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Bulk Density Estimates of Buildings Using Cosmic Rays

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A simple formula is derived for propagation of cosmic rays through matter to calculate intensities inside and outside large objects of different densities. The bulk densities of the objects are estimated by comparing calculations and measurements. Evaluations for normal concrete building are made as an example of large structural material; the bulk density is shown to be around 0.5 g/cm^3.

1. Introduction

Cosmic rays are an extremely penetrating radiation compared to γ rays and neutrons from usual radioisotopes. Several attempts have been made for the practical application of cosmic rays for estimating snow depth, soil moisture content and upper atmospheric temperature.[1]

Although non-destructive testing by means of isotopes is widely used in a variety of industries, the size of test pieces is severely limited by the energy of the radiation. In addition, the use of stronger sources gives rise to a certain degree of insecurity on handling. If the cosmic rays were effectively applied, we would be able to inspect larger objects in safety. From this point of view; we tested a method of estimating densities of large structural materials as one of a set of feasibility studies on the practical application of cosmic ray non-destructive testing. For the study reported in this paper, concrete buildings of several different types were chosen as test pieces.

2. Method

The intensity of cosmic rays transmitted through material is represented as a function of the shape and density of the material. We can, therefore, estimate the bulk density of a building by analyzing the shape and the measured intensity data.

We assume that the cosmic rays penetrate rectilinearly and that a building is a homogeneous and uniform body. Indoors, we express the exposure rate due to cosmic rays as

$$J = \int_S F(\theta) G(\theta, \rho r) \frac{\cos\beta \, dS}{r^2}. \qquad (1)$$

Here, J is the cosmic ray exposure rate at a point of interest, $F(\theta)$ the incident exposure rate per unit solid angle with respect to zenith angle θ, $G(\theta, \rho r)$ the ratio of exposure rate after a 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, S the surface area of the building, β the angle between the direction of incidence and normal incidence of the surface element dS, and $\cos\beta \, dS/r^2$ the solid angle which area dS subtends to the point of interest. The terms θ, r and β are functions of the position of dS.

Outdoors,

$$J = \int_{S-S'} F(\theta) G(\theta, \rho l) \frac{\cos\beta \, dS}{r^2} + 2\pi \int_0^{\pi/2} F(\theta) \sin\theta \, d\theta - \int_{S'} F(\theta) \frac{\cos\beta \, dS'}{r^2}, \qquad (2)$$

where l is the path length of cosmic rays inside the building along the straight line intersecting dS and the points, S' the visible surface area subtending to the point, and $S - S'$ the surface out of sight. The sum of the second and third terms of the right-hand side of equation (2) represents the exposure rate due to the component which does not pass through the area S'.

If we can determine the form of the functions G and F, the unknown parameter ρ can be obtained from equations (1) and (2) and measured exposure rate J.

3. Analytical Approximation

Here, we try to express F and G analytically. To do

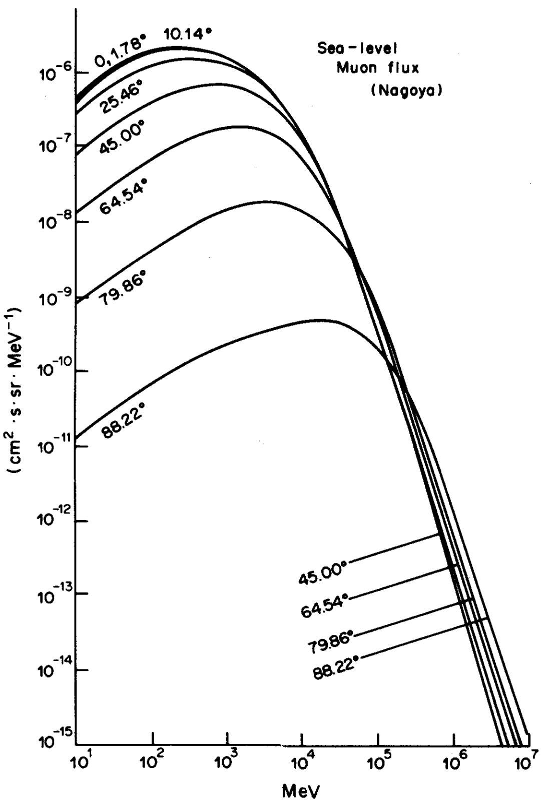

Fig. 1. Muon energy spectra for different zenith angles.

