

Muon flux measurement of tunnel overburden by mobile cosmic ray muon detectors

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ABSTRACT: Muon detectors used in previous studies are often large and inconvenient to carry, making it difficult to measure at multiple measuring locations. There are several methods for measuring muons, but they are generally performed using a large measuring device with scintillators arranged in parallel. The device is complex and expensive, which is a barrier to its application in increasing the number of observation objects. The main purpose of this study is to investigate the usefulness of a muon counts estimation method using a compact muon detector and measuring natural and artificial ground as close to the objects as possible. Since it is easy to carry, it is possible to obtain the muon counts as close as possible to the objects, and it can be installed on close outcrops, especially in order to understand the internal structure of the ground surface layer. If a method for understanding the internal structure of an object using a compact muon detector is established, it will be possible to easily maintain and manage infra-structures. In this study, a detector was manufactured based on a compact muon detector (Cosmic Watch) opened by MIT. By connecting two detectors with an audio cable, it is possible to detect only muons that pass through both detectors simultaneously. The number of muon counts measured was converted to the muon flux, the number of muons arriving per unit area, unit time, and unit solid angle for comparison. By installing this compact muon detector inside a tunnel, it is possible to measure muons passing through the tunnel overburden, the ground above the tunnel. Furthermore, by carrying and moving this compact muon detector in the longitudinal direction of the tunnel, it is possible to continuously investigate the geomorphological and geological structure above the tunnel in the longitudinal direction.

KEYWORDS: Cosmic ray muon, tunnel overburden, compact cosmic ray muon detectors

1 INTRODUCTION

In recent years, the deterioration of underground infrastructure such as sewer pipes and the collapse of sloping and vertical ground due to natural disasters like heavy rainfall and earthquakes have become significant social problems. To mitigate such geotechnical disasters, it is essential to understand the internal structure of the ground in advance and identify high-risk areas beforehand. Although non-destructive testing methods such as ground-penetrating radar and electrical resistivity surveys have been used to investigate the subsurface, these techniques require the artificial generation of radar waves or electrical currents, which limits their applicability depending on the environmental conditions. Furthermore, these methods are constrained in terms of the depth that they can effectively probe, making it difficult to examine subsurface structures non-destructively at depths ranging from several tens to several hundreds of meters. As a result, muon radiography—a technique utilizing cosmic ray muons that are less affected by artificial noise - is being explored as a promising alternative.

Cosmic ray muons are subatomic particles found in cosmic rays and possess high penetration capabilities due to their high energy. The technique of muon radiography, which leverages muons to image the internal structure of large-scale objects non-destructively, has been applied in fields such as civil engineering and volcanology (Nagamine, 1995; Tanaka and Takeuchi, 2014; Suzuki and Kanazawa, 2017; Namikawa et al., 2022). Notably, it has been used to observe the internal structure of Mt. Fuji (Ijima et al., 2019).

However, cosmic ray muon detectors used for applications such as the geological properties of volcanic mountains are typically large and require significant installation space, making them difficult to relocate. These large-scale detectors are primarily designed for fixed-point observation, and there are very few examples where muon detection has been performed continuously while moving the detector. If muons could be measured while the detector is in motion, it would be possible to continuously capture the internal structure of the ground.

In this study, we developed a compact muon detector that is lightweight and portable by a single person. We first conducted fundamental measurements to examine the reliability and reproducibility of muon detection using the device (Goto et al., 2024a). Then, we carried out measurements

of upward-going muons entering vertically within a tunnel by either fixing or continuously moving the compact detector from the tunnel entrance into its interior. Based on the resulting muon count data, we attempted to analyze the topographical and geological characteristics of the ground above the tunnel in a continuous manner, which is reported herein.

2 COMPACT COSMIC RAY MUON DETECTOR

2.1 Development

The muon detector used in this study (Figure 1) was developed based on the "CosmicWatch" compact muon detector, for which the construction method is publicly available from the Laboratory for Nuclear Science at the Massachusetts Institute of Technology (MIT). Each detector contains a 5 cm × 5 cm square scintillator (25 cm² in area) to detect muons. By stacking two detectors vertically and connecting them with an audio cable, it becomes possible to count only those muons that pass through both scintillators. The housing dimensions of a single detector are 108 mm × 85 mm × 40 mm, and the weight is approximately 215 g. The authors have used this detector in fundamental studies as well as for measurements inside tunnels and along river levees (Goto et al., 2024b; Goto et al., 2024c).



