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Evaluation of Low-Density Regions in the Ground Using Cross-Hole Muography Considering Measurement Variability

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The inspection and maintenance of infrastructure, such as earthen structures, require the detection of weak zones through geotechnical investigations. This paper describes cross-hole muography, in which multiple compact muon detectors are installed within boreholes drilled into the ground, to evaluate the detection of weak zones in the subsurface - specifically, low-density regions. Firstly, cross-hole muography is carried out by installing detectors on both sides of a soil tank, as well as utilizing boreholes within an embankment. Next, a numerical analysis is performed using Lasso regression, considering spatial variations due to the shape of the detector scintillators. The analysis targets an embankment with a low-density region at its center. A method for evaluating such low-density regions is examined in this paper by determining the density distribution, the probability that the density is lower than that of the surrounding ground, and the standard deviation. The numerical results indicate that the identification of low-density regions is possible when the number of detected muons is 25 or more in the case of a density of 0.0 g/cm³, and 50 or more in the case of a density of 1.0 g/cm³.

Keywords: Cross-hole muography, Lasso regression, Ground density, Low-density region

1 Introduction

In recent years, the impact of climate change has caused an increase in heavy rainfall disasters, and the probability of large-scale earthquakes, such as the Nankai Trough earthquake, has also increased. As a result, concerns about potential damage to infrastructure in the event of disasters have also increased. Furthermore, many infrastructure facilities have been in service for long periods, namely, since their construction, and deterioration has progressed in numerous cases. Therefore, proper maintenance has become increasingly important. The inspection and maintenance of infrastructure, such as earthen structures, require an evaluation of the subsurface conditions through geotechnical investigations. However, conventional geophysical exploration methods, such as ground-penetrating radar, seismic surveys, and electrical prospecting, involve a trade-off between the exploration depth and the resolution, and no established method can currently achieve both an exploration depth of 1 to 10 meters and a resolution of 0.1 to 1 meter. Muography, an investigation method that utilizes cosmic-ray muons, is considered a technique capable of satisfying both the aforementioned exploration depth and resolution requirements, and has been applied in broader fields to date.

This paper describes “cross-hole muography,” in which small muon detectors are installed in boreholes. Based on the muography measurements, a method using Lasso regression for evaluating weak zones in the ground—namely low-density regions—is presented. Firstly, an experiment using a soil tank is conducted to verify the measurement conditions of muons and to understand the distribution of muon counts. Next, muography is applied to an embankment, and the density estimated from the measurement results, along with its statistical characteristics, is examined. Based on these results, the potential of muography to detect low-density regions is evaluated through numerical analysis using Lasso regression.

2 Cross-hole Muography

Muons are measured with the small-size muon detector shown in Fig. 1, which consists of a spherical plastic scintillator and a photomultiplier tube. Due to its small size, the detector can be installed in a borehole.

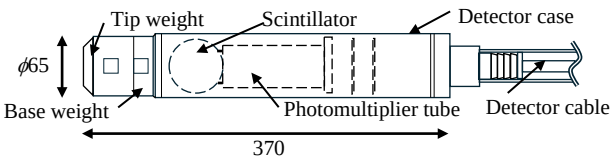


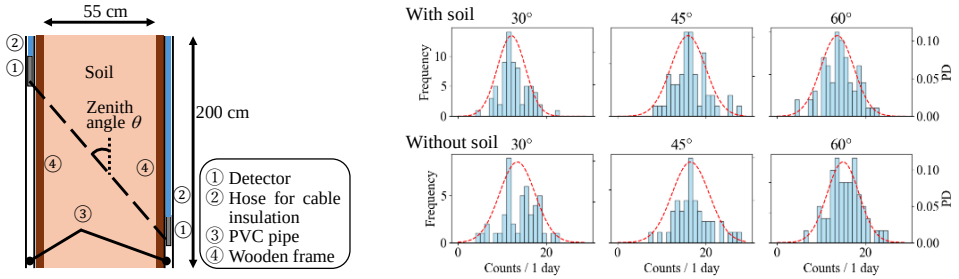
Figure 1. Schematic of muon detector. (Modified form Shibata et al. 2026)

When installed below the groundwater level, a weight can be attached to the tip of the detector to prevent it from

floating. Muons that pass through the scintillator emit faint light, which is converted into electrical signals by a photomultiplier tube and counted as muon detections. The detector is connected to the measurement unit via a cable, and the data are stored as digital files on a computer connected to the measurement unit. Two detectors are prepared, and by detecting the muons that pass through both scintillators, the arrival direction of the muons can be determined.

