Study of Time Variation of Terrestrial Gamma Radiation Due to Depth Distribution of Soil Moisture Content

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An empirical equation was deduced from studies of time variations of terrestrial gamma exposure rate and soil moisture content with depth distribution in the surface layer. It was definitely suggested that the variation of terrestrial gamma exposure rate is most strongly influenced by the change of soil moisture content at 5 cm depth. The seasonal variation with a relative maximum in early autumn and a relative minimum in early spring was clearly obtained in the consequence of long time measurements of terrestrial gamma exposure rate and degree of soil dryness. The diurnal change and phase difference due to the effect of depth were also obtained in the dynamic characteristics of soil moisture content at 3 different depths. From the comparison between measured terrestrial gamma exposure rate and that evaluated from soil moisture content using the empirical equation, it was seen that seasonal variations of the both agreed fairly well as a whole.

Key Words: terrestrial gamma radiation, soil mixture, total bulk density of soil

1. Introduction

The terrestrial gamma radiation level is ascribed to natural radioactivities at a concerned place — potassium 40, nuclides of uranium series and thorium series — and this variation is strongly influenced by the effect of soil moisture. The soil moisture content depends on depth in the surface layer and is affected by various factors in the environment, e.g., rainfall and/or solar radiation. The relationship between variations of terrestrial gamma radiation and soil moisture has been studied in several papers\(^1\)\(^-\)\(^3\), but these papers have not discussed the dependence of the soil moisture content on the depth. These factors were observed simultaneously for a long term and studied in this relation by Minato\(^3\), but the soil moisture was observed at only 10 cm depth.

In the present study, we will discuss the variation of terrestrial gamma exposure rate and dynamic characteristics of soil moisture with depth distribution and suggest an equation on these subjects and estimate the depth of soil which influences the terrestrial gamma exposure rate most strongly. Defining this relation makes it possible to apply information of terrestrial gamma radiation to hydrology, soil science and/or earth science. It is important to know the property of terrestrial gamma radiation when possible radioactive contamination is found in interpreting results of the survey of radioactive fallout or environmental monitoring in the vicinity of nuclear facilities.

2. Experimental Procedures and Results

Observations were practiced in our laboratory at an alluvial plain; the lakeshore of Shinji at a
2.1 Soil moisture contents at 3 different depths

Three plaster blocks were laid at \( d = 5 \), 10 and 30 cm depths in the surface soil. After a while, the wetness of each plaster block was balanced with the soil moisture and electric resistance of these blocks was measured several times in the daytime. Results were converted to soil moisture contents using a conversion factor which was derived from relationship between electric resistance and weight of soil water by using the direct method in which some samples of wet soil are collected and desiccated with an oven. In the process of this conversion, the difference of electric resistance due to the dependence of electric conductivity on the temperature was roughly corrected with air temperature. The soil moisture content \( M_d \) is defined by weight of soil water \( W_m \) and that of dry soil \( W_s : M_d = W_m/W_s \). But in this study, the total bulk density of soil \( \rho_d \) is meaningful. Hence, the degree of soil dryness \( D_d \) is defined by dry bulk density of soil \( \rho_0 \) and \( \rho_d \) expressed by \( M_d : D_d = \rho_0/\rho_d = 1/(1+M_d) \).

Figure 2 shows the soil moisture content at 3 different depths in which diurnal changes are seen in \( M_5 \) and \( M_{10} \). These were measured in the daytime alone, but from this figure it can be inferred that the values are higher in the nighttime. Figure 3 shows the dynamic characteristics of \( D_d \) since Jul. 1986. The value fluctuates with short periods central part in Shimane Peninsula faced on the Japan Sea. The stratum is mainly subarkose and the surface soil is of silt by reference to the subsurface geological map.
Fig. 4 Diurnal changes of terrestrial gamma exposure rate.

Fig. 5 Time variation of terrestrial gamma exposure rate.

and demonstrates seasonal variations in \( D_5 \) and \( D_{10} \) with relative maximum in early autumn — from late Aug. to early Sep. — and relative minimum in early spring — Mar. The relative maximum of \( D_5 \) was +11.3% higher than the total average and the relative minimum was 6.5% lower. The mean values of \( D_5, D_{10} \) and \( D_{30} \) were \( \bar{D}_5 = 0.90 \pm 0.024, \bar{D}_{10} = 0.87 \pm 0.019 \) and \( \bar{D}_{30} = 0.83 \pm 0.010 \), respectively, in the observed term.