Figure 1. Compact cosmic ray muon detector.

In muon measurements, it is common to use two or more detectors arranged such that only muons passing through all detectors simultaneously are counted. The farther apart the

detectors are placed, the narrower the measurement area becomes, but spatial resolution improves, allowing for more precise determination of muon incident direction. However, the number of detected muons decreases, requiring longer measurement times. Conversely, if the detectors are placed closer together, the measurement area widens and measurements can be completed in a shorter time, though with reduced spatial resolution. Therefore, it is necessary to fully understand the target structure and available measurement time to design measurements that are well-suited to the characteristics of the detector system.

In muon measurements, the evaluation is typically expressed in terms of the number of muons per unit area, per unit time, and per unit solid angle - referred to as muon flux. This study also uses muon flux as the primary metric for analysis.

When using circular scintillators, the solid angle corresponds to the angle formed by lines drawn diagonally between the surfaces of the upper and lower scintillators. The effective detection area forms a conical spread defined by the circular scintillator surfaces. In contrast, for square scintillators, the solid angle varies depending on the location of the observation point on the surface, requiring more complex calculations for precise determination. Consequently, when square detection surfaces are used, errors in the calculation of solid angles can lead to inaccuracies in determining muon trajectories. Furthermore, the method for calculating the solid angle depends on the effective detection range, making it essential to clearly define the area in which muons are being detected.

This section investigates how variations in the measurement range influence the relationship between the observed muon flux and its empirical value. It also examines the effects of different solid angle calculation methods on the resulting muon flux.

2.2 Calculation of solid angle

The method for calculating the solid angle is based on the simple equation. It involves approximating the detection surface as a circle with an equivalent area and determining the spread of a cone corresponding to that circle. Figure 2 illustrates the conceptual diagram. In the figure, l is the length of the receiving area, w is the width, A is the area, h is the cone height, and r is the slant height. The solid angle Ω is then given by simple formula as Equation (1).

$$\Omega = \frac{A}{r^2} = \frac{lw}{\frac{lw}{\pi} + h^2} \quad (1)$$

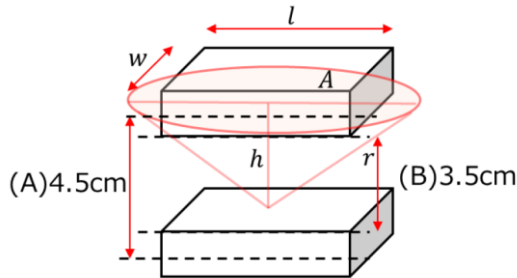


Figure 2. Solid angle.

In this study, the cone height h was determined using two methods for calculating the solid angle: (A) the distance between the centers of the scintillators (4.5 cm), and (B) the distance between the lower edge of the upper scintillator and the upper edge of the lower scintillator (3.5 cm). All other values depend on the dimensions of the scintillators.

2.3 Fundamental muon flux measurements

In October and November 2023, measurements were conducted on the rooftop of the Faculty of Engineering at University of Yamanashi, Japan, with the detection surface oriented northward. The elevation angle was varied across seven settings: 90°, 80°, 60°, 45°, 30°, 15°, and 0°. The measurement time was calculated theoretically to obtain 100 muon counts; however, if the theoretical time was less than one hour, a full hour of measurement was performed. In this study, square scintillators with side lengths of 5 cm, 4 cm, 3 cm, and 2 cm were used, and measurements were taken for each type of detector. Figure 3 shows a cross-sectional diagram of the scintillators.

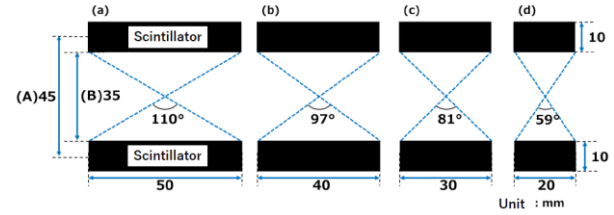


Figure 3. Size and distance of scintillators used for measurement (cross-section).