this, we calculate the depth exposure rate distribution in concrete for cosmic ray muons, electrons and photons.

3.1. Muon

In this study, double differential spectra with respect to energy and angle are used as sea-level muon fluxes at Nagoya, which were calculated by O'Brien using the computer code LUIN.[2] Those given in Fig. 1 are for the solar minimum. Assuming the rectilinear muon transport and neglecting the decay during transit, the muon spectrum $\phi(E, \theta, r)$ at a distance r in concrete can be calculated under the continuous slowing down approximation. Since aluminum is similar in atomic number to common building material, and since fundamental data concerning interaction of a number of types of radiation with this element are available, in this study the muon range of aluminum was used for concrete, taken from the work of Barkas and Berger.[3] The exposure rate in the unit of μR/h* at a distance r is obtained from the relation

$$j(\theta, r) = \frac{1.73}{W} \int_0^\infty \left(\frac{dE}{dx}\right)_{air} \phi(E, \theta, r)\, dE, \quad (3)$$

* Strictly speaking, the quantity "exposure rate" is only applied to γ rays of certain energies; however, we extend the meaning to include the exposure rate equivalent of ionization due to cosmic rays, since this is conventionally used in environmental radiation research.

where $W(=33.7\,\text{eV})$ is the energy required to produce an ion pair in air by muons and $(dE/dx)_{air}$ is the stopping power, data for which were also taken from Barkas and Berger.[3] Figure 2 shows the results.

This simple treatment on the calculation of exposure rate is slightly inaccurate near the air–concrete interface because of both the effect of electronic non-equilibrium and the difference in critical energy in the two materials which governs the cascade shower transport initiated by muon-produced knock-on electrons. The correction for this will be made in a later section.

The angular flux is often expressed in the form of the n-th power of $\cos\theta$. Analogically, we approximate the incident muon exposure rate by

$$F(\theta) = F_v \cos^n \theta, \quad (4)$$

where F_v is the vertical component.

As for the transmission fraction, we assume the exponential form

$$G(\theta, \rho r) = e^{[-\kappa(\theta)\rho r]}, \quad (5)$$

where κ is the mass attenuation coefficient.

Figure 3 gives the results derived from Fig. 2. The figure shows that $\kappa(\theta)$ can also be approximated by a power of $\cos\theta$ as

$$\kappa(\theta) = \kappa_v \cos^m \theta, \quad (6)$$

where κ_v is the vertical component.

3.2. Electron and photon

The LUIN code also provides the cosmic ray electron and photon spectrum. This, however, does not compute the double differential spectrum but only the scalar flux spectrum with respect to energy for pion- and muon-decayed electron and photon transport. In this section we calculate the variation of

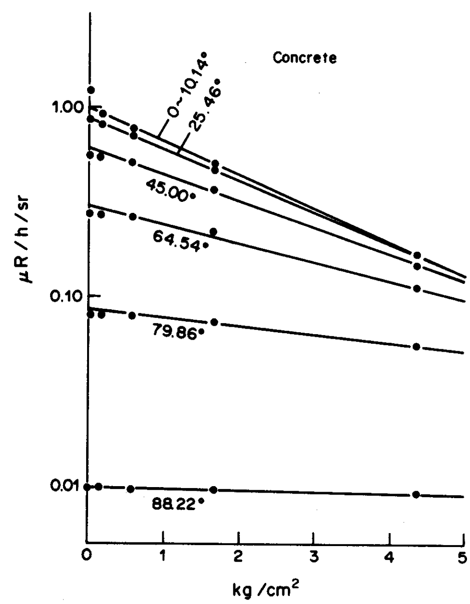

Fig. 2. Exposure rate due to muons transmitted.

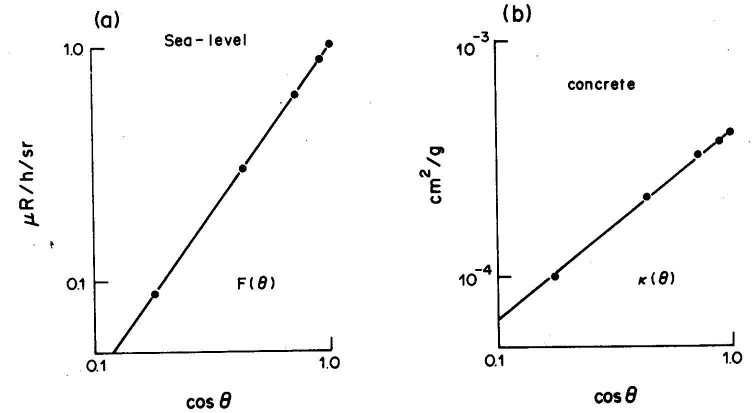

Fig. 3. Angular distribution of (a) sea-level muon flux and (b) of mass attenuation coefficient.

normally incident electron and photon exposure rate with depth in concrete using the scalar flux spectrum. Here, the angular distribution at sea level is approximated in the form of the third power of cos θ, as is described in Ref. (4). Furthermore, we incorporate the muon-produced knock-on component in order to precisely assess the influence of the effect of the air–concrete interface as was stated in the preceding section. The entire electron and photon components as input data are shown in Fig. 4. In a previous paper,[5] we have computed the depth exposure rate distribution for the transport of normally incident pion- and muon-decayed electrons and photons and muon-produced knock-ons for the scalar flux spec-

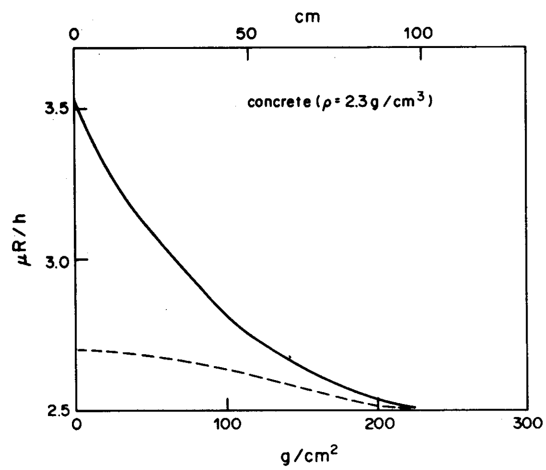

Fig. 5. Calculated total (solid line) and muon (broken line) components of omnidirectional cosmic rays for normal incidence.

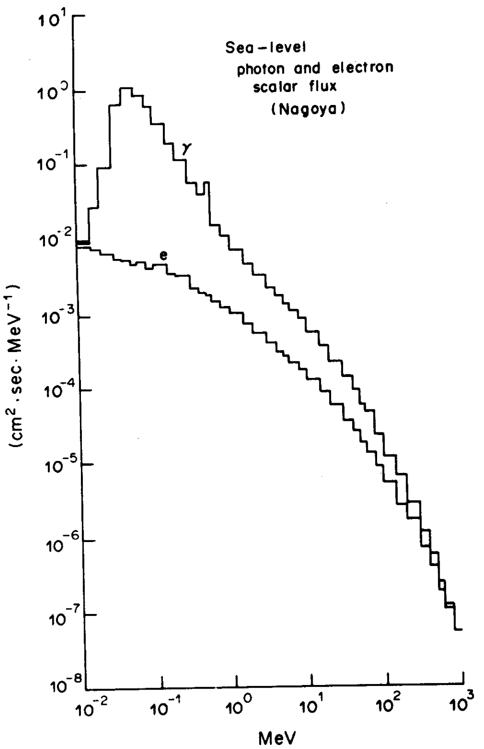

Fig. 4. Omnidirectional cosmic ray electron and photon energy spectrum.

