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Cosmic Ray Radiography

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On the analogy of X-ray or gamma-ray radiography, it is shown that cosmic radiations are applicable to non-destructive estimations of various environment materials closely concerned with human life. Two ways of approach are introduced with respect to spatial and temporal characteristics of the materials. One is a continuous measurement of cosmic ray neutrons above and below the ground level, which plays an important role as a remote sensing of day-to-day variations of water equivalent depth of snow cover or soil moisture content. Another one is based on spatial distribution of cosmic ray muon fluxes against the different many sites under a soild construction. This provides a bulk density distribution of the underground construction such as a subway tunnel. We call these techniques 'cosmic ray radiography'.

Key words: Cosmic ray, Radiography, Non-destructive examination

1. Introduction

At present, natural and artificial radioactive isotopes are widely utilized as a kind of tracer in a variety of scientific and industrial fields such as technology, agriculture, medicine and so on. They are allowed to establish the so-called gamma-ray or X-ray radiography. Furthermore, some high-energy radiation beams artificially accelerated, muon or neutron, are being considered as another powerful tool to search enough deeply in the thick layer of materials or human body. However, these radiography techniques occasionally suffered from serious radiation hazards and also their application is usually restricted within a finite size of the object of interest.

On the other hand, very little interest has so far been paid on the radiography using cosmic radiations, because their absolute flux is as small as the background radiation level, despite their extremely high transparency power. The first attempt was given for estimation of sea wave or tide using cosmic ray muon[1]. This point of view was based on a definite attenuation of sea-level muon flux due to the bulk mass of sea-water above the muon detector sunk near the shore. This first try suggested that amplitudes of muon flux changes caused by sea wave or tide are much greater than the statistical uncertainties, if an appreciable experimental device is given. Thus it follows that some other components of cosmic rays could be available for estimations of not only bulk mass of any other object but also its temporal or spatial characteristics.

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One of the authors proposed a new research field of 'Applied Cosmic Ray Physics' based on a few experimental evidences.[2] This work is extended further into an establishment of 'cosmic ray radiography', which estimates snow water equivalent and soil moisture content using cosmic ray neutrons, and bulk density distributions of subway tunnels using cosmic ray muons.

2. Cosmic-Ray Neutron Radiography

Since the diffusion length of a neutron propagating through various materials is the smallest in water, environment neutron fluxes are affected most sensitively by the water content distributed in the vicinity of measurement cite. Here the environment neutrons are defined by cosmic-ray-produced neutrons with energies of less than 1 MeV, as detected by using a moderated BF_3 counter surrounded by a 2 cm-thick polyethylene cylinder. For example, the environment neutron flux on the lake surface is always about 40% lower than that on land, and also the attenuation length of neutrons over seawater is about 30% smaller than that over land within the altitude range of about 50 g/cm^2 above sea level.[3] Such water-sensitive character of neutrons leads us to a feasibility of inspecting the physical state of the environment closely related to water resources. Moreover, the diffusion length of neutrons in water is about one order of magnitude longer than that of gamma radiation, so that neutron radiography is applicable to much more thick target beyond the application limit of gamma ray radiography. Needless to say, cosmic ray radiography is fully free from any radiation hazard.

2.1 *Snow water equivalent*

For the aim of estimating water equivalent depth of snow by the nuclear radiation technique, two different methods have been applied by using natural and artificial gamma radiations, respectively.[4)-6)] They all proved effective in laboratory system, but they have many disadvantages in practical use. The gamma radiations are so easily absorbed by water that the practical limit of measurable snow cover thickness is found in the range of 30 to 40 cm water equivalent. The attenuation mode of gamma rays through different density layers of snow cover is so complicated that the gamma ray beams emitted from artificial isotopes must be collimated as narrow as possible. This situation amplifies serious radiation hazards. Whereas the natural gamma ray technique is occasionally difficult to discriminate between terrestrial and extra-terrestrial origins.

Kodama et al.[7] noticed the attenuation in snow of cosmic-ray-produced neutrons, or, environment neutrons, instead of gamma rays. They determined the attenuation curve empirically from laboratory and field experiments as follows:

$$N_w = N_0 \exp(-0.753(1-\exp(-0.077w))), \quad \text{for } w \leq 30 \text{ cm} \qquad (1)$$

and

$$N_w = N_{30} \exp(-0.00578(w-30)), \quad \text{for } w > 30 \text{ cm} \qquad (2)$$

where N_w is the neutron count measured under snow cover having a water equivalent of w cm. N_0 and N_{30} are neutron counts at w=0 and w=30 cm, respectively.[8] Using these curves shown in Fig. 1, one can easily convert any neutron count N_w to the corresponding water equivalent of snow.