2.4 Minato's empirical formula

The measured muon flux values were compared to those estimated using Minato's empirical formula (Minato, 1992). This formula, proposed by Minato, describes the relationship between muon flux, zenith angle, and surface density (the product of density and travel path length). The equation is shown below.

$$I_{\mu}(h, \theta) = I_{\mu 00} \cos^{\alpha + \beta h} \theta \exp\left(-\frac{h}{A + Bh + Ch^2}\right) \quad (2)$$

$$I_{\mu 00} = 0.00723 \left(\frac{1}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}\right), \alpha = 1.495,$$

$$\beta = 0.02018 \left(\frac{\text{cm}^2}{\text{hg}}\right), A = 17.61 \left(\frac{\text{cm}^2}{\text{hg}}\right),$$

$$B = 0.1404 (\text{cm}^2 / \text{hg}^2), C = -7.069 \times 10^{-5} (\text{cm}^2 / \text{hg}^4)$$

$I_{\mu}(h, \theta)$: muon flux, θ : zenith angle

2.5 Results and discussions

Figure 4 and 5 illustrate the relationship between elevation angle and the measured muon flux by using Equation (1). For elevation angles from 0° to 30°, no significant differences were observed among the detectors. However, at angles from 45° to 90°, greater variation was seen. In the case of calculation method (B), it was found that the measured values approached the Minato equation as the scintillator width decreased. This is attributed to the fact that wider scintillators have a broader detection range, reducing directionality and leading to detection of muons from unintended directions. Conversely, in the case of method (A), the measured value using a 5 cm scintillator was the closest to the Minato equation, and the deviation increased as the scintillator size decreased. This may be due to underestimation of the solid angle caused by using the distance between scintillator centers as the cone height. These results suggest that muons are being accurately detected regardless of the passage point within the scintillator.

Figure 6 and 7 illustrate the relationship between elevation angle and the measured muon flux by using polar coordinates. These figures show that the effect of the scintillator size is smaller when polar coordinates are used than when using Equation 1. Therefore the following muon flux value was calculated using polar coordinates, and the distance between the bottom and top ends of scintillators.

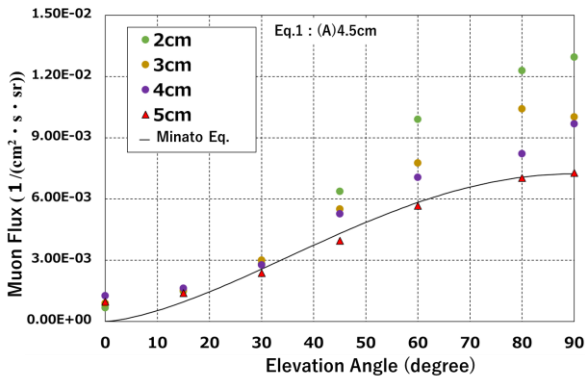


Figure 4. Relationship between elevation angle and muon flux when using the Eq.1 and (A)4.5cm : the distance between the centers of scintillators.

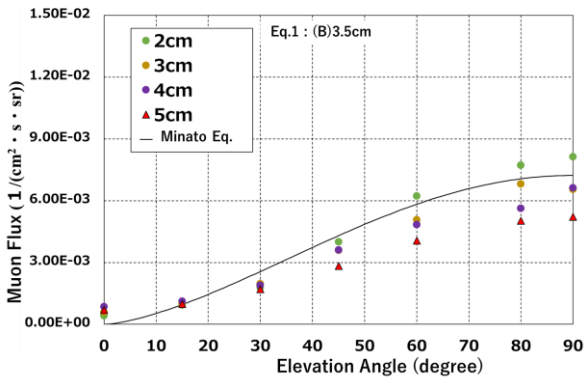


Figure 5. Relationship between elevation angle and muon flux when using the Eq.1 and (B)3.5cm : the distance between the bottom and top ends of scintillators.