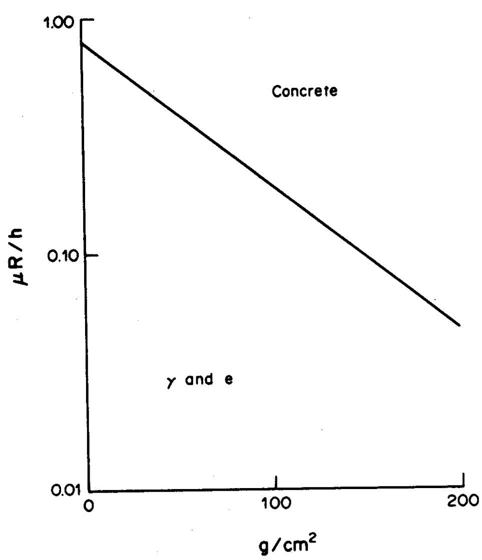

Fig. 6. Variation of electron and photon exposure rate with depth.

trum, adapting the cascade shower theory.[6] The production of knock-on electrons inside a concrete medium was also considered. Figure 5 shows the calculated total and muon-originated components. The difference between them is given in Fig. 6.

The mass attenuation coefficient is obtained from the slope of the curve in the figure.

4. Measurements and Comparison with Calculation

The measurements were carried out for two normal rectangular concrete buildings in our institute and inside Nagoya Castle using 3 in. ϕ spherical NaI(Tl) scintillation counter. The method of evaluating the exposure rate from the count rate has already been reported elsewhere.[5,7] Indoors, the exposure rate was measured at the center of the floor of each story of the building.

Next, numerically integrating equations (1) and (2), we calculated cosmic ray exposure rates for the above buildings, where 0.5 × 0.5 m was chosen as the surface element area. The constants in equations (4) and (6) used in the calculations are given in Table 1.

Figure 7(a) shows the calculated exposure rate variation with height for various bulk densities of the building, along with measured results inside the buildings of dimensions 15 × 33 × 24 m. It is found from the figure that the curve for a bulk density of 0.5 g/cm^3 fits fairly well to the measured data on the third floor or higher. The measured value of lower floors shows a slightly greater value than this, due to the existence of a covered passage attached to the end of the building (broken lines in Fig. 7), which is not taken into account in this calculation. The calculations and measurements outside at ground level are given in Fig. 7(b).

Figure 8 is another comparison, made along the line normal to the building intersecting the center of the base of the building, which is 16.6 × 94.3 × 11.0 m in size. Generally speaking, it seems satisfactory when the shape of the calculated curve is the same as the measured curve. In other words, the value of 0.5 represents the bulk density of these buildings. As the statistical error in measurement was within 5% for these cases, the difference between them might reflect the fine structure of the building. As a matter of fact, the exposure rate is somewhat perturbed at the right-hand side of

Table 1. Constants used for the calculations

	n	m	F_v (μR/h/sr)	κ_v ($\times 10^{-4}$ cm^2/g)
Muon	1.32	0.8	1.00	4.10
Electron and photon	3.00	0.0	0.522	135

