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TECHNICAL REPORT

The Effect of Some Soil Characteristics on Soil Radon Concentration and Radon Exhalation from Soil Surface

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To find out the impacts of soil characters on radon concentrations in soil and radon exhalation from soil, field measurements on soil radon concentrations (60 cm under the soil surface) and radon exhalation rate from soil surface were carried out in totally 31 points with different types of soil in three cities in both South and North China. Soil radium contents, water contents, soil porosity and grain size were concretely analyzed in our laboratory. The linear simulation was used to analyze the above data. The results showed that radon exhalation rate from soil and radon concentrations in soil have direct proportion to soil radium contents. Rather high radium content and radon exhalation rate were measured in Guiyang area, 67±28 Bq/kg and 40±59 mBq/m^2·s, however no high soil radon concentration was found due to the difficulties in the measurements on clay soils with high water saturation. Compared with soil radium contents, radon exhalation rate from soil and soil radon concentrations are more easily impacted by soil characters and change in a rather large range.

KEYWORDS: radium content, soil characteristics, soil radon concentration, radon exhalation

I. Introduction

Radon (^{222}Rn) is the gaseous radioactive products of the decay of the radium isotopes ^{226}Ra, which is present in all terrestrial materials. Soil is the source of radon. In the bungalows and low buildings, the entry of radon coming from soil or rock is the main contributor to indoor radon levels.1) Therefore, it is necessary to study on the sources of radon for the evaluation of atmosphere radon levels, consequently.

The processes of radon generation and transport in porous materials, such as soil, involve emanation, diffusion, advection and adsorption. Radon concentrations in soil within a few meters of the surface of the ground and radon exhalation rates from soil surface are the important two parameters in determining radon rates of entry into pore spaces and subsequently in to the atmosphere. Radon concentration in soil and radon exhalation from soil surface depend on many physical parameters related to soil characters, such as radium contents, the internal structure of soil, grain size of soil, type of mineralization, soil porosity, soil permeability and emanation coefficient, *etc.*2,3) Synchronously, they may also be affected, directly or indirectly, by the weather factors such as air pressure and air temperature.4) Most aspects of the above processes have been characterized individually, however, for practical applications, complex study involves all the processes simultaneously is required.

The objective of this study was to analysis the impacts of soil characteristics on radon concentrations in soil and radon exhalation from soil surface. Theoretical review and analysis was done. Field measurements in totally 31 points were carried out, and four soil physical parameters, *i.e.*, radium contents, soil moisture saturation, porosity and grain size of soil samples collected from each area were measured. The correlativity within these results and parameters were analyzed and discussed.

II. Theoretical Review

1. Radium Contents

As the direct source of radon, the radium isotope ^{226}Ra content in soil is the most important factor in determining the level of soil radon and radon exhalation from soil surface. In a previous study, the authors even evaluated the soil radon level on the assumption that 1 Bq/kg radium is equivalent to 1,700 Bq/m^3 radon concentration in soil.6) For radon exhalation from soil surface, it has a direct proportion with soil radium content in many mathematical models even though it is also affected by some other factors as well.

2. Soil Water Content

The soil water content affects soil radon concentration mainly through its influence on radon emanation coefficient in soil. For general types of soil, the emanation coefficient reaches maximum at the water content of about 5%. In gravel, radon emanation reaches its maximum at about 1–2% water content, when the internal pores within the grains fill up. In clay, the specific grain surface areas are rather high, so fairly high water content as 10–15% are needed to cover all the surface.7) The above study also showed that water is assumed to occupy the adsorption sites of radon which leads to an increase in radon emanation.

The influence of soil water content on radon exhalation from soil surface is relatively complex. At a lower water content, the radon emanation increases with a increasing water content, which leads to an increase in the radon exhalation rate from soil surface. However, when certain water content is reached, the radon diffusion and advection process

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is largely weakened by the water in soil pores, which leads to a decrease in the radon exhalation rate from soil surface.