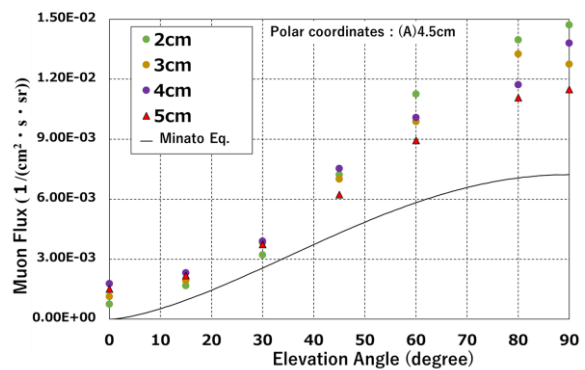


Figure 6. Relationship between elevation angle and muon flux when using the polar coordinates and (A)4.5cm : the distance between the centers of scintillators.

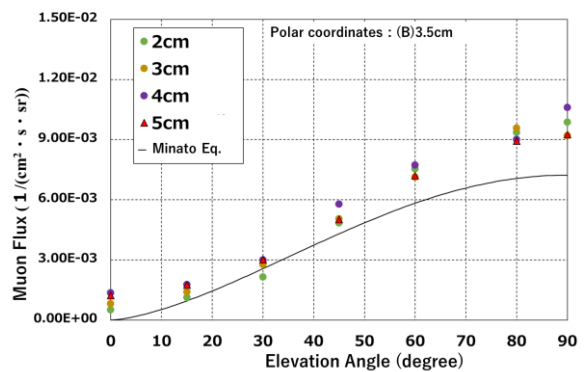


Figure 7. Relationship between elevation angle and muon flux when using the polar coordinates and (B)3.5cm : the distance between the bottom and top ends of scintillators.

3 MUON FLUX MEASUREMENT OF TUNNEL OVERBURDEN

3.1 Location and method

In August and October 2024, walking measurements were conducted using 12 muon detectors by a team of eight people in the Shichiriwa Tunnel, located in Nirasaki City, Yamanashi Prefecture. The total measurement time was three hours, comprising a cumulative total of 27.5 round trips. Figure 8 shows an aerial photograph of the tunnel area. The Shichiriwa Tunnel is 584 meters in length, 9.75 meters in width, and 4.5 meters in height. This tunnel was selected due to its geologically uniform tunnel overburden composed of Nirasaki debris avalanche deposits, and its cross-sectional shape approximating a trapezoid without ridges or valleys, making it suitable for two-dimensional analysis of the overburden.

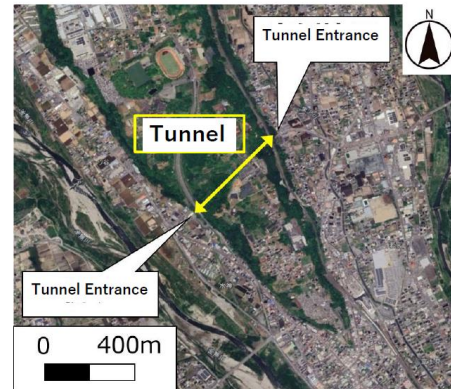


Figure 8. Aerial photograph of Shichiriwa Tunnel (Google Earth).

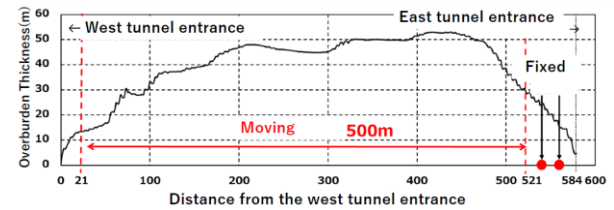


Figure 9. Overburden thickness of Shichiriwa Tunnel.

Figure 9 presents the tunnel overburden thickness, walking measurement section, and fixed-point measurement locations. Walking measurements were conducted over a 500-meter section, beginning 21 meters from the west entrance of the 584-meter-long tunnel. Additional fixed-point measurements were performed at 540 m and 560 m, outside the walking section. During the walking measurements, the detectors were held horizontally, and lap times were recorded every 50 meters while walking back and forth. Each detector recorded the exact time of muon detection. Using the start time and walking speed, the detection positions were estimated and aggregated into 10-meter segments. Figure 10 shows a histogram of muon counts for each 10-meter segment.