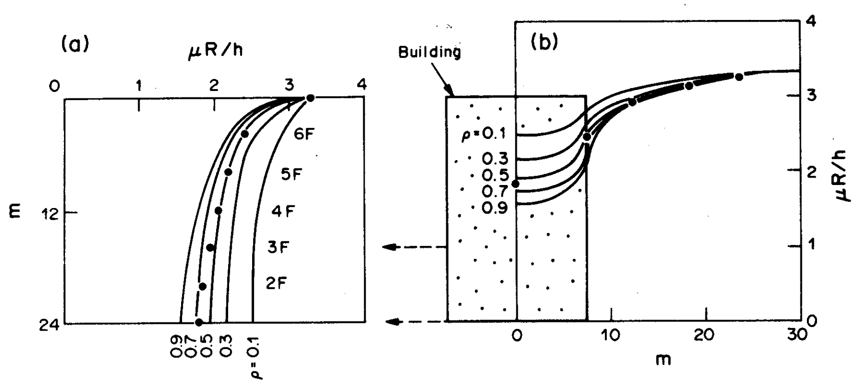

Fig. 7. Comparison of the calculated exposure rate curves for various bulk densities with measurements (closed circle) for a six-story concrete building at (a) each floor and (b) at ground level.

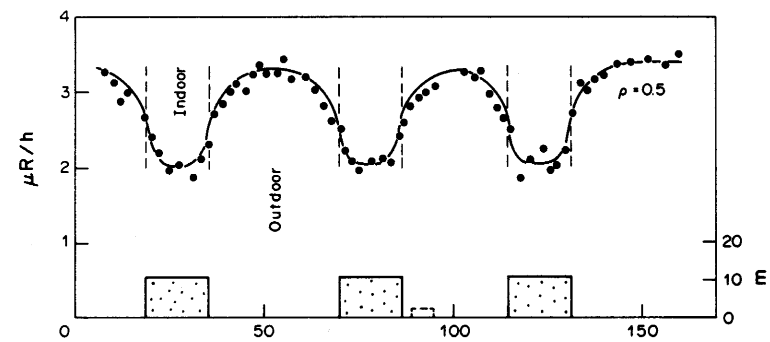

Fig. 8. Comparison of the calculation with measurements (closed circle) at ground level for three-story concrete buildings drawn up in three lines.

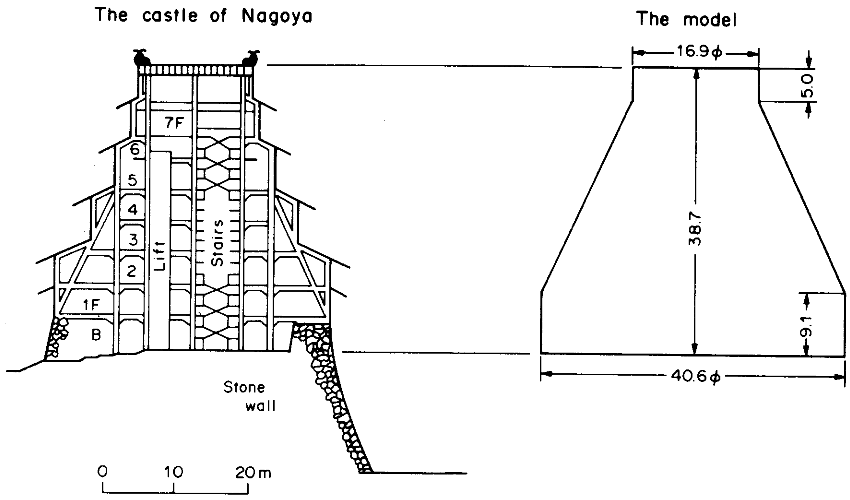

Fig. 9. The structure of Nagoya Castle and the model for calculation.

the second building due to a bicycle storage shed (broken line in Fig. 8) which is not taken into account in this calculation.

Nagoya Castle was built in 1609. The keep of this castle was reduced to ashes during the Second World War. The existing castle was rebuilt with concrete, to the exact scale in 1959, on the original foundation. The structure and the model used in the calculation are given in Fig. 9. Although the roof is made of Japanese-style tile, the calculation was performed assuming all materials to be concrete. Figure 10 shows the comparison. The bulk density value amounts to around 0.5 g/cm^3 for lower floors, and is gradually reduced for higher floors, as is seen in the figure. This decrease may be caused by the tiled roof.