Fig. 2 shows one of the observation results obtained at mountain sites, where day-to-day plots of the snow water equivalent depths are given together with those taken by the Co-60 gamma ray radiography technique.

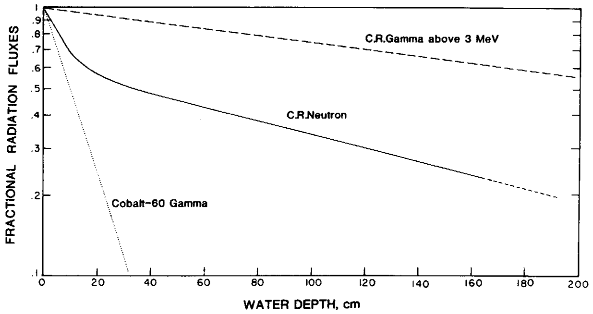

Fig. 1 Water attenuations of three different radiations: cosmic ray gamma with energies above 3 MeV, cosmic ray neutrons and gamma radiations from Cobalt-60 isotope.

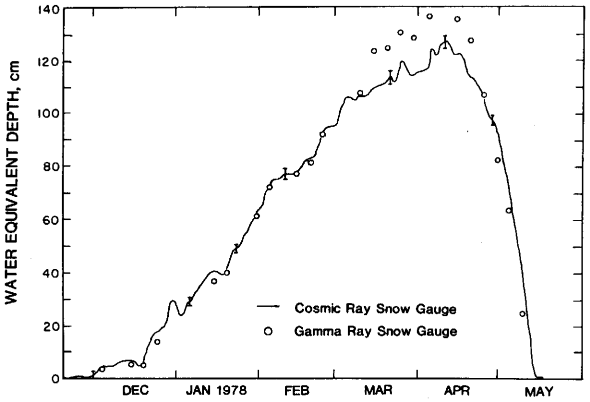

Fig. 2 Daily variations of water equivalent of snow determined by cosmic ray neutron radiography. Open circles are those estimated by gamma-ray radiography using a Cobalt-60 isotope.

An excellent agreement is found in day-to-day variations of snow water equivalents between the both techniques, except for the short period before and after the maximum value of water equivalent. Such higher values obtained by the gamma ray snow gauge could be attributed to a little bend of a suspension pole of the detector due to transverse stress in deep snow cover. Hence it is concluded that the cosmic ray neutron radiography is superior to the gamma-ray one, particularly for the measurement of deep snow covers.

2.2 *Soil moisture content*

A technique is already established that measures soil moisture contents by using an artificial neutron source.[9] But serious radiation harzards again are innevitable in this case. Kodama et al.[10] have examined whether or not cosmic ray neutrons are available in place of artificial neutrons. If a neutron detector is buried at an underground depth, the neutron fluxes thereby obtained are modulated by soil moisture contents surrounding the detector,because neutrons in soil move upward as well as downward. This means that there should exist an optimum depth where it appears the maximum response of neutron flux to soil moisture content. A quantitative relationship between the both parameters has been investigated under some artificial rainfall experiments.

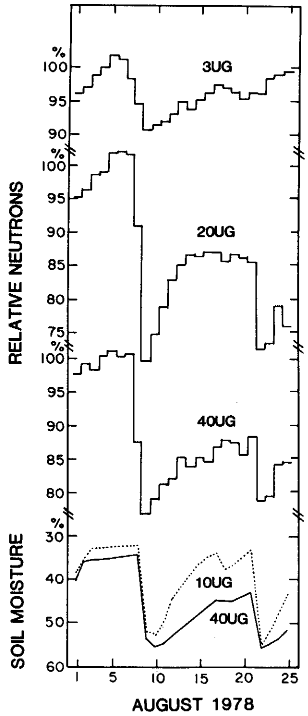

Fig. 3 Daily variations of relative neutron fluxes and soil moisture contents(eg. 20 UG means 20 cm underground depth).

Fig. 3 shows time profiles of the neutron fluxes and the soil moisture contents measured by the tensiometers during a month. This leads us to a quantitative relation of a fractional change ratio of 1% per 1% over a variational range of soil moisture content from 33% to 52% at 20cm depth.
Fig. 4 gives two correlation diagrams between neutron fluxes at the 40-cm depth and soil moisture contents at two different depths.