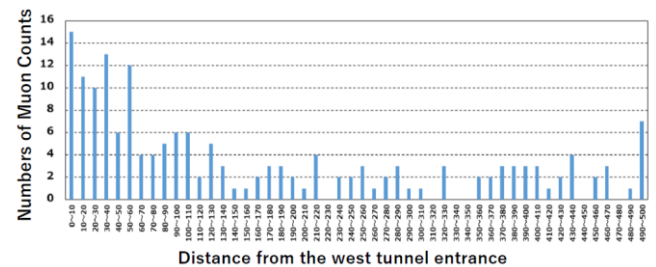


Figure 10. Muon counts per 10m section.

3.2 Results and discussions

From the measured muon counts, the muon flux—defined as the number of muons per unit area, per unit time, and per unit solid angle by polar coordinates—was calculated. In this measurement, the scintillator area was 25 cm², the solid angle was 0.697 sr, and the measurement times were 458 seconds for the walking measurement section and 900 seconds for the fixed-point locations. The time used for calculating flux in the walking section was the cumulative time that each detector was present at every 10-meter interval. Figure 11 shows the relationship between measured muon flux and overburden thickness. Muon flux is known to depend on the product of ground density and travel path length. In this study, the tunnel overburden consists of debris avalanche deposits, which are assumed to be of uniform density. Therefore, it was considered that the muon flux depends only on the travel path (overburden thickness), and it was confirmed that greater overburden thickness corresponded to lower muon flux, and vice versa.

Because the overburden above the Shichiriwa Tunnel consists of Nirasaki debris avalanche deposits, it was assumed to have uniform density. Debris avalanches are mass movements involving rock fragments and gases flowing down slopes due to mountain collapse, and the resulting deposits typically contain evenly distributed voids.

Muon flux was calculated using Minato's formula for densities of 2.0 g/cm³ and 2.5 g/cm³. Additionally, a density of 2.7 g/cm³—representing typical soil particles—was also used for comparison. Figure 12 shows the measured muon flux values alongside the calculated values from Minato's formula for each assumed density. Although some variation was observed, most of the measured values fell within the range corresponding to densities between 2.0 and 2.7 g/cm³. This variation is likely due to insufficient count statistics resulting from the short measurement durations, which can be resolved by accumulating more data through extended future measurements.

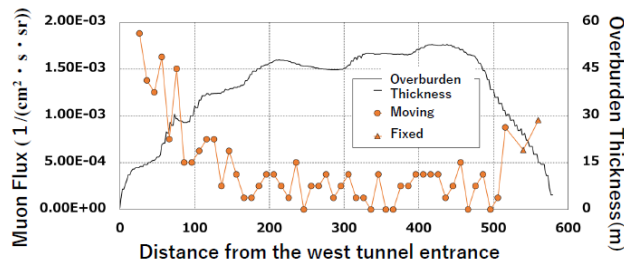


Figure 11. Overburden thickness and muon flux.

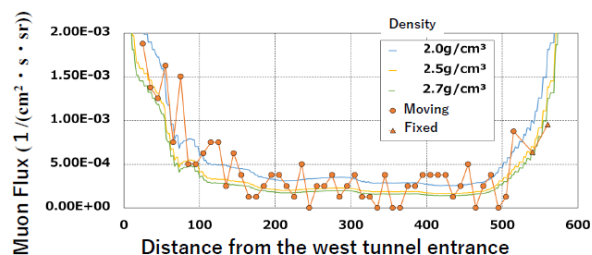


Figure 12. Comparison of actual measurements of muon flux and muon flux calculated by the Minato equation.

4 CONCLUSIONS

In this study, muon measurements were conducted using four different scintillator detection areas to evaluate how changes in detection range and two solid angle calculation methods affect the measured muon flux. It was confirmed that the effect of the scintillator size is smaller when polar coordinates are used than

when using Equation 1. These measurements and empirical formula show that muon flux value should be determined to calculate using polar coordinates, and the distance between the bottom and top ends of scintillators. These fundamental measurements also indicate that muons are being reliably measured by using compact cosmic ray muon detectors.

Muon flux measurements of tunnel overburden by mobile and fixed cosmic ray muon detectors were evaluated and discussed about the length and density of tunnel overburden. It is succeeded to obtain the muon flux values by using compact muon detectors, which are possible to explain the effect of length and density of tunnel overburden. If measured muon flux value is larger than the calculated value by empirical formula, then density of the tunnel overburden may be small. These muon measurements will contribute the maintenance of tunnel.

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