2.2 Terrestrial gamma exposure rate

The natural background gamma exposure rate \( E \) had been continuously observed with a NaI (TI) scintillation detector at a height of 1.5 m above the ground. The terrestrial gamma exposure rate \( E_t \) was estimated by subtracting evaluated values of airborne gamma exposure rate \( E_a \) — due to short-lived radon daughters in the atmosphere — and that of precipitation \( E_p \) — due to those in precipitation — from the measured \( E \). \( E_a \) was evaluated using an empirical conversion factor from short-lived radon daughters’ concentration in the atmosphere observed by a filter method. \( E_p \) was evaluated by an interpolation method from data of \( E \) before the beginning of rainfall and after its end.

Figure 4 shows the terrestrial gamma exposure rate in which the value usually fluctuates with short periods. But the diurnal change cannot be seen. Figure 5 shows the time variation of \( E_t \) since Jul. 1986. While there are small fluctuations, it demonstrates a relative maximum in early autumn and a relative minimum in early spring. The mean value, range of variation and ratio between maximum or minimum and total average are \( 5.0 \pm 0.2 \mu R/h, 4.6 - 5.4 \mu R/h, \) and \( \pm 8\% \), respectively.

3. Analysis and Discussion

3.1 Equation between terrestrial gamma exposure rate and total bulk density of soil at 3 different depths

The gamma flux density \( \phi(E) \) of soil activities, in which the distance between the detector and the point of interest is \( r \), is expressed by the undermentioned Eq. (I) with the following assumptions. The principal assumptions are (1) the activities are uniformly distributed in the soil and form an isotropic volume source of the intensity \( S \); (2) the material is homogeneous and semi-infinite in extension; (3) the linear attenuation coefficient \( \mu \) and total bulk density \( \rho \) are constant in the soil; (4) the mass attenuation coefficient \( \mu_m \) is \( \mu_m = \mu / \rho \).

\[
\phi(E) = \int_0^\infty (S/4\pi r^2)2\pi r^2e^{-\mu rdr}
\]
In the energy range between about 0.2 and 3 MeV, $\mu_m$ is almost constant for low atomic number materials\(^4\). Consequently, $\psi$ is strongly influenced by $\rho$ alone. As for scattered radiation, we can see the similar relation\(^5\).

We can infer that $E_i$ is approximately an exponential function of $D_d$ at all depths from Figs. 6a and 6b: $E_i$ can be expressed by an integral exponential equation of $\rho_d$ in reference to Eq. (I). Hence, in applying Eq. (I) to this case, the above assumption (3) should be modified as follows: $\rho$ is $\rho_d$ in $d$ cm depth of soil and $\rho_d$ is constant between $d_{n-1}$ and $d_n$ depth, where the soil layer 0 $-$ $d$ cm depth is divided into $n$ sub-layers, and $\rho_0$ is constant at all depths. In this case, an equation between $E_i$ and $\rho_d$ is obtained experimentally from Eq. (I) with a proportional constant $K$:

If $n \geq 2$

$$E_i = K \cdot S \left( \int_{Z_0}^{Z_1} e^{-\mu_m \cdot \rho_n \cdot Z} dZ + \int_{Z_1}^{Z_2} e^{-\mu_m \cdot \rho_1 \cdot Z_1 \cdot e^{-\mu_m \cdot \rho_2 \cdot (Z_2-Z_1)}} dZ + \cdots \right)$$

$$\cdots + \int_{Z_{n-1}}^{Z_n} e^{-\mu_m \cdot \rho_1 \cdot Z_1 \cdot e^{-\mu_m \cdot \rho_2 \cdot (Z_2-Z_1)} \cdot e^{-\mu_m \cdot \rho_3 \cdot (Z_3-Z_2)}} dZ + \cdots$$

$$= S / 2 \left( \mu_m \cdot \rho \right)$$

Fig. 6a: Relation between terrestrial gamma exposure rate and degree of soil dryness at 5 cm depth.

Fig. 6b: Relation between terrestrial gamma exposure rate and degree of soil dryness at 10 cm and 30 cm depths.

$\square : d = 10$ cm, $\triangle : d = 30$ cm

$= \int_0^{\infty} \frac{S}{2} \cdot e^{-\mu_m \cdot \rho \cdot r} dr$

$= S / 2 \left( \mu_m \cdot \rho \right)$

(1)

Fig. 7: Integral terrestrial gamma exposure rate due to sources at various depths in the soil.