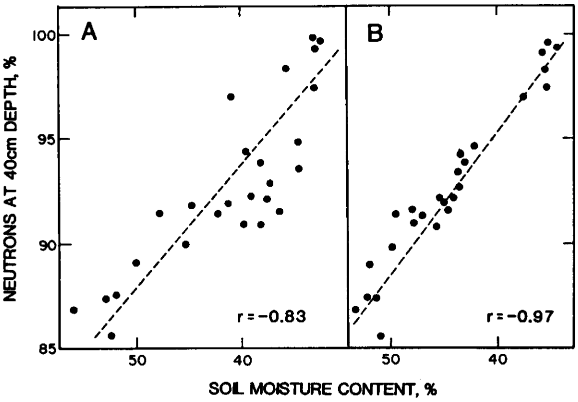

Fig. 4 Correlations between neutrons at 40cm deep and soil moisture contents measured at (A) 10 cm and (B) 40cm deep.

A better correlation in the case (B) means that neutrons measured at a depth are more sensitive to the water content distributed around the neutron measuring point than at any other depth. This character suggests a feasibility of estimating soil moisture contents as a function of depth.

3. Cosmic-Ray Muon Radiography

The cosmic rays observed near the ground level consist mainly of muons and electromagnetic cascade showers, whose exposure rates are 2.7 and 0.8 μR/h, respectively, in Nagoya, Japan at the minimum phase of solar activity.[11] Most of the electromagnetic components are absorbed within a few meters of water, while the relaxation length of the muon component amounts to around 20m water. We have so far studied cosmic ray exposure rate perturbations due to normal concrete building,[12] Nagoya Castle[13] and subway tunnel.[14,15]

3.1 *Method*

We present how to estimate bulk densities of a construction using cosmic ray muons. Cosmic ray exposure rate is expressed as

$$J=G(\theta,\rho r)F(\theta)dw \qquad (3)$$

where J is the exposure rate at a point inside or under the construction, $F(\theta)$ the above-mentioned incident exposure rate per unit solid angle with respect to zenith angle θ, $G(\theta,\rho r)$ the ratio of exposure rate after a transit distance r to $F(\theta)$, with r and ρ being the distance between the surface element dS and the point and the bulk density, respectively, dw the solid angle which area dS subtends to the point of interest. The functions F and G are reported in the previous paper.[11] The unknown parameter ρ can be obtained from eq.(3) when the exposure rate is measured by using a 3-inch ϕ spherical NaI(Tl) scintillation counter. This method of detection has already been reported of evaluating the exposure rate from the count rate for the absorbed energies above 3 MeV, which is the threshold energy level for discriminating environmental gamma rays emitted from natural radioelements, i.e., Uranium, Thorium and Potassium included in soil or constructions.[16]

3.2 *Subway Experiment*

Muon flux measurements were carried out at the 64 stations on the Nagoya City subway network consisting of four main lines as shown in Fig. 5. The cosmic ray exposure rates obtained at a point on the platforms are indicated there by five different circular symbols in unit of μR/hr. The time required for the measurements is only ten minutes each. It is evident that these exposure rates are different widely from station to station, as well as from line to line. They should essentially be subject to both the soil cover thickness over the platform and the geometrical depth of the platform.

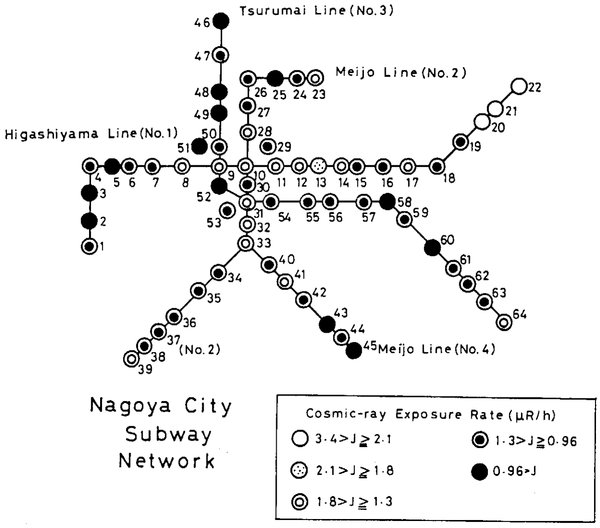

Fig. 5 Map of the cosmic ray exposure rates measured in the Nagoya City subway network. The exposure rates obtained at subway stations are represented by five steps of circle symbols.

As an example, let us examine the cross section structures on the line No. 1. Assuming the bulk density of medium between the ground surface and the platform, we can derive from the observed exposure rates the expected depths by using eq.(3). Fig.6 shows the platform depths calculated for three different bulk densities of the medium, together with the depths measured in practice. A gross consistency between the both depths, calculated and measured, is found in the case of ρ =1.5. However, there still remains a significant difference between the both at some stations. Such deviations suggest that the bulk densities for individual stations are not always identical or homogenous but complicated or inhomogenous throughout the entire line. This seems to be due to different array of concrete buildings on the ground or different constructions of underground housing.

