Research Article

Effect of Thickness and Compaction Degree of Overburden Soil on Radon Reduction for Uranium Tailings Reservoir

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The thickness and compaction degree of the overburden soil on the beach of the uranium tailings reservoir has an important influence on the radon reduction rate. A theoretical model of radon exhalation is established and an experimental device is designed. The main results are as follows. (1) The radon reduction rate increases with the increase of thickness. When the soil compaction degree is 85.5%, 90.2%, and 94.8%, the radon reduction efficiency increases significantly when the thickness increases from 5 cm to 10 cm, and when the soil thickness is over 10 cm, the increase of radon reduction efficiency tends to be stable. When the compaction degree is 80.9%, the radon reduction rate always increases obviously with the increase of the thickness of the overburden soil, but the increase rate shows a downward trend. (2) The radon reduction rate increases gradually with the increase of compaction degree, and the increasing trend becomes less obvious when the compaction degree is more than 85.5%. Besides, the effect of the change of soil compaction on radon reduction rate decreases with the increase of soil thickness. The calculation formulas about the effect of thickness and compaction degree on radon reduction rate can guide the design and construction of radiation protection of uranium tailings reservoir.

1. Introduction

A large amount of uranium tailings produced in the process of uranium extraction and utilization is accumulated to form a uranium tailing reservoir. And, the radionuclide radon produced can be migrated to residential quarter through seepage and exhalation from the surface [1, 2]. It is an economical and effective measure to reduce radon exhalation by covering soil on the surface of uranium tailings reservoir [3].

The physical properties of the overburden soil, such as moisture content, compaction degree, and thickness, will affect the migration of radon. Radon exhalation rate refers to the activity of radon exhaled into the air through the surface of the medium in unit time [4]. The influence of volumetric moisture content of emanation media on the radon

exhalation rate of the beach of the uranium tailings reservoir has been studied in several research studies [5]. The results show that, at first, with the increase of volumetric moisture content, the radon exhalation rate rises; after that, the radon exhalation rate decreases with the increase of volumetric moisture content of the beach of the uranium tailings reservoir. Besides, the researchers studied the influence of the density of laterite on radon diffusion and found that the radon diffusion coefficient decreased with the increase of laterite density, which was mainly caused by the change of laterite porosity [6].

Soil compaction degree is the ratio of soil dry density to the dry density corresponding to the optimum moisture content in the soil compaction degree test curve. The larger the soil thickness is, the larger the volume is, which means that, under the condition of covering the same quality of soil,

the larger the soil thickness is, the smaller the soil dry density is and the smaller the compaction degree is. The improvement of compaction degree is conducive to improving the resistance ability of the overburden soil to natural wind erosion and rainwater scouring and is also conducive to reducing the porosity of the overburden soil and reducing the radon precipitation rate [7]. The thicker the overburden soil is, the lower the radon exhalation rate will be [8]. This is because the thicker the overburden soil is, the longer the time for radon atoms produced in the uranium tailings reservoir to transfer to the overburden soil surface will be. Thus, reducing the radon flux in the atmosphere, the radon reduction rate of overburden soil corresponds to its ability to reduce the radon flux of tailings [9]. Therefore, it is necessary to analyze the radon reduction rate under the conditions of different thicknesses and compaction degree of the overburden soil, to know the appropriate soil thickness and compaction degree of the overburden soil, to achieve reliable technology and reasonable construction cost, and, at the same time, to meet the requirements of maximizing the reduction of the radon exudation rate.

Taking a uranium tailings reservoir in South China as an example, the research analyses the influence of overburden soil thickness and compaction degree on radon reduction rate by using a self-made test device and RAD-7 radon detector, providing a reference for decommissioning disposal of the uranium tailings reservoir.

2. Experimental Principle

2.1. Theoretical Model of Radon Exhalation. Radionuclides with sequential decay relations in nature consist of three natural decay systems, namely, uranium, thorium, and actinide. Because their half-life is equal to the life of the earth, we regard them as nearly constant in practice. In the three decay systems, there is a radionuclide in a gas state at normal temperature and pressure, which is Rn-222, Rn-220, and Rn-219. Only the half-life of Rn-222 is relatively long, and the life of its radon daughters is relatively short, so it is easier to accumulate to a higher concentration. The radon described in the following paper is Rn-222. Rn-222 decays from U-238, and its direct parent nuclide is Ra-226. The brief decay process is shown in (see Figure 1) [10, 11]. Because Ra-226 has a fairly long half-life, Rn-222 can be produced continuously for a fairly long time when Ra-226 is contained in the medium. Therefore, the medium containing Ra-226 is called emanation media [12].

Radon exhalation means that radon produced in the emanation media enters the atmosphere through the surface of the medium. It is the boundary phenomenon of radon migration in the emanation medium. The porous emanation media such as uranium tailing and soil are all composed of particles of a specific size, and radon can migrate in the gap between these particles. The results show that the porosity of the emanation media is the main factor affecting the migration of radon [13]. In this research, the radon migration media is abstracted into a homogeneous porous medium, thus simplifying the porosity of the medium, which is conducive to the theoretical model of radon migration.

According to the model, the thickness and compaction degree of the overburden soil will change the migration path of radon in the emanation medium, thus affecting the radon reduction rate of the overburden soil.

2.2. Measurement of Radon Concentration and Calculation of Radon Exhalation Rate. Radon is separated from the surface of homogeneous porous media and enriched in radon collecting housing space [14]. The radon collecting cover is provided with air inlets and air outlets, which are connected with a radon measuring instrument through an air pipe to make it a closed space. The radon detector introduces the radon gas in the radon collecting cover (see Figure 2) into its internal measuring chamber through the built-in gas pump to sample the radon concentration and automatically measures the radon concentration according to the gas flow generated by the instrument itself and the sampling time. The radon gas circulates inside the device and does not affect the original radon concentration in the space [15].

The radon concentration in space will continue to increase. The radon concentration data collected by the radon detector before and after the test can be used to calculate the increase of radon concentration C in unit time [16, 17]:

$$\frac{dC}{dt} = \frac{JS}{V} - \lambda C, \quad (1)$$

where J is the radon exhalation rate on the surface of the measured medium, $\text{Bq} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, S is the bottom area of radon collecting hood, m^2 , V is the space volume of radon collecting hood, m^3 , JS/V is the change of radon concentration caused by radon exhalation into radon collecting hood per unit time [18], $\text{Bq} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$, λ is the decay constant of radon, $2.06 \times 10^{-6} \text{s}^{-1}$, λC is the change of radon concentration caused by radon decay in radon collecting hood, $\text{Bq} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$, λC is the radon concentration at time t in radon collecting hood, $\text{Bq} \cdot \text{m}^{-3}$, and t is the accumulation time of radon in radon collecting hood, s .

Substituting the initial conditions $t = 0$ and $C = 0$ into Equation (1), the expression of J is obtained:

$$J = \frac{\lambda V}{S(1 - e^{-\lambda t})} (C - C_0 e^{-\lambda t}), \quad (2)$$

where C_0 represents the initial radon concentration in the radon collecting cover. Because $\lambda t \ll 1$, drive 1, λt can be regarded as an infinitesimal value in the equation. Extreme value operation is performed on Equation (2), and the approximate calculation equation of J is obtained as follows:

$$J = \frac{V}{St} (C - C_0). \quad (3)$$

In the research, to reduce the error, the radon concentration data of 12 different time points were collected in the process of radon accumulation in the radon collecting housing space, and the first data of radon concentration was discarded. In MATLAB software, the point of radon concentration on the time axis is linearly fitted, and the slope of the fitted line is regarded as the approximate ratio of

TABLE 1: Main chemical mineral components of the chosen uranium tailings sample.

Component	SiO ₂	Al ₂ O ₃	MnO	MgO	Fe ₂ O ₃	CrO ₂	TiO	FeO	CaO	U
Content (%)	85.82	10.25	2.33	1.38	1.24	0.58	0.35	0.16	0.13	0.07

TABLE 2: Main physical parameters of laterite.

The sample	Relative density (g · cm ⁻³)	Maximum dry density (g · cm ⁻³)	Optimum moisture content (%)
Laterite	2.72	1.73	17.6

carried out in a self-developed temperature-condition room at 14°C (the appearance and relevant design parameters of self-developed temperature-condition room (see Table 2 and Figure 1 in the supplemental files). The temperature-condition room can only determine whether the temperature adjustment compressor is heating or cooling based on the room temperature detected by the temperature sensor and the temperature parameter set by the user. However, the air temperature transmitted by the compressor fan is uncontrollable, which easily leads to the local temperature in the room higher or lower than the user's set value. Therefore, the inner wall of the sample box is pasted with 5 cm thick insulation cotton to stabilize the temperature of the sample box. Similarly, the inner wall of the sample box cover is also pasted with heat preservation cotton after plastic sealing treatment. While achieving the purpose of stabilizing the temperature, the space volume of radon collection in the upper part of the overburden soil should be appropriately reduced so that the radon exhalation can be enriched in a smaller space, to reduce the measurement error. The tailings and overburden soil are stacked in layers in the sample box, and the box cover is connected with the box through a flange. There are four air outlets left on the box cover, which are connected with the lower end of the drying pipe with anhydrous calcium sulfate after being connected through the three-way pipe and air duct made of PVC; the upper end of the drying pipe is connected with the inlet of the radon measuring instrument; the air inlet on the box cover is connected with the outlet of the radon measuring instrument after passing through the radon daughter filter (see Figure 3).

3.3. Experimental Methods.

- (1) Debugging of radon detector: before the experiment, disconnect the connector between the catheter and the cover of the sample box, adjust the radon meter to the purge mode, introduce the dry and clean air into the measuring chamber of the radon meter, and discharge the radon and water vapor [15, 20]. When cycle is set to 5 and recycle is set to 9, it means that the time for the radon detector to sample and measure radon concentration is 5 minutes and the sampling time is 9 [21].
- (2) Calculation of radon exhalation rate: after purification, the radon detector and the sample box are connected with the cover of the sample box according to the above method to measure the radon exhalation on the surface of uranium tailing which is not covered with any soil in the sample box.

- (3) Measurement and calculation of radon exhalation after covering the soil: according to Table 3, the soil is sampled, and the density of overburden soil is controlled by compacting a certain quality soil sample to a certain height, to control and calculate its compaction degree. In this study, a total of 16 groups of different parameters of overburden soil were tested.

4. Results and Discussion

4.1. Radon Exhalation Rate after Covering. According to Equation (3), the radon exhalation rate of uranium tailings without covering any soil is $0.66\text{Bq} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (for the radon concentration data of uncovered soil see Table 1 in supplemental files). Table 3 shows the results of measurement and calculation of radon exhalation rate on the surface of 16 groups covered with laterite with different attributes, and the radon concentration data are shown in Table 1 of supplementary materials. After converting these data according to Equation (4), the radon reduction rate data of soils with different attributes were analyzed.

4.2. Effect of Thickness on Radon Reduction Rate. Figure 4 shows the test and calculation results of radon reduction rate of soil with different thicknesses under four conditions of compaction degree. It can be seen from Figure 4 that there is a nonlinear polynomial relationship between the radon reduction rate and the thickness of overburden soil. By fitting the data by MATLAB software, the relationship between radon reduction rate and thickness of soil with the compaction degree of 80.9%, 85.5%, 90.2%, and 94.8% is

$$\begin{aligned}
 \eta_1 &= 0.18 + 0.11x - 5.93 \times 10^{-3}x^2 + 1.12 \times 10^{-4}x^3, \\
 \eta_2 &= 0.30 + 0.13x - 8.26 \times 10^{-3}x^2 + 1.81 \times 10^{-4}x^3, \\
 \eta_3 &= 0.39 + 0.11x - 6.89 \times 10^{-3}x^2 + 1.43 \times 10^{-4}x^3, \\
 \eta_4 &= 0.43 + 0.10x - 6.1 \times 10^{-3}x^2 + 1.23 \times 10^{-4}x^3.
 \end{aligned} \tag{5}$$

That is, the radon reduction rate increases gradually with the increase of thickness. For soils with high compaction degree (85.5%, 90.2%, and 94.8%), this increasing trend is particularly obvious when the thickness increases from 5 cm to 10 cm, and when the thickness is greater than 10 cm, the increase of radon reduction rate tends to be stable. For the soil with low compaction degree (80.9%), the radon reduction rate always increased with the increase of cover thickness, but the increase showed a downward trend.

FIGURE 3: Device structure design. (a) Schematic diagram. (b) Appearance.

TABLE 3: Radon exhalation rate after covering different attribute soils.

Thickness (cm)	Compaction degree (%)	80.9	85.5	90.2	94.8
5		0.262	0.191	0.0469	0.0221
10		0.241	0.091	0.0362	0.0217
15		0.216	0.049	0.0324	0.0176
20		0.183	0.037	0.0214	0.0165

FIGURE 4: Relation curve between radon reduction rate and thickness.

The reason is that, with the increase of the soil thickness of the cover layer, the radon migration channel is blocked to a certain extent, and the possibility of radon passing through

the soil decreases so that the radon exhalation rate decreases, so the radon reduction rate increases. However, when the cover thickness increases to a certain value, the radon exhalation rate is closer and closer to the background level of the covering material, so the decreasing rate of radon exhalation rate slows down gradually, which slows down the increasing rate of radon reduction rate. For the cover soil with higher compaction degree, its density is higher, compared with the cover soil with lower compaction degree, and it is easier to reduce the radon exhalation rate to the background level of the cover, so the radon reduction rate tends to be stable in advance.

4.3. Effect of Compaction Degree on Radon Reduction Rate. Figure 5 shows the test and calculation results of radon reduction rate of soil materials covered with different compaction degrees under four kinds of thickness. The data of radon reduction rate and thickness of overburden soil are fitted by MATLAB software. The relationship between radon reduction rate and compaction degree of soil with thicknesses of 5 cm, 10 cm, 15 cm, and 20 cm is

$$\begin{aligned}
 \eta_5 &= -107.40 + 354.14y - 386.55y^2 + 140.69y^3, \\
 \eta_6 &= -74.83 + 247.62y - 269.74y^2 + 97.94y^3, \\
 \eta_7 &= -8.33 + 26.50y - 24.80y^2 + 7.59y^3, \\
 \eta_8 &= -18.43 + 63.09y - 68.39y^2 + 24.72y^3.
 \end{aligned} \tag{6}$$

It can be seen from Figure 5 that the radon reduction rate increases gradually with the increase of compaction degree, and the decreasing trend becomes not obvious when the compaction degree is more than 85.5%. Furthermore, with the increase of soil thickness, the effect of soil compaction degree on the radon reduction rate decreases.

FIGURE 5: Relation curve between the radon reduction rate and compaction degree.

FIGURE 6: Relationship between the radon reduction rate and thickness and compaction degree.

The increase of soil compaction degree represents the increase of density, and the increase of density decreases the soil porosity, which leads to the decrease of radon passage, the decrease of radon exhalation rate, and the increase of radon reduction rate. However, when the soil compaction degree of the cover layer increases to a certain value, the soil radon exhalation rate approaches the background value of the mulch material, so the decreasing rate of the radon exhalation rate slows down gradually, which slows down the increase rate of the radon reduction rate. With the increase of the soil thickness of the cover layer, the original radon migration channel of the soil decreases, which makes the radon exhalation rate more easy to reach the lowest value, so the influence of compaction degree on radon reduction rate is getting smaller and smaller.

4.4. Comprehensive Effect of Thickness and Compaction Degree on Radon Reduction Rate. The relationship among soil thickness, compaction degree, and radon reduction rate was fitted by MATLAB software data, and the fitting function relationship among them was

$$\begin{aligned} \eta = & -139.1 + 0.43x + 454y - 9.82 \times 10^{-3}x^2 \\ & - 0.61xy - 493.2y^2 + 5.15 \times 10^{-5}x^{-3} \\ & + 8.12 \times 10^{-3}x^2y + 0.19xy^2 + 179.3y^3, \end{aligned} \quad (7)$$

$$R^2 = 0.998.$$

The relationship is reflected in the three-dimensional coordinate diagram, as shown in Figure 6. The radon

reduction rate is the lowest when the cover thickness and compaction degree reach the minimum, and with the increase of both, the radon reduction rate increases rapidly at first and then tends to smooth.

5. Conclusion

With reference to the theoretical model of radon exhalation and the calculation principle of the radon exhalation rate, a series of radon reducing experiments were carried out on soils with different properties, and the effects of thickness and compaction degree on the radon reduction rate were analyzed, and the following conclusions were drawn.

The radon reduction rate will be increased with the increase of soil thickness and compaction degree, but when they reach a certain value, the radon reduction rate tends to be stable, so after reaching these conditions, continuing to increase the thickness or compaction degree will not significantly increase the radon reduction effect, and the resulting ratio of environmental economic benefits to cost input will decrease. The functional relationship between the radon reduction rate and soil thickness and compaction degree is

$$\begin{aligned} \eta = & -139.1 + 0.43x + 454y - 9.82 \times 10^{-3}x^2 \\ & - 0.61xy - 493.2y^2 + 5.15 \times 10^{-5}x^{-3} \\ & + 8.12 \times 10^{-3}x^2y + 0.19xy^2 + 179.3y^3, \quad (8) \\ R^2 = & 0.998. \end{aligned}$$

In engineering practice, under the condition of meeting the requirements of radiation protection, engineering designers are required to find an optimal coverage, thickness, and compaction degree, to make the environmental and economic benefits as optimal as possible. And, this study can provide some guidance for the radiation protection of related uranium tailings reservoirs.

Data Availability

The data used to support the findings of this study are included within the article and the supplementary information file.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

First author Xingwang Dai and the second author Yifan Chen contribute equally to the article.

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Supplementary Materials

The radon concentration data are shown in Table 1 of Supplemental Files. The design parameters of self-developed temperature-condition room are shown in Table 2 of Supplemental Files. The appearance of self-developed temperature-condition room is shown in Figure 1 of Supplemental Files. (*Supplementary Materials*)

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