3. Soil Porosity

The total soil porosity p is defined as the ratio of the volume of air and water in soil pores to the total soil volume. Obviously, higher total soil porosity can provide larger possibility for radon to escape the grain surface and then lead to higher soil radon concentration. But the total soil porosity itself cannot express the volume ratio of air to water in soil pores, which affects both radon emanation and transportation in soil. Therefore, the soil moisture saturation m was introduced to express the volume ratio of water to air in soil pores. In addition, the soil effective porosity p_{eff} calculated as Eq. (1) was introduced to express the ratio of the air volume to the total soil volume. Then we can use the soil effective porosity to evaluate the influence of soil porosity on both soil radon concentration and radon exhalation from soil surface:

$$p_{eff} = p(1 - m). \tag{1}$$

4. Grain Size

Grain size is one of important factors that control radon concentration in soil. Further more it was suggested by previous studies that the radioactivity of the soil relate to the grain size of soil, *i.e.*, soil radioactivity decreases with sand content in the soil and increases with clay content. If the radium atoms are present only on the surface of the soil particles, the radium concentration is inversely proportional to the radius of the particles and the radon emanation coefficient is independent of grain size. While if the radium is uniformly distributed throughout the soil grains, the radon emanation coefficient is inversely proportional to the radius of soil particles and the radium concentration is independent of grain size.[8,9)]

III. Materials and Field Measurements

Field measurements of radon concentrations in soil, 60 cm under the soil surface, and radon exhalation rate from soil surface were carried out in totally 31 points in different soil textures in Beijing (North of China), Guiyang (Guizhou province, Southwest of China) and Huhhot (Inner Mongolian Municipality), from June to August, 2003. However, the majority of the measurements points were around Beijing area, and measuring points in Beijing could be divided into Beijing Suburb and Tsinghua Campus which located inside the city. The measurement points were usually selected at farms, gardens or schools which were representative of soil texture in the local area. At each point, radon concentration in soil and the radon exhalation rate from soil surface were measured at least two times, respectively. In simultaneity, two soil samples were taken by an annular steel sample container. All the soil samples were measured in the laboratory, and relative soil parameters, such as radium contents, soil water contents, soil porosity and grain sizes were analyzed.

The measurements on radon exhalation rate were performed with the device ERS-2 (TRACERLAB Co., Germany), which is an Electrostatic-Radon-Sampler for the determination of the ^{222}Rn (Radon) gas-concentration and for the determination of the exhalation-rate. The ERS-2 operates with an Alpha-Spectroscopy detector and MCA with 256 channels. For the determination of the radon flux rate, the ERS-2 was placed on the soil surface with sealed condition. Usually, at each point, the measurement was performed for 4–5 cycles and the cycle time was 10 min. The ERS-2 gave the radon gas-concentration of each cycle in the unit of Bq/m^3. The radon concentration data for each cycle was automatically stored in the memory of ERS-2. To calculate the exhalation-rate, firstly the data in ERS-2 was read into an external PC-system, and then the data was linear simulated to derive the exhalation-rate with the result of mBq/m^2·s by using the Tracerlab-Spectrum-Software.

Radium content of each soil sample was measured with a HPGe (high purity germanium) detector with a relative efficiency of 48.3% (E_γ=1.33 MeV). Firstly, each soil sample was dried for about 24 h at the constant temperature of 105±2°C in an oven. Then the dry sample was grind and sifted through a special soil sifter with 0.25 mm aperture. Thirdly, the sifted dry soil was put into an standard plastic container (Φ75×50 mm) and sealed for at least 20 days before the spectrometric measurement. Finally, the sample was measured with the HPGe for approximately 6–8 h to achieve the spectrum for the determination of radium content.