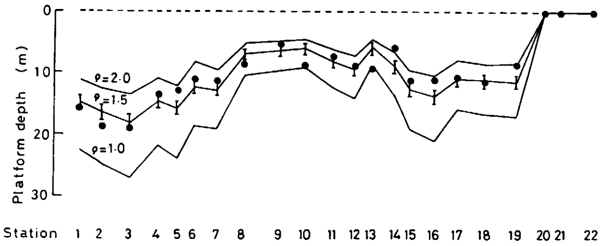

Fig. 6 Underground depths of subway stations. Three solid lines are those estimated by cosmic ray muon radiography under the assumption of three different bulk densities of medium between the ground and the subway platform. Solid circles are those measured actually.

4. Discussion

Cosmic ray radiography should be evaluated in the light of the following four factors: a) attenuation length, b) primary cosmic ray modulations, c) atmospheric effects, and d) counting rate statistics. The factor a) determines which is more suitable muon or neutron radiography, and the other three factors are directly related to continuous monitorings or spatial surveys of an object. As for b), possible time variations of primary cosmic radiations such as the Forbush decrease and solar cosmic ray events must be corrected, if they reveal the comparable order of magnitude with the environment perturbations of interest. The correction for the barometric pressure variations is always essential for the neutron radiography, because cosmic ray neutron flux is most sensitive to any barometric pressure change.

Now let us consider the factor d) which gives an applicable limitation of cosmic ray radiography. It is an essential point for the cosmic ray radiography whether or not the amplitude of cosmic ray flux changes measured for an object as a function of time or position is large enough beyond the statistical uncertainty. Fig.7 shows the mutual-relation among neutron flux, N_w,the standard deviation, σ_w, and snow water equivalent depth, W, choosing 10^4 as the neutron counting rates without snow cover. It should be noted that the relative errors of σ_w/W are less influenced by W-values beyond 100 cm depth. This means that the neutron radiography is effective even for deeper snow cover.

In case of the soil moisture measurement, availability of cosmic ray neutron radiography is subject to somewhat severe condition of measurement. A relative response of neutron flux to any change of water content in soil is found to be~1%/1% from Fig.4, while it is ~1%/5% from eq.(1) for thinner snow cover. However, the entire range of possible soil moisture change is far smaller than that of the snow water equivalent change. This situtation requires more sensitive response of neutron fluxes to soil moisture content, particularly for preferable measurements against different underground depths. Some improvements will be necessary for the method of neutron measurements.

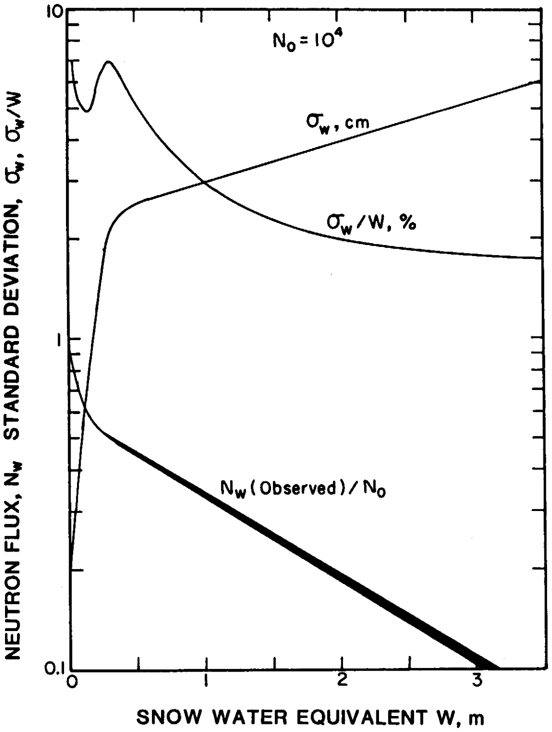

Fig. 7 Relations of the experimental errors based on observed neutron counting rates and snow depth. Absolute and relative standard deviations, σ_w and σ_w/W, are shown together with the observed counting rates, N_w/N_0 as a function of snow water equivalent depth W, where the standard count level N_0 ia assumed as 10^4.

As for the cosmic ray muon radiography, further measurements of directional muon components by the coincidence method could be essential for finner estimations of cross section structure of any construction or soil layer. Since the absolute flux of muon component is higher than that of the nucleonic component in the vicinity of ground surface, it seems possible to measure the directional fluxes of muons with appreciable statistics under some conditions of measuring method, site and time. The present subway experiment certainly suggests such a feasibility.

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