2.1 *Experiment Using Soil Tank*

An experiment using the above-mentioned soil tank was conducted to examine the distribution characteristics of muon measurements. As shown in Fig. 2 (a), a soil tank was constructed from a wooden frame measuring 200 cm in height, 55 cm in width, and 90 cm in depth, and filled with soil. Rigid polyvinyl chloride (PVC) pipes were fixed on the outside of the frame, and a detector was installed in each pipe to measure the muons. The measurements were performed for three cases with θ = 30°, 45°, and 60°. To evaluate the effect of the soil tank, measurements were also conducted with the pipes fixed at a horizontal position of 85 cm without the soil tank, using only the two detectors installed inside the pipes. Fig. 2 (b) shows the number of muon counts per day. The dashed curves in the figure represent normal distributions based on the mean and standard deviations calculated from the measurements. It was confirmed that, regardless of the presence or absence of the soil tank, the number of muon counts over a given period follows an approximately normal distribution.

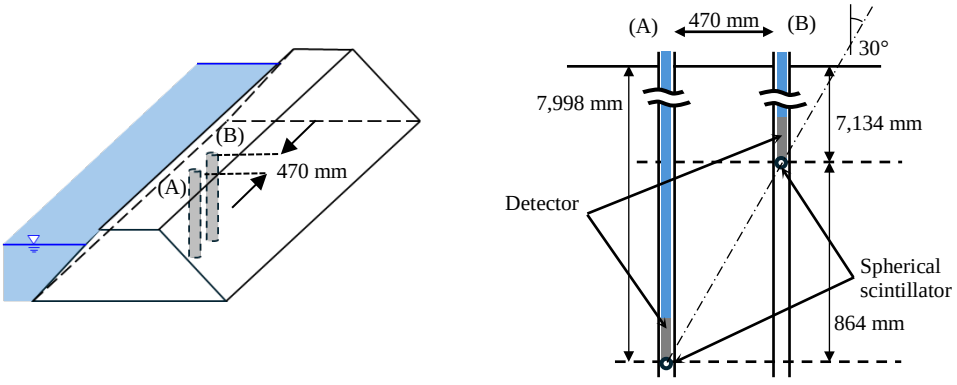


(a) Schematic diagram of experimental setup. (b) Distribution of muon counts.

Figure 2. Overview of soil tank experiment. (Reproduced from Shibata et al. 2026)

2.2 *Experiment on Embankment*

On-site measurements for cross-hole type muography were carried out on an embankment with a height of 4.2 m, a length of 38.0 m, and a total storage capacity of 2,000 m³. Fig. 3 (a) presents a diagram of the embankment with two boreholes for the muon measurements. Two scintillators were installed in the two boreholes, (A) and (B), respectively. Fig. 3 (b) shows the positions of the detectors, with the detector in borehole (A) being installed at a deeper location than borehole (B). In this paper, measurements were performed for muons with zenith angles of 30° and 60°.



(a) Schematic diagram of embankment with two boreholes. (b) Positions of two scintillators in boreholes.

Figure 3. Overview of experiment on embankment. (Modified from Shibata et al. 2026)

To determine the density from the number of measured muons, Minato's formula was used. The flux I, defined as the number of muons incident per unit area, per unit time, and per unit solid angle, is expressed in Minato's formula by Eqs. (1) – (3).

$$I = I_0 \cos^n \theta \exp\left(-\frac{h}{\Lambda(h)}\right). \tag{1}$$

$$\Lambda(h) = A + Bh + Ch^2 . \tag{2}$$

$$n = \alpha + \beta h . \tag{3}$$

where I is the flux, h is the mean density multiplied by the vertical distance, θ is the zenith angle, and I_0, A, B, C, α, and β are parameters with I_0=0.00723 (/cm^2/s/sr), A=17.61 (cm^2/hg), B=0.1404 (cm^4/hg^2), C=-7.069×10^{-5}(cm^6/hg^4), α=1.495, and β=0.02018(cm^2/hg). In using the above equations to derive the muon flux from the measured muon counts, the value of h could be calculated. The ground density was determined by dividing the value of h by the overburden thickness. Table 1 (a) presents the measured values from field observations and the test values, while Table 1 (b) shows the mean (Mean) and standard deviations (SD) calculated from the measurement results for one- and two-day periods, the standard deviation (SD-eq) obtained from Eq. (4), the coefficient of variation (CV), and the coefficient of variation (CV-eq) obtained from Eq. (4), in which N is the number of counts.

$$\sigma = \sqrt{N} \ . \tag{4}$$

Table 1. Field measurement results. (Modified from Shibata et al. 2026)

(a) Comparison of measured and experimental values.

