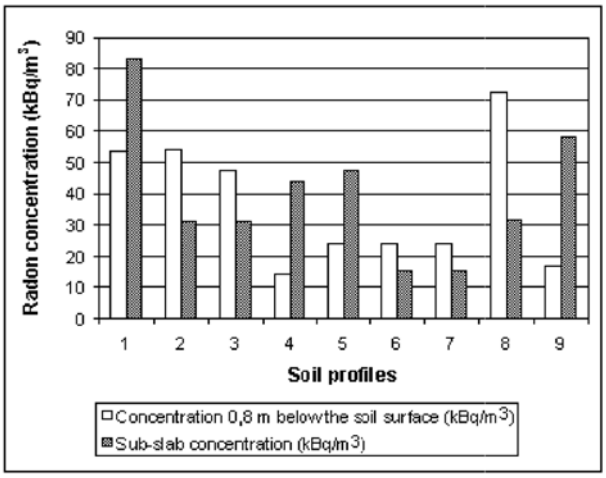

Fig. 9. House on the ground – correlation between simulated soil gas radon concentration at the depth 0.8 m and sub-slab concentration.

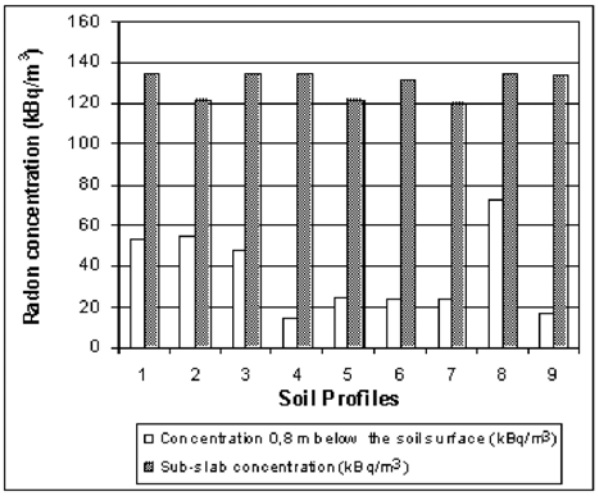

Fig. 10. House embedded 2 m below the ground level – correlation between simulated soil gas radon concentration at the depth 0.8 m and sub-slab concentration.

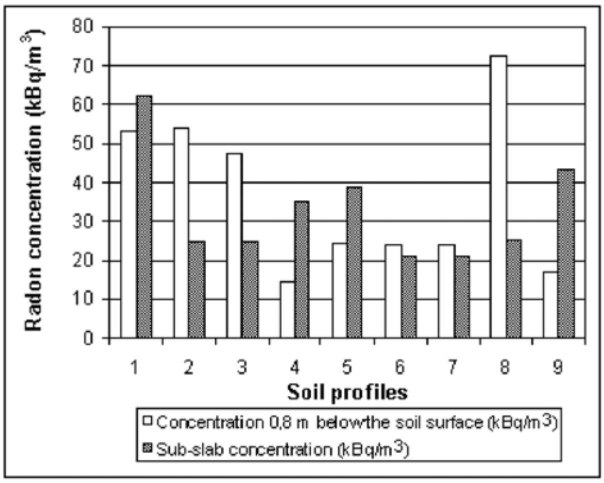

Fig. 11. House raised 0.6 m above the ground level – correlation between simulated soil gas radon concentration at the depth 0.8 m and sub-slab concentration.

differences. A slight positive pressure of 1 or 2 Pa on the ground surface decreases the radon concentration not only in the soil around the house, but also in the sub-floor layer. A slight underpressure on the ground surface increases the transport of radon rich air from deeper soil towards the soil surface, which results in higher concentrations of radon near the soil surface and under the house (Fig. 12). Underpressure between the house interior and the subsoil propagates through cracks in the substructure into the pore spaces of sub--floor layers and influences the radon concentration in the soil mainly in the vicinity of cracks. The higher the underpressure, the higher concentrations under the house can be achieved. On the other hand, radon distribution in the soil around the house is not affected by changes of indoor/soil pressure differences.

Conclusions

It can be concluded that any building placed into a highly permeable soil layer influences the radon distribution in the soil air under the building and in its vicin-

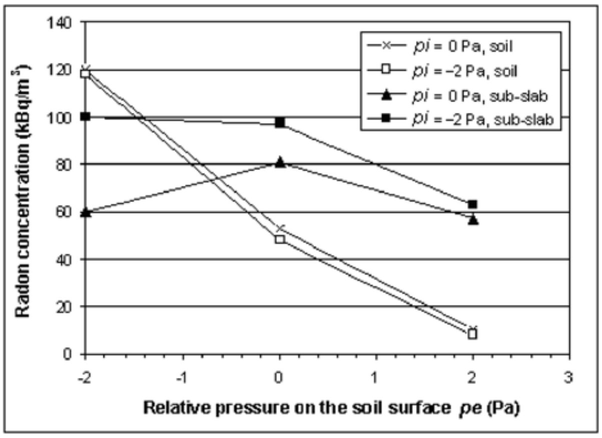

Fig. 12. Radon concentration in the soil outside the house in the depth 0.8 m below the soil surface and in the sub-slab layer in the distance of 2 m from the perimeter foundation in dependence on the relative pressure on the soil surface p_e and interior surfaces p_i.

ity. Soil gas radon concentrations under the houses can significantly differ from concentrations measured on the building site and used for the assessment of radon risk categories. The highest differences were predicted for soil profiles with highly permeable upper layers. We have found out that numerical modelling is a powerful tool applicable for the prediction and evaluation of such differences.

The results of numerical simulation showed that under the floor of the houses resting on the ground level soil gas radon concentration can be up to 3.4 times higher compared to the concentration measured at a depth of 0.8 m. This finding is in close agreement with our experimental results indicating that sub-floor concentrations can be up to 3.3 times higher. An even higher increase was predicted for houses with the floor embedded 2 m below the ground level. In this case, the sub-floor concentrations increased up to 9.3 times. In general, the smallest differences were observed for houses with floors raised 0.6 m above the ground level. Concentrations calculated in the sub-floor layer of such houses were a maximum 2.6 times higher compared to the values at a depth of 0.8 m. In particular cases the sub-floor radon concentrations are influenced mainly by the arrangement of soil layers of different permeability and radon production rate and by house parameters, such as the air-tightness of floors, underpressure within the house or the presence of highly permeable drainage layers made of coarse gravel under the house.

Numerical modelling based on reliable inputs describing soil conditions and house parameters can be used for the prediction of cases, when the sub-slab concentration is considerably higher than the concentration measured at a depth 0.8 m below the unbuilt soil surface. Model calculations can thus contribute to the improvement of the design of radon protective measures that are directly influenced by the radon concentration under the house. Among such measures occur radon-proof membranes (the thickness of the membrane is directly proportional to the radon concentration in the soil gas) and sub-slab or air gap ventilation systems. Numerical predictions can, therefore, ensure higher reliability and functionality of radon preventive and remedial measures.

Moreover, numerical calculations can constitute a theoretical background for detailed measurements *in situ*. Information, whether radon concentrations measured in the soil around the house can be influenced by the house itself and to what extent, is very useful for the correct interpretation of measured data.

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