5. Discussion

To assess the validity of the results provided by the theory described here, we compare them with experimental measurements by other researchers of simpler geometry.

Kvasnička[8] has measured cosmic ray muon dose rates in lake water in Czechoslovakia at depths up to 25 m using TLD's. The comparison of the calculated result obtained using mass attenuation coefficient for water with his data is given in Fig. 11. The broken line in the figure passes through the value of the sea-level muon exposure rate at Nagoya and is parallel to the line obtained from Kvasnička's measurements (chain line). The agreement between them is fairly good. Discrepancy at longer distances might be attributable to the rectilinear approximation, because, although at the beginning of its path, a muon suffers energy loss but very little scattering and thus moves in an almost straight line, with decreasing energy scattering increases. Supplemental data in seawater in Japan measured by Tokuyama *et al.*[9] are also shown in the figure for reference. Judging from these data, it seems that more experimental mea-

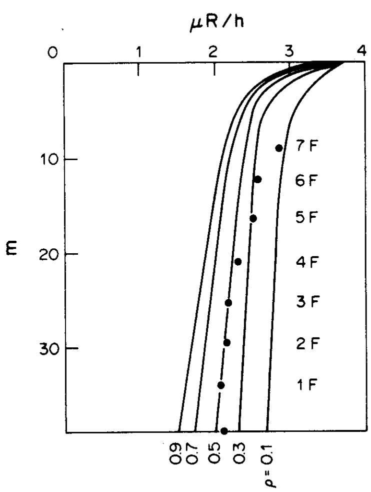

Fig. 10. Comparison of the calculation with measurements (closed circle) for Nagoya Castle.

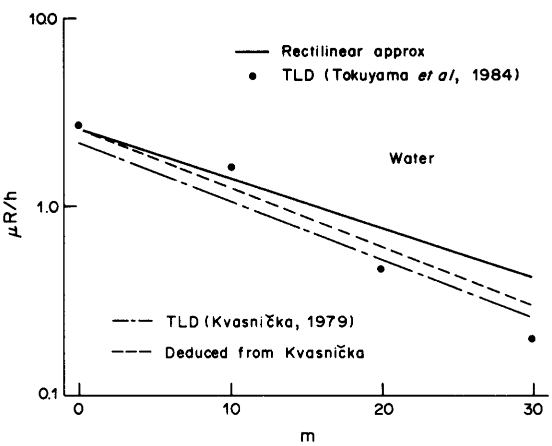

Fig. 11. The muon exposure rate dependence in water measured with TLD's and calculated from rectilinear approximation.

surements and theoretical considerations may be needed to obtain a more accurate result.

We found the bulk density of the buildings from evaluation in the preceding section to be about 0.5 g/cm^3. Let us discuss here whether or not this value is reasonable. The porosity, which means the relative pore volume in the building, amounts to 80% from the above bulk density value, assuming the concrete density to be 2.35 g/cm^3. This figure may be acceptable through rough eye-measurements of the surroundings. Deducing from a statistical report[10] on concrete building structures in Japan, we obtained a bulk density value of 0.3 g/cm^3 on average. Considering the many research installations and office fixtures inside the buildings, this would approach to some extent the observed value. Moreover, as the observed bulk density is evaluated as a weighted mean for cosmic ray angular and energy distributions, the true value would differ somewhat from the observed value, which depends on the structure of the building.

6. Concluding Remarks

If cosmic ray non-destructive testing becomes an established technique, it would enable us to provide a wide variety of applications, such as continuous monitoring of the water level of large rivers, the oil level of huge tanks, the water resources stocked in mountains, and the inspection of ancient ruins. It is hoped that this kind of study will be performed in collaboration with researchers in many fields.

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