Zenith angle (°)	30°	60°
Measurement period (day)	68	27
Number of counts	499	301
Measured value (g/cm^3)	2.20	1.27
Experimental value (g/cm^3)	1.95	

(b) Statistical indicators of measured values.

	One day		Two days
Zenith angle	30°	60°	30°
Mean (g/cm^3)	7.31	10.96	14.66
SD (g/cm^3)	2.54	2.57	3.40
SD-eq (g/cm^3)	2.70	3.31	3.83
CV	0.35	0.23	0.23
CV-eq	0.37	0.30	0.26

From Table 1 (a), it can be seen that the differences between the measured values and the experimental values are 0.25 g/cm³ and 0.67 g/cm³ for zenith angles of 30° and 60°, respectively. These errors can be explained by the small number of measured counts. Although the overburden is the same for zenith angles of 30° and 60°, the positions of the measurement lines on the ground surface differ, which indicates that measurement errors in the shape of the embankment do have an effect. In addition, the measurement lines for zenith angles of 30° and 60° include regions of high and low densities, respectively. From Table 1 (b), it can be seen that the measurement results are close to the values calculated using Eqs. (1) – (3) for all statistical indicators, which shows that Eq. (4) is also valid for muon measurements. It is evident that the daily number of measured counts can be approximated by a normal distribution.

3 Analysis Conditions

The analysis conditions, such as the size and density of the embankment, the locations of the low-density regions, and the positions of the detectors, are set, and the number of muons to be measured under these conditions is determined. Then, for these muon counts, their values are varied by considering the temporal and spatial fluctuations, and the corresponding mean density multiplied by the vertical distance is determined for each count. These densities are treated as observed values, and using the ground density as prior information, the original density distribution of the embankment is estimated to evaluate the low-density region.

Fig. 4 shows a two-dimensional model with a low-density region, measuring points, and measuring lines. The mesh size of the ground is 0.5 m × 0.5 m, the diameter of the four boreholes is 70 mm, and the diameter of the detector scintillators is 51 mm. The low-density region is square, with dimensions of 1 m × 1 m. The ground density is set to 2.0 g/cm^3, and the density of the low-density region in the ground is set to 1.0 and 0.0 g/cm^3.

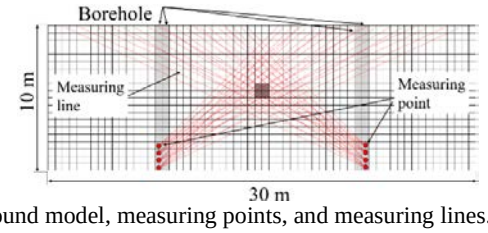


Figure 4. Schematic diagram of ground model, measuring points, and measuring lines. (Modified from Shibata et al. 2026)

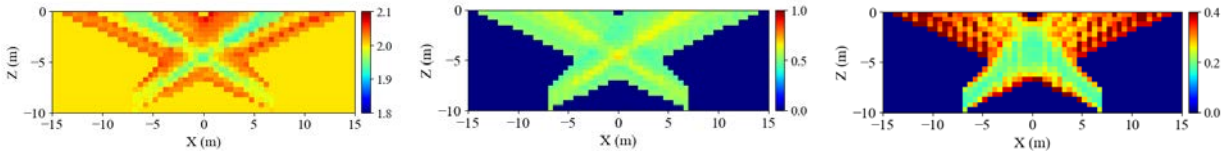
As shown in Fig. 4, the number of measurement points is set to a total of eight on both sides, and the measurement angles for each point are 45°, 50°, 55°, 60°, and 65°. The muon measurement count is simulated by the Monte Carlo method, and the results are estimated using Lasso regression. When using the Monte Carlo method, the temporal and spatial variations occurring during the muon measurement process are considered.

With regard to the temporal variations, muon counts can be approximated by a normal distribution, as mentioned above. From the position of the measurement point, the mean density multiplied by the vertical distance is determined, and the number of muons to be measured at that point is set as the mean value. The measurement time can be calculated from the values. Since the standard deviation is determined from Eq. (4) and this mean value, random numbers following a normal distribution are generated based on these values. Next, the spatial variations are discussed. As the detector scintillators are spherical, muons can pass through the center of the sphere or near its surface. Although the configurations of the detectors are the same, variations occur. Therefore, random numbers that account for shape effects are generated to simulate the actual measurement conditions. This method represents the spatial variation of the muons.

4 Analysis Results

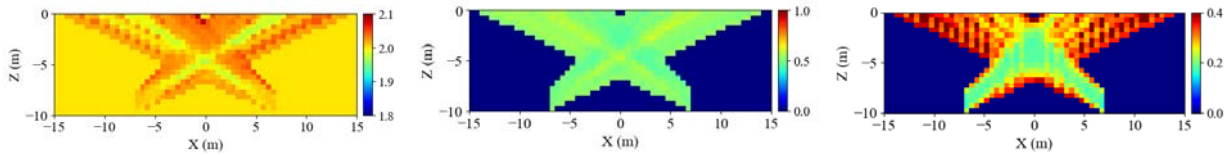
Numerical analyses were conducted for a low-density region with densities of 0.0 g/cm³ and 1.0 g/cm³, using muon counts of 25, 50, and 100. Figures 5 and 6 show the distributions of the analysis results for each density, and Table 2 presents the values of the low-density region obtained from the numerical analyses for all cases. From Fig. 5 (a) and Table 2, the mean density of the low-density region in Case 1 is seen to be is 1.944 g/cm³, and the probability that the density is lower than that of the surrounding ground in the low-density region is 0.645. This indicates that, at 25 measured muons, there is a possibility that the central area corresponds to a low-density region. Furthermore, Fig. 5 (c) shows a low standard deviation of density at the center of the ground, which is due to overlapping measurement lines in the low-density region. Here, the measurement time was up to three days for each measurement angle. Low-density regions can be identified and their locations can be determined based on the intersections of the measurement lines.

Next, the values of each distribution in Figs. 6 (a), (b), and (c) are similar to those in Figs. 5 (a), (b), and (c), but the differences in density and standard deviation between the low-density region and the surrounding ground are smaller in Figs. 6 (a), (b), and (c). From the values in Case 4 in Table 6, both the density and standard deviation of the low-density region are larger than those in Case 1, and the probability P(d<2.0) is lower. This indicates that, when the density of the low-density region increases from 0.0 g/cm³ to 1.0 g/cm^3, it becomes more difficult to identify the region. However, in Case 5 (50 measurements) and Case 6 (100 measurements), the probability P(d<2.0) is higher, indicating improved accuracy. From these results, it is clear that, for a low-density region with a density of 1.0 g/cm³, a measurement count of 50 or more - corresponding to approximately six days of measurement time - provides a high likelihood of identifying the low-density region.



(a) Mean density. (b) Probability of density falling below 2.0 g/cm^3. (c) Standard deviation of density.

Figure 5. Results for low-density region with density of 0.0 g/cm³ and 25 measured muons (Case 1).
(Reproduced from Shibata et al. 2026)



(a) Mean density. (b) Probability of density falling below 2.0 g/cm^3. (c) Standard deviation of density.

Figure 6. Results for low-density region with density of 1.0 g/cm³ and 25 measured muons (Case 4).
(Reproduced from Shibata et al. 2026)

Table 2. Values for each case.

Case	Density of low-density region (g/cm^3)	Number of measured muons	Mean density (g/cm^3)	Probability P (d < 2.0)	Standard deviation (g/cm^3)
1	0.0	25	1.944	0.645	0.186
2	0.0	50	1.909	0.763	0.132
3	0.0	100	1.896	0.838	0.107
4	1.0	25	1.991	0.545	0.189
5	1.0	50	1.947	0.667	0.130
6	1.0	100	1.941	0.711	0.102

5 Conclusion

A method for evaluating ground density using cross-hole muography with boreholes has been presented in this paper. When the density of the low-density region was 0.0 g/cm³, a muon count of 25 or more - corresponding to a measurement period of approximately three days - was sufficient to indicate candidate locations for the low-density region. When the density of the low-density region was 1.0 g/cm³, a muon count of 50 or more, corresponding to a measurement period of about six days, was found to provide a high likelihood of distinguishing the low-density region.

References

Shibata, T., Nishimura, S. and Takahashi, K., Evaluation of low-density regions using cross-hole myography, *Japanese Journal of JSCE*, 82(15), 25-15006, 2026. (in Japanese)