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Study on the Applicability of Muography Exploration Technology in Underground Space Development

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지하공간개발에서 뮤오그래피 탐사기술의 적용성에 관한 연구

서승환, 임현성, 고영훈, 곽기석, 정문경

Abstract Recently, the frequent occurrence of ground subsidence in urban areas has caused increasing anxiety in residents and incurred significant social costs. Among the causes of ground subsidence, the rupture of old water and sewer pipes not only halts the operation of the buried pipes, but also leads to ground and water pollution problems. However, because most pipes are buried after construction and cannot be seen with the naked eye, the importance of maintenance has underestimated compared to other structures. In recent years, integrated physical exploration has been applied to the maintenance of underground pipes and structures. Currently, to investigate the internal conditions and vulnerable portions of the ground, consolidated physical surveys are executed. Consolidated physical surveys are analysis techniques that obtain various material data and add existing data using multiple physical surveys. Generally, in geotechnical engineering, consolidated physical surveys including electrical and surface wave surveys are adopted. However, it is difficult to investigate time-based changes in under ground using these surveys. In contrast, surveys using cosmic-ray muons have been used to scan the inner parts of nuclear reactors with penetration technology. Surveys using muons enable real-time observation without the influence of vibration or electricity. Such surveys have great potential for available technology because of their ability to investigate density distributions without requiring as much labor. In this paper, survey technologies using cosmic ray muons are introduced, and the possibilities of applying such technologies as new physical survey technologies for underground structures are suggested.

Key words Muography, underground space, ground exploratioin, application feasibility

초 록 최근 도시지역의 지반침하가 빈번하게 발생하여 주민들의 불안이 증가하고 막대한 사회적 비용이 발생하고 있다. 지반침하의 원인 중 노후 상하수도관의 파열은 매설관의 가동을 정지시킬 뿐만 아니라 지반 및 수질오염 문제를 야기한다. 그러나 대부분의 파이프는 시공 후 매설되어 육안으로 볼 수 없기 때문에 다른 구조물에 비해 유지보수의 중요성이 저평가되고 있다. 최근 몇 년 동안 지하 파이프 및 구조물의 유지 보수에 통합 물리적 탐사가 적용되었다. 현재 지하 공간 내부와 지반취약점을 조사하기 위해 통합물리조사를 실시하고 있다. 통합물리조사는 여러 가지 물리조사를 이용하여 다양한 물성자료를 얻고 기존 자료를 추가하는 분석기법이다. 일반적으로 지반 공학에서는 전기 및 표면파 조사를 포함한 통합 물리 조사가 채택되지만, 이러한 조사를 이용하여 지하

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공간의 시간적 변화를 조사하는 것은 어렵다. 이에 반해 원자로 내부를 스캔하기 위한 투과기술로 우주선 뮤온을 이용한 탐사가 이루어지고 있다. 뮤온을 이용한 측량은 진동이나 전기의 영향 없이 실시간 관찰이 가능하다. 이러한 조사는 많은 노동력을 요구하지 않고 밀도 분포를 조사할 수 있기 때문에 활용 가능성 측면에서 큰 잠재력을 가지고 있다. 본 논문에서는 우주선 뮤온을 이용한 측량 기술을 소개하고, 이러한 기술을 지하 공간 및 지하 구조물에 대한 새로운 물리 측량 기술로 적용할 가능성을 제시한다.

핵심어 뮤오그래피, 지하공간, 물리탐사, 적용 가능성

1. Introduction

For a long time, scientists and engineers in geotechnical engineering have desired to be able to see structures or facilities buried in the ground or rock mass, as such masses are complex and opaque natural solids that cannot be fully penetrated by common techniques such as the usage of X-rays.

One method to understand information from the inside of ground or a rock mass is to do a ground survey accompanying core drilling from a ground or rock mass. However, it is very costly to thoroughly investigate the inside of a rock mass because a large number of drill holes are needed. This approach is limited for examining the ground beneath the structure. In addition to the drilling method, there are many conventional geophysical methods available for ground exploration, such as electromagnetic, magnetic, and ground-penetrating radar, seismic imaging, and gravity methods (Takahashi, 2004; Takahashi et al., 2006). Each of these methods has shortcomings in terms of usefulness or usability in geotechnical engineering applications (e.g., inadequate coverage, low resolution, high logistical costs, difficulties in availability, and the need for specifically trained or even outsourced professional personnel). Therefore as information on the ground is often lacking, geotechnical engineers face difficulties when checking the condition of facilities buried in the ground or mapping underground structures.