---: After Beck, $\bigcirc$: present study
where $Z_0 = 0$ — at the ground surface:

If $n = 1$

$$E_i = K \cdot S \cdot \left( \frac{1}{(\mu_m \cdot \rho_1)} \right) \cdot \left( 1 - e^{-\mu_m \cdot \rho_1 \cdot Z_i} \right)$$

(II)

3.2 Validity of relational equation

To discuss the validity of Eq. (II), we would compare it with the calculation result of Beck1). Beck has carried out the calculation using a polynomial series expansion approximation to the Boltzman transport equation. The present calculation made use of the same constants of Beck and was put into operation by an interval of 2.5 cm depth. The integral exposure rate due to terrestrial gamma radiation of present calculation completely agrees with Beck’s as seen in Fig. 7. As a result of this comparison, we can conclude that Eq. (II) represents accurately the contribution of terrestrial gamma exposure rate due to individual depth of soil, and Eq. (II) is sufficiently useful to analyze the variation of terrestrial gamma exposure rate due to the dependence of total bulk density of soil on the depth.

3.3 Diurnal and seasonal variations

The diurnal variation is demonstrated in the time variation of $M_d$ as Item 2.1 above and it depends on the depth of soil. In contrast with that $M_5$ is higher value in the morning than evening, $M_{30}$ shows opposite feature. The soil moisture may be moved from the upper to lower layers in the daytime but reverse in the night due to the dependence of soil temperature on the depth in the subsurface6). For this reason, the phase difference is generated among time variations of $M_d$ in various depth. Moreover, as shown in Item 2.1 above, the seasonal variation is recognizable in the time

![Fig. 8](image)

Fig. 8 Monthly means of terrestrial gamma exposure rate and degree of soil dryness at 3 different depths.

- : Terrestrial gamma exposure rate, ○ : degree of soil dryness at $d = 5$ cm, □ : $d = 10$ cm, △ : $d = 30$ cm

![Fig. 9](image)

Fig. 9 Relation of monthly means between terrestrial gamma exposure rate and degree of soil dryness at 3 different depths.

○ : $d = 5$ cm, □ : $d = 10$ cm, △ : $d = 30$ cm
Fig. 10 Comparison of monthly means between observed and estimated values of terrestrial gamma exposure rate.

Fig. 11 Comparison of degree of deviation to the total average between observed and estimated values.

variation of $D_5$ but is not clear in $D_{10}$ and $D_{30}$. This is because the underlayer of soil is influenced by effects of solar radiation and/or rainfall later than the upper side has experienced it, and the soil moisture is moved from the underlayer to the upper side when the surface soil gets into dry state due to evaporation.

Meanwhile, the seasonal variation is clearly seen in the time variation of $E_t$ but the diurnal variation cannot be found in the measurement as Item 2.2 above. It can be considered that the magnitude of diurnal change is too small for gamma ray detector to measure or it is within the experimental error.

The monthly means are shown in Fig. 8 and their correlations with the soil dryness are shown in Fig. 9. There is a tendency that it becomes independent of the soil dryness as the depth becomes large. From these analyses, we can say that the seasonal variation of $E_t$ definitely depends on the soil moisture content — i.e. total bulk density of soil — in the surface layer, especially of 5 cm depth.

3.4 Comparison between observation and estimation

The measured $E_t$ was compared with values evaluated from data of soil moisture content using Eq. (II). In process of this calculation, $\rho_e$ was calculated by $\rho_e = \rho_0 / D_e$. Moreover, monthly relative values of $E_t$ to the total average and those of estimated values were calculated. Results are shown in Figs. 10 and 11. The estimated value is not completely equal to the measured in the magnitude of deviation to its total average, but tendencies of the both variations agree fairly well as a whole.

4. Conclusion

(1) The terrestrial gamma exposure rate can be expressed by the integral exponential equation of total bulk density of soil with depth distribution.

(2) The variation of terrestrial gamma exposure rate is most strongly influenced by the change of soil moisture content at 5 cm depth.

(3) The variation of terrestrial gamma exposure rate demonstrates the clear seasonal change but little diurnal change. The diurnal and seasonal variations are clear in soil moisture content in the surface layer and there are phase differences in
their dynamic characteristics due to the dependence on depth.

(4) For the estimation of change of terrestrial gamma exposure rate, it is reasonable to consider that the depth and horizontal distributions of soil moisture are reflected in the data obtained at an observation point.

(5) The observation of terrestrial gamma radiation makes it possible to estimate the total average soil moisture within about 30 cm depth.

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References