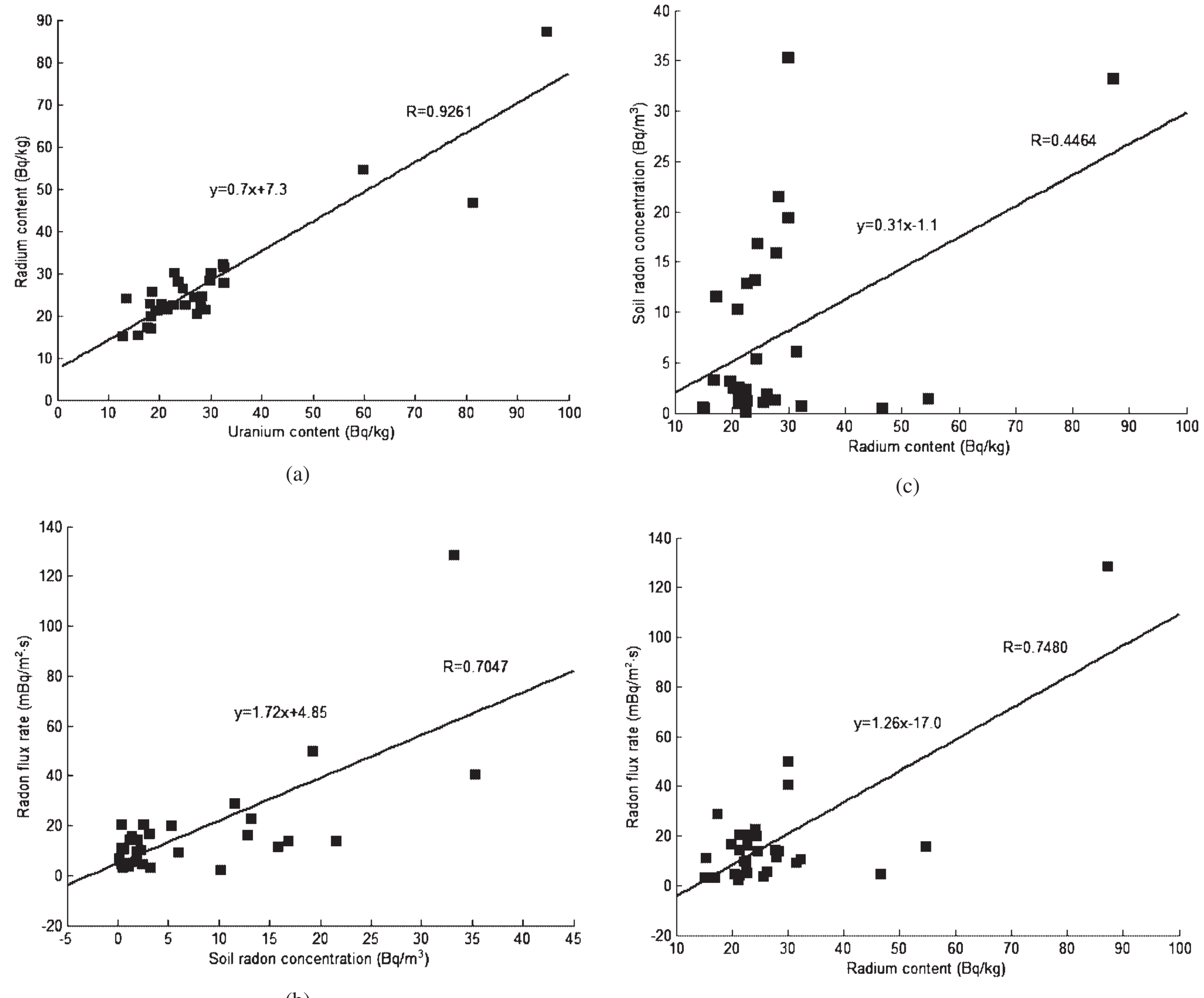
Soil dry bulk density and soil water content were measured with the annular steel sample container (Φ70×52 mm), an oven (105±2°C) and an electrical balance (Scale: 0–500 g, Precision: 0.1 g). The soil grain size for determining soil texture of each sample was commercially measured with a laser granularity instrument (which was produced by Malvern Instruments Ltd, and the type was Mastersizer 2000) in China University of Geosciences.

Soil radon concentration was measured by a soil radon monitor (FD-3017, Made in China), which was composed of a pump with one meter long steel soil probe and a silicon-semiconductor detector. Radon concentration was calculated according to the counts of ^{218}Po which was collected by an electrode.

IV. Results and Discussion

Firstly, to see the correlativity within the following parameters, all the measurements results including field measurements of soil radon concentrations (60 cm under soil surface), radon exhalation rates from soil surface, and laboratory measurements on relative soil characteristics were analyzed, **Fig. 1** showed the linear relation between every two parameters.

From the correlative coefficients in linear simulation shown in the four sub-figures of Fig. 1, the following phenomena can be observed: (1) The uranium content and radium content in the samples have a fairly good linear relation, which suggests that in most measurement point, the uranium and radium in soil are in the situation of equilibrium; (2) The linear relation between radon exhalation rate from soil and radium content as well as the linear relation between radon exhalation rate and soil radon concentration are obvious in



(a)

(c)

(b)

(d)

Fig. 1 The linear relation between every two parameters: (a) The relation between radium content and uranium content of the samples; (b) The relation between radon flux rate from soil surface and soil radon concentration; (c) The relation between soil radon concentration and radium content; (d) The relation between radon flux rate from soil surface and radium content

spite of a certain degree of departure, which agrees with the theoretical analysis in part II; (3) The linear relation between soil radon concentration and radium content is unexpectedly unclear. The difficulties in measuring radon concentration in clay soils with high water saturation in Guiyang may be the possibly answer for the abnormal phenomenon in Fig. 1(c).

In Fig. 1 all the 31 data are used to make linear simulation. But in fact, the soil characters in different regions are very different, while in a certain region, the characters of soil samples show high consistency. So in the following text, the arithmetic means of soil radium content, moisture saturation, porosity and grain size in the four regions Guiyang, Beijing Suburb, Huhhot and Tsinghua Campus are taken to estimate the effect of the soil physical parameters on soil radon concentration and radon exhalation from soil surface.

The results of soil radon concentrations, radon flux rates, soil ^{238}U and ^{226}Ra contents of the four areas were shown in **Table 1**. Because it is very difficult for FD3017 to draw out air from the wet clay soils in Guiyang area, no high soil radon concentration was gotten as expected in the area where soil radium contents were high. It was clear that the soil radon concentration and radon flux rate have a trend of increase with the increasing soil uranium and radium contents excepting the inveracity of the measurement on soil radon concentrations.

Figure 2 showed the soil radon concentration and radon exhalation compared with soil ^{226}Ra contents in 10 samples of Beijing Suburb. It was shown that the fluctuation of both soil radon concentration and radon exhalation were far larger than that of the radium content, this phenomenon can be understood as the great influence of both soil physical parameters and meteorologic factors. In addition, for the limited samples in Beijing Suburb, there was no clear positive relation to be found between radium contents and soil radon con-

Table 1 Soil radon concentration and radon exhalation compared with soil ^{238}U/^{226}Ra contents in four regions

Regions	Sample number	^{238}U content (Bq/kg)	^{226}Ra content (Bq/kg)	Soil radon concentration (kBq/m^3)	Radon flux rate (mBq/m^2·s)
Guiyang	4	55±23	67±28	9±16	40±59
Beijing Suburb	10	26±6	27±4	14±10	21±13
Huhhot	3	18±2	18±3	7±6	14±14
Tsinghua Campus	14	22±5	22±3	2±3	9±6

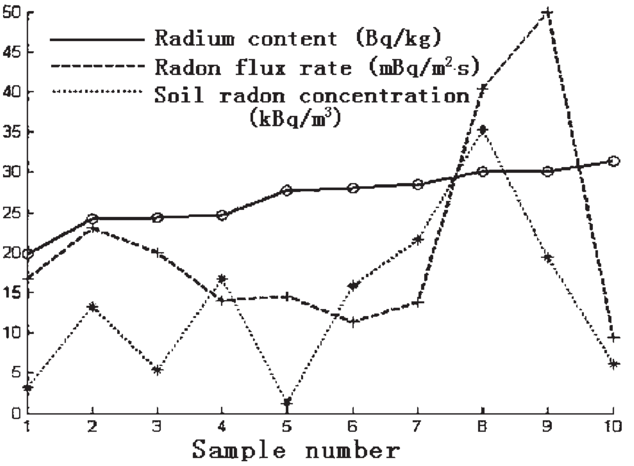


Fig. 2 Soil radon concentration and radon exhalation compared with soil ^{226}Ra contents in Beijing Suburb

centration or radon exhalation rate.

The effects of soil moisture saturation and effective porosity on soil radon concentration and radon exhalation are shown in **Table 2**. It was obvious that the region with high soil moisture saturation has low soil effective porosity. The ratio of soil radon concentration to radium content showed evident consistency with the ration of radon flux rate to radium content. It could be observed that both the wet region such as Guiyang and the dry region such as Tsinghua Campus have relatively low soil radon concentration and radon exhalation rate, which could be easily explained by the radon emanation and transportation theories, discussed in part II.

Table 3 showed the effects of soil grain size. It was suggested that the soil radon concentration and radon exhalation rate generally decrease, although not strictly, with the increasing average soil grain size. Considering on the complicated relation between radium content and grain size, the analysis on the effect of soil grain size was done only with the results of field measurements but without radium contents. The abnormal low soil radon concentration in Guiyang area was discussed in the above text.

V. Conclusion

Field measurements on soil radon concentration and radon exhalation were carried out in totally 31 point in China. Some soil characters of soil samples including soil radium content, water situation, porosity and grain size were measured. Linear simulation method and region division method were used to deal with the measurement data. The results showed the general trends of the effects of the four soil physical parameters on soil radon concentration and radon exha-

Table 2 The ratio of soil radon concentration and radon flux rate to soil radium content compared with soil moisture saturation and soil effective porosity

Regions	Soil moisture saturation	Soil effective porosity	Soil radon concentration /radium content (kBq/m^3)/(Bq/kg)	Radon flux rate /radium content (mBq/m^2·s)/(Bq/kg)
Guiyang	0.69±0.06	0.15±0.03	0.11±0.18	0.55±0.63
Beijing Suburb	0.49±0.15	0.24±0.09	0.50±0.35	0.79±0.43
Huhhot	0.46±0.19	0.25±0.10	0.39±0.33	0.83±0.79
Tsinghua Campus	0.19±0.06	0.41±0.04	0.11±0.14	0.42±0.28

Table 3 Soil radon concentration and radon exhalation rate compared with average soil grain size

Regions	Soil radon concentration (kBq/m^3)	Radon flux rate (mBq/m^2·s)	Soil texture	Average grain size (μm)
Guiyang	9±16	40±59	Loamy clay	39.2±16.2
Beijing Suburb	14±10	21±13	Sandy loam	47.4±13.7
Huhhot	7±6	14±14	Sandy loam	86.3±24.1
Tsinghua Campus	2±3	9±6	Sandy loam	66.7±21.8

lation rate from soil surface.

Different from former studies on soil radon gas and radon flux from soil, this work did not build the soil column artificially to control all the soil parameters.10) All the measurements were performed on natural soil so that the data could suggest a real trend of radon gas concentration and radon flux from natural soil, at the same time however, the method led to some difficulties in analyzing the relationship among the many parameters quantificationally. The measured soil radon concentration and radon flux rate results are the synthesis of many influencing parameters, some of which are even not considered.

Although this work included limit number of samples, the measured data on comprehensive parameters such as radon concentration in soil gas, radon flux rate from soil, soil radium content, soil porosity and moisture saturation and soil texture will provide valuable references for future researches. In spite of the large uncertainties in the measurements which are influenced by so many factors, the considerable consistency of the general trends reflected by the measurement data with the theoretical analysis could be seen. All the above work is the foundation for the nationwide investigation on soil radon concentration and radon flux rate from soil surface in China.11)

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