In general to investigate changes or vulnerable spots in the ground, it is essential to perform consolidated physical surveys using electrical and surface wave surveys. An electrical survey is a physical survey technique used to investigate the state of the ground by measuring its electrical properties (Sayed et al., 2011; NCHRP, 2006; Olson et al., 1998; Deng and Cai, 2010; Harry, 2005; Kim et al., 2005; Kim et al., 2004; Anderson et al., 2008; Pelekis and Athanasopoulos, 2011; Richart et al., 1970; Park et al., 1999; Das and Sobhan, 2006; Sagar et al., 2021). The distribution of underground resistivity can be measured by measuring the potential differences of another pair of current electrodes through the discharge of electric current from a pair of current electrodes installed on the ground surface. Using resistivity, it is possible to estimate soil structure through the distribution of resistivity because resistivity depends on various causes such as the types of minerals of the rocks, pore rates, saturation, the ratio of mineral components and surrounding temperature, etc. In addition, the permeability of the ground may be evaluated based on the correlation between the resistivity and permeability coefficients. A surface wave survey is a method to measure and analyze surface waves (Rayleigh waves) that pass through the ground surface in order to obtain the shear wave speed distribution of the ground. The speed of the shear wave is correlated with the N value and is treated as an index to denote the hardness of the ground; therefore, loose sections of ground can be estimated from the distribution of shear wave speed. When specifying vulnerable spots of the ground from the results of the consolidated physical surveys, the adequacy of observed values and settings of thresholds may be enumerated, and the validity of measured data needs to be closely examined. Additionally, threshold settings should be considered based on the properties of the target ground, characteristics of existing material data, and soil properties. Therefore, it is necessary to determine whether there is any correlation between the resistivity and shear wave speed obtained by the consolidated physical surveys and the safety evaluation index of the target ground. In addition, consolidated physical surveys are executed only for special checking; such surveys cannot handle changes occurring underground over time.

In addition to the above mentioned exploration methods, there are various nondestructive testing methods to detect underground spaces and structures inside the ground. Most of the nondestructive evaluation methods are seismic survey methods that artificially generate seismic waves using seismic wave generators installed on the surface, sea level, or boreholes, and then measure the waves reflected from the underground or stratum interface to determine the physical properties of the geological structure or strata (Wightman et al., 2003). Analyze. Tables 1 and 2 summarize the characteristics and application limitations of the existing non destructive physical exploration methods in investigating the weaknesses of the underground space and the ground.

Some shortcomings of the traditional methods mentioned above can be overcome by a relatively new remote mapping method called muography. This method is conceptually similar to X-ray imaging and hence is sensitive to density. However, unlike

Table 1. Comparison of nondestructive evaluation methods

Method	Applications	Advantages
Sonic Echo/Impulse Response	Most useful for columnar or tabular structures. Best penetration attained in loose soils. Good for determining thickness and geometry.	Lower cost equipment and inexpensive testing. Data interpretation may be able to be automated. Theoretical modeling should be used to plan field tests.
Bending Wave	Most useful for a purely columnar substructure. Best penetration attained in loose soils.	Lower cost equipment and inexpensive testing. Theoretical modeling should be used to plan field tests. The horizontal impacts are easy to apply.
Ultraseismic	Best penetration attained in loose soils. Good for determining thickness and geometry.	Lower cost equipment and inexpensive testing. Can identify the bottom depth of foundation inexpensively for a large class of bridges. Combines compressional and flexural wave reflection tests for complex substructures.
Spectral Analysis of Surface Wave	Good for determining thickness and geometry.	Lower cost equipment and inexpensive testing. Shows variation of bridge material and subsurface velocities verses depth and thickness of accessible elements.
Surface Ground Penetrating Radar	Can indicate geometry of inaccessible elements and bedrock depths.	Lower testing costs. Fast testing times.
Parallel Seismic	Accurate for determining foundation bottom depths for a large range of structures. Under certain conditions can indicate foundation orientation.	Lower cost equipment and inexpensive testing. Can detect foundation depths for largest class of bridges and subsurface conditions.
Borehole Radar	Good at determining foundation parameters. Sensitive to detecting steel or steel reinforced members.	Relatively easy to identify reflections from the foundation; however, imaging requires careful processing.
Induction Field	Highly sensitive to detecting steel or steel reinforced members that are electrically connected to the surface.	Lower cost equipment Easy to test. Compliments Parallel Seismic in determination of pile type.

X-ray-based methods, muography does not require any form of artificial radiation or radioactive sources. Instead, it relies on the natural muon flux that originates from the Earth's atmosphere. The application of muography in geotechnical engineering may have both technical and economic benefits. It can be used to investigate facilities or cavities buried in the ground through the muon penetrating through the ground. By counting the muon flux, it is possible to classify the material through the density difference according to the material in the ground. In addition, it can be used, for example, to monitor the stability of the upper ground layer in underground spaces like a downtown area.

Muons are subatomic particles that form in the atmosphere's higher layers. Muons are secondary cosmic ray products with a very high penetrating capacity. Only the highest energetic muons can travel from the surface to a depth of almost 2000 meters before stopping or decaying into other particles (Jillings, 2013; Wu et al., 2013). Muons were discovered in 1936 by Neddermeyer and Anderson (Neddermeyer, 1937). There are two important studies that have begun to utilize muon for research (George, 1955, Alvarez et al., 1970). The former measured the rock overburden of a hydroelectric plant tunnel in Australia, while the latter surveyed a pyramid in Egypt. Imaging based on muon detection is now referred to as muography (Tanaka et al., 2009). The rapidly growing applications of muography in the fields mentioned above have opened new possibilities for underground space, in which muography has great potential. Although muography has been employed in a variety of industries, including geotechnical engineering, its applicability in this field are currently limited. Therefore, it is necessary to introduce muography to underground space and geotechnical engineering so that this relatively new technology can be applied to solve problems such as overcoming the limitation of current physical exploration in these fields. Accordingly, this paper will briefly introduce the basic properties and characteristics of muons before describing the potential applications of muography to underground space.

Table 2. Comparison of nondestructive evaluation limitations

Method	Limitations
Sonic Echo/Impulse Response	Response complicated by bridge superstructure elements. Can only detect large defects. Stiff soils and rock limit penetration.
Bending Wave	Response complicated by various bridge superstructure elements. Response complicated by stiff soils that may show only depth to the stiff soil layer.
Ultraseismic	Cannot image piles below cap. Difficult to obtain foundation bottom reflections in stiff soils.
Spectral Analysis of Surface Wave	Cannot image piles below cap. Use restricted to bridges with flat, longer access for testing.
Surface Ground Penetrating Radar	Higher cost equipment. Signal quality is highly controlled by environmental factors. Adjacent substructure reflections complicate data analysis.
Parallel Seismic	Difficult to transmit large amount of seismic energy from pile caps to smaller (area) piles.
Borehole Radar	Radar response is highly site dependent (very limited response in conductive, clayey, salt-water saturated soils).
Induction Field	The reinforcement in the columns is required to be electrically connected to the piles underneath the footing. Only applicable to steel or reinforced structures.

2. Muons and Muography

2.1 Cosmic Radiation Muons

Muons are elementary particles generated by the collision of high-energy cosmic rays with atomic nuclei in the atmosphere. Elementary particles are generally divided into Fermi particles consisting of materials; gauge particles, which are mediated by the force; and Higgs particles, which give mass to the objects (Bonechi et al., 2019). Among the Fermi particles, the most well-known are electrons, which are also part of the elementary particle group called leptons; muons are also leptons. Leptons have high penetration, as they show no strong interactions.

Cosmic rays are high-energy particles that come from space and are called primary cosmic rays. Primary cosmic rays generate various particles by colliding with molecules or atomic nuclei in the atmosphere (Bugaev et al., 1998). Newly generated particles are called secondary cosmic-rays, and most exist only shortly; therefore, they are quickly broken into other particles or absorbed in the air (Kvasnicka, 1979; Marteau et al., 2013). However, muons have a low decay rate and therefore can penetrate up to several meters into the ground.

2.2 Principle of Exploration through Muography

The principle of surveying using cosmic-ray muons is to calculate surface densities (density × height) in each direction through the thickness of the ground up to a specific depth by measuring the number of muons at each angle after placing a muon detector in an underground space (e.g., a tunnel). The angle at this time is called the zenithal angle (θ) with 0° in the vertical direction and is defined as a direction whose value increases as it becomes closer to the horizontal plane (Fig. 1).

At any time, a nearly constant number of cosmic-ray particles reaches the ground surface. If the ground surface is horizontal and the ground density is constant, the number of absorbed particles will increase as the penetration distance increases, so the number of muons reaching the detector will decrease. Thus, in measurements at the same depth, the quantities of muons decrease as the zenithal angle increases.

Meanwhile, if the ground density is not consistent and there exists an area with low density, the number

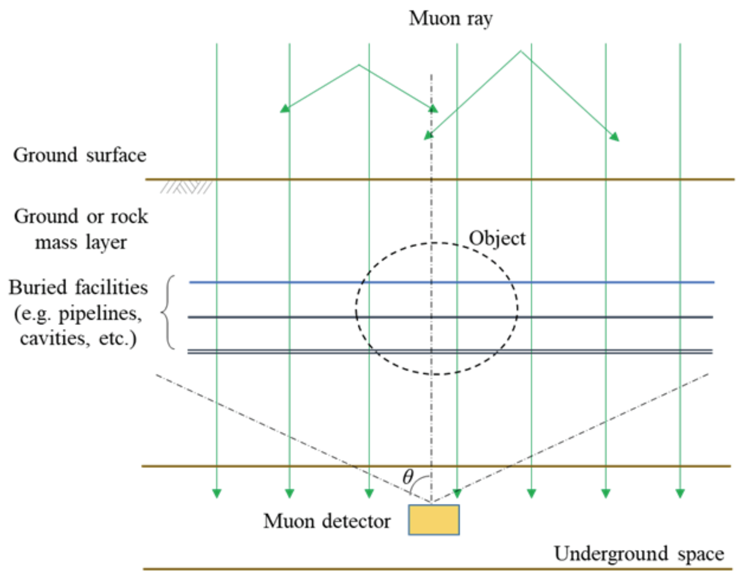

Fig. 1. Diagram of muon travel and detector for underground space.

of muons that reach the detector will increase, as the absorption of the ground will decrease at a sidetrack that passes the position. In this method, the ground density distribution can be obtained by calculating the zenithal angle distribution of the counting results through the measurement of muons in the direction of each zenithal angle.

As for the relationship between surface density and muon flux (the number of muons per unit time × unit area × unit solid angle), we suggest two experimental equations prepared by Minato (1986) and Miyake et al. (1964). Assuming that the surface density is h(g cm^{-2}), and assuming the zenithal angle is θ, the muon flux is given in the following Equation (1) by Minato.

$$I_{\mu}(h,\theta) = I_{\mu 00}\cos^{n}\theta \bullet \ln\left(-\frac{h}{\Lambda(h)}\right) \tag{1}$$

$\Lambda(h)$ and n are expressed using Equations (2), (3).

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

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

where, $I_{\mu 00} = 0.00723(cm^{-2}s^{-1}sr^{-1})$, $A = 17.16(cm^2g^{-1})$, $B = 0.1404(cm^4g^{-2})$, $C = -7.069 \times 10^{-5}(cm^6g^{-4})$, $\alpha = 1.495$, $\beta = 0.2018(cm^2g^{-1})$.

In Miyake's Equation (4),

$$I_{\mu}(h,\theta) = \frac{A_M}{h+H}(h\sec\theta + a)^{-\alpha}\exp(-\beta h\sec\theta) \tag{4}$$

where, $A_M = 174(cm^{-2}s^{-1}sr^{-1})$, $H = 400(g \bullet cm^{-2})$, $a = 11(g \bullet cm^{-2})$, $\alpha = 1.53$, $\beta = 8 \times 10^{-4}(cm^2g^{-1})$.

Equations (1), (4) show that the muon flux exponentially decreases as the incidence angles and surface densities. If the incidence angles of muons are known, the surface densities can be calculated using Equation (1) