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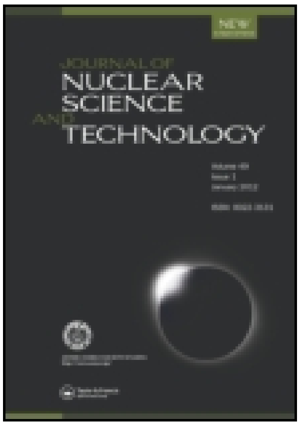


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**TECHNICAL DATA**

# Feasibility for Mapping Radon Exhalation Rate from Soil in China

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Radon exhalation rate from soil is one of the most important factors for evaluation of the environmental radon level. For rough estimation of the nationwide radon exhalation rate from soil in China, a simple model was derived under the review and analysis of several previous works on radon exhalation theories. To show the feasibility of the model, some nationwide databases were summarized and discussed, and a trial estimation was made and compared with the measured data for Beijing. The results show that it is possible to map the radon exhalation rate from soil in China based on the present databases.

***KEYWORDS: radon exhalation rate, model, radium, soil moisture, grain size, China***

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## I. Introduction

Over the past few decades, there has been a large scientific interest in the study of environmental radon. One of the main reasons is its associated health hazard, another is its widespread use as an environmental tracer.[1)]

Soil is a source of radon. The infiltration of radon gas ($^{222}$Rn) from soil has been identified as one of the main mechanisms influencing indoor radon levels in many buildings. It was reported that a worldwide average of 60.4% of indoor radon comes from the ground and surrounding soil of buildings.[2)] Information on the spatial variability of radon exhalation rate would be useful for identifying areas with a risk of high radon exposure. On the other hand, the well understood chemical behavior (inert gas) of $^{222}$Rn and its convenient half-life (3.82 d) make radon to be a useful tracer in studies of air mass transportation. For example, it is often used in validating global atmospheric transport models.[3,4)]

Several studies on mapping radon exhalation rate from soil have been reported in local, regional or national scale with different methods. For example, Ielsch *et al.* proposed a methodology based on radon exhalation rate quantification, starting from a precise characterization of the main local geological and pedological parameters.[5)] Kemski *et al.* mapped radon-affected areas based on soil-gas radon measurements in conjunction with geological and soil investigation in representative test areas.[6)] Similar work was also carried out in the U.K. and U.S.A.[7–9)]

In China, because of the large area and complex distribution of soil types, a large number of field measurements in national scale are extremely difficult. Therefore, it is essential to develop an effective, economical and practical method for the classifying and mapping of radon exhalation rate from soil in China. In this work, the mechanisms of radon emanation, transportation and exhalation in soil were reviewed and theoretically analyzed, and a simple model is introduced for the estimation of radon exhalation rate from soil in China. To show the feasibility of the model, some nationwide databases, such as the soil $^{226}$Ra content, soil moisture and soil texture, are summarized and discussed, and a trial estimation is made and compared with the measured data for Beijing.

## II. Theoretical Review and a Simple Model

### 1. Mechanism of Radon Emanation and Transportation

The exhalation of radon from soil involves two mechanisms: emanation and transportation, which are both affected by many factors including the properties of the soil.[10)] Emanation is the process that controls the movement of radon atoms from within solid grains into free space of materials.[11)] The fraction of radon atoms released into a rock or soil pore space from a $^{226}$Ra-bearing grain is expressed in terms of 'radon emanation coefficient', which is mainly affected by the size of soil grain and soil moisture conditions.[12)] Radon transportation takes place in the communicating pore space generally directed to the earth's surface. The process also involves two mechanisms: diffusion and advection.[13)] Diffusion, which is usually the main form of radon transportation, is caused by radon concentration gradient and often estimated in 'diffusion coefficient'. The main factors influencing radon diffusion in soil are the soil characteristics such as soil porosity and moisture. Advection takes place when there is pressure difference between the airs of pore space and ground surface.[14)] The most important factor affecting advection is the soil permeability. Other meteorological parameters like temperature difference between soil and surface air, wind velocity and rainfall also affect the advection process.[15)]

The radon emanation rates of soil are known to strongly depend on the moisture content of the soil. A certain experiment has observed that the emanation coefficients increased with the increasing moisture content and then decreased before reaching saturated conditions.[16)] Grain size is another important factor controlling the soil's emanation coefficient. If $^{226}$Ra is uniformly distributed throughout the soil grains, the emanation coefficient is inversely proportional to the

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grain radius.[12] Several experiments have verified the theory mentioned above.[10,11,17]

### 2. A Simple Model for Estimating Radon Exhalation Rate from Soil

Since the influence of most meteorological parameters on advection is usually temporary, instantaneous and difficult to be modeled,[15,18] only diffusion mechanism is considered in this work for estimating long-term averaged values. Based on the conservation of mass, an idealized, one dimensional, steady-state model for the transportation and distribution of radon in soil can be expressed as the following differential equation:

$$D_e \frac{d^2C}{dx^2} - \lambda C + \frac{A}{p_{eff}} = 0, \tag{1}$$

where $D_e$ is the effective radon diffusion coefficient, $C$ is the radon concentration in pore air of the soil, $x$ is the distance from the ground surface with its positive direction downward, $\lambda$ is the radon decay constant, $p_{eff}$ is the effective porosity of the soil and $A$ defined as Eq. (2) is the production rate of radon gas into the pore space:

$$A = \lambda \rho R E, \tag{2}$$

where $\rho$ is the dry bulk density of the soil, $R$ is the $^{226}$Ra activity in the soil particles and $E$ is the radon emanation coefficient.

Given the boundary conditions: $C|_{x=0}=C_0$ and $C|_{x\to\infty}$ is infinite, the solution for Eq. (1) is:

$$C = \frac{A}{\lambda p_{eff}} + \left(C_0 - \frac{A}{\lambda p_{eff}}\right)\exp\left(-\frac{\sqrt{\lambda D_e}}{D_e}x\right). \tag{3}$$

On the other hand, as radon flux is continuous at the ground surface between soil and atmosphere, the exhalation rate ($F$) of radon from ground surface can be expressed as follows:

$$F = p_{eff} D_e \left.\frac{dC}{dx}\right|_{x=0}. \tag{4}$$

Combined into Eq. (3), Eq. (4) can be rewritten as:

$$F = p_{eff}\sqrt{\lambda D_e}\left(\frac{A}{\lambda p_{eff}} - C_0\right). \tag{5}$$

In general, $C_0$ is negligible, Eq. (5) can be further simplified as:

$$F = \sqrt{\lambda D_e}\,\rho E R. \tag{6}$$

On the other hand, the effective radon diffusion coefficient ($D_e$) in soil has been experimentally studied, which can be expressed as the following equation:[19]

$$D_e = pD_0 \exp(-6mp - 6m^{14p}), \tag{7}$$

where $p$ is the total soil porosity which can be estimated by Eq. (8),[20] $D_0$ is the radon diffusion coefficient in open air with a constant of $1.1\times10^{-5}\,\mathrm{m^2\cdot s^{-1}}$ and $m$ is the volume fraction of water saturation which can be calculated from water mass content ($w$) by Eq. (9):

$$p = (93.947 - 32.995\rho)/100 \tag{8}$$

$$m = w\rho/1{,}000p. \tag{9}$$

The above equations indicate that the radon exhalation rate can be estimated if the parameters of $R$, $w$, $\rho$ and $E$ in the soil are known.

## III. Main Parameters and a Trial Estimation in China

### 1. Radium-226 Contents in Soil in China

Nationwide surveys on the contents of natural radionuclides in soil were carried out in China from 1983 to 1990.[21] Survey areas covered 80% of the country, included 29 provinces or regions. Both the methods of chemical analysis and gamma spectrum analysis were used for measurements, and the measurement quality was well controlled throughout the survey. A total of 7,777 soil samples collected in a sizing grid of 25×25 km in most areas or 50×50 km in partial rural areas were measured.

The distribution based on averaged $^{226}$Ra contents of each province or region is plotted in **Fig. 1**. Some provinces or regions with average $^{226}$Ra content higher than $50\,\mathrm{Bq\cdot kg^{-1}}$ are selected out and listed in **Table 1**. The national averaged $^{226}$Ra content in soil is $36.5\pm22.0\,\mathrm{Bq\cdot kg^{-1}}$, which is nearly the same of world average ($35\,\mathrm{Bq\cdot kg^{-1}}$).[22] The area weighted $^{226}$Ra content varies from 2.4 to $425.8\,\mathrm{Bq\cdot kg^{-1}}$, and it is generally higher in the South than that in the North. In some heavily populated southern provinces such as Fujian, Hunan and Guangxi provinces, the $^{226}$Ra contents in soil are significantly higher than the national average value. As the nationwide database on $^{226}$Ra contents in soil has been established, the parameter of $R$ in Eq. (6) is available.

### 2. Soil Moisture State in China

Soil moisture is one of the most important determinant factors for estimating radon exhalation rate, affecting not only diffusion coefficient but also emanation coefficient. The distribution of soil moisture in China was studied during last two decades, a model for evaluation soil moisture was established based on ground meteorological data, such as precipitation, temperature, solar radiation, wind velocity and so on.[23] **Figure 2** shows a rough distribution of soil moisture state in China based on the mathematical model and the climatic data of ground surface from 656 weather stations throughout China. Three regions and six sub-regions are plotted out according to the soil dryness index. It is showed that soil moisture is generally higher in the Southeast than in the Northwest of China. As the distribution of soil dryness index in China is known, the parameter of $w$ in Eq. (8) can be inferred.

### 3. Soil Texture in China

The physical properties of soil are also important factors influencing radon exhalation from soil. Nationwide surveys on soil properties had been systematically carried out in China by early 1980s.[24] **Figure 3** shows the distribution of soil texture in China. Its classification was based on the composition and proportion of soil components with different grain sizes. Four regions are plotted out according to the Chinese standard on soil texture taxonomy, which is slightly different with the international standard. As the distribution of soil

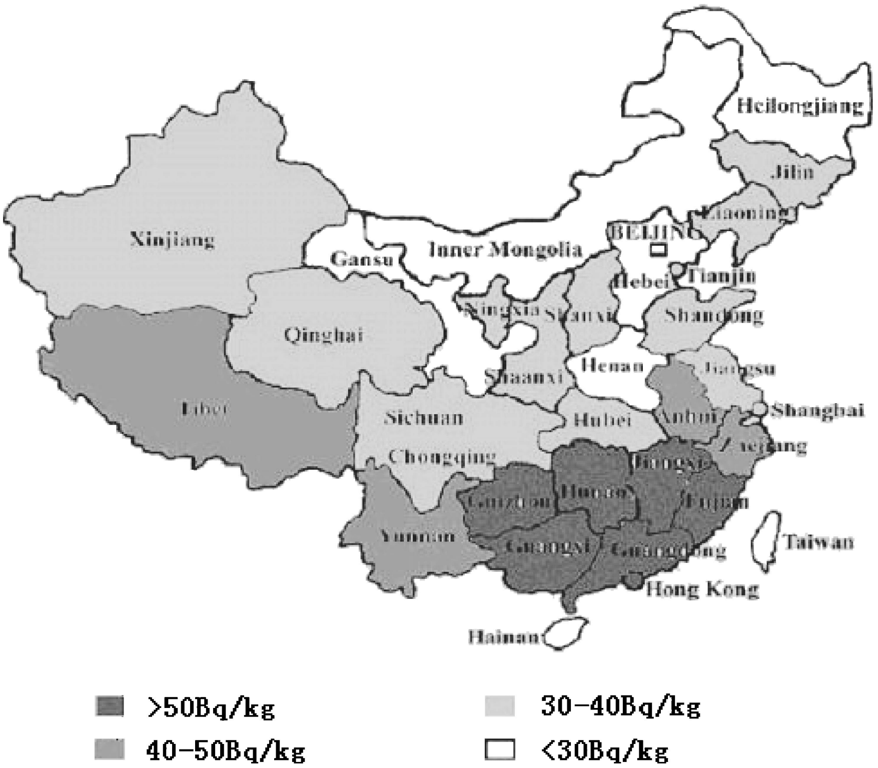


**Fig. 1** The geographical distribution of $^{226}$Ra contents in soil in China

**Table 1** Soil $^{226}$Ra contents in some provinces of China ($Bq{\cdot}kg^{-1}$)[21,22)]

| Province | Samples numbers | Average (area weighted) | Range |
|---|---|---|---|
| Guizhou | 244 | 67.3±36.5 | 3.7–266.1 |
| Fujian | 143 | 62.0±36.0 | 18.0–201.0 |
| Hunan | 309 | 59.4±30.2 | 9.7–437.8 |
| Guangxi | 360 | 53.1±35.2 | 15.5–270.2 |
| Jiangxi | 270 | 52.9±34.7 | 10.2–199.5 |
| Guangdong | 144 | 50.8±2.2 | 1.0–152.7 |
| National average | | 36.5 | 2.4–425.8 |
| World average | | 35.0 | |

texture in China is known, the dry bulk density of the soil ($\rho$) can be inferred,[25)] and the soil porosity can be estimated. Also from the soil texture, the radon emanation coefficient ($E$) can be inferred. **Table 2** shows the reported typical radon emanation coefficient for different types of soil.[26)]

### 4. Estimated and Measured Results in Beijing

Based on the simple model discussed above and the existed databases, the annual averaged radon exhalation rate from soil was estimated for Beijing. In Beijing, the averaged soil $^{226}$Ra content is $21.4\,Bq{\cdot}kg^{-1}$, the soil dryness index is between 1.0 and 2.7, and the soil texture is sandy roam. For sandy room, its bulk density and emanation coefficient are referred as $1{,}500\,kg{\cdot}m^{-3}$ and 0.23, respectively. Assumed a water mass content ($w$) of 10%, the volume fraction of water saturation ($m$) was estimated to be 0.34. According to Eqs. (6) and (7), the annual averaged radon exhalation rate

**Table 2** Typical values of radon emanation coefficient for different types of soils[26)]

| Soils | Emanation coefficient |
|---|---|
| Sand | 0.14 |
| Silt | 0.23 |
| Loam | 0.25 |
| Clay | 0.28 |

is estimated to be $16.7\,mBq{\cdot}m^{-2}{\cdot}s^{-1}$, which is about 30% lower than the measured average value ($24.9\,mBq{\cdot}m^{-2}{\cdot}s^{-1}$, $n$=30).[27)] However, the measurements were not carried out in rainy days. Therefore, it is considered that the estimated value is in general agreement with the measured results.

## IV. Conclusions

For evaluation of radon exhalation rate from soil in China, large amount of field measurements are extremely difficult. On the other hand, even though several detailed models have been introduced for estimating the exhalation rate, some nationwide parameters are still unavailable. In this work, a simple model is introduced for the estimation of radon exhalation rate from soil in China. An example shows that the estimated value with the simple model is in general agreement with the measured data. Compared with other models, even though the model is very crude, its simplicity and practicability make it possible to estimate the radon exhalation rate from soil in China based on the present existed nationwide databases. However, there is still a lot of work to do for the direct application of the nationwide databases. As an ex-



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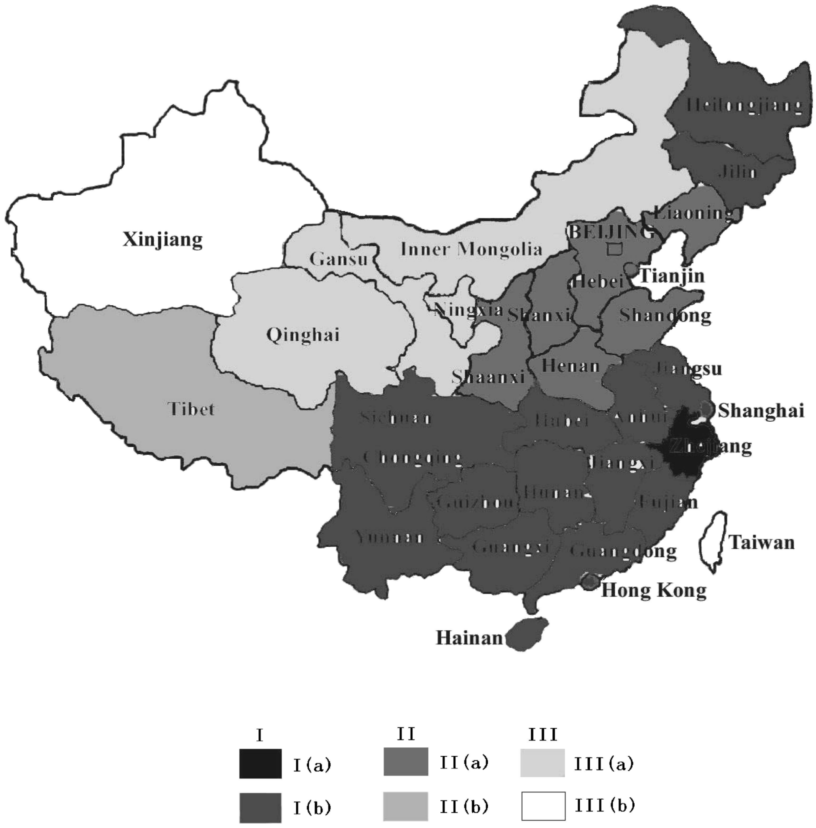


**Fig. 2** The distribution of soil moisture in China

I is the general wet region, and I (a) is the sub-region with soil dryness index ($D$)$<$0.45, I (b) is the sub-region with 0.45$\leq D<$1.0; II is the transitional region, and II (a) is the sub-region with 1.0$\leq D<$2.7, II (b) is the sub-region with 2.7$\leq D<$3.5; III is the general dry region, and III (a) is the sub-region with 3.5$\leq D<$16.0, III (b) is the sub-region with $D\geq$16.0.

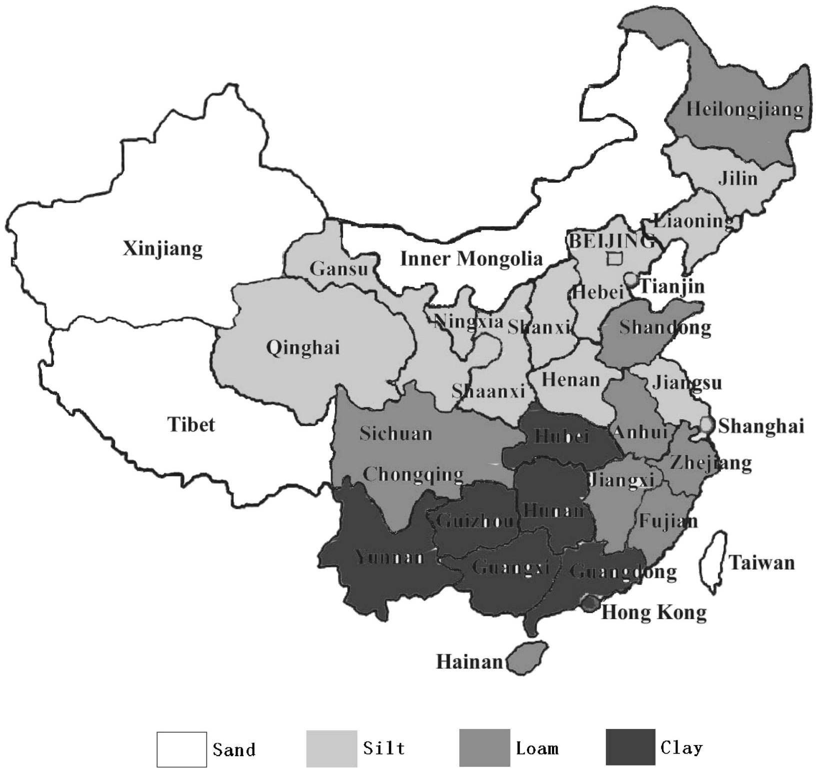


**Fig. 3** Map of soil texture of China

ample, the method for estimating the volume fraction of water saturation from the soil dryness index is needed in further studies. Furthermore, field measurements in some representative sites are also needed to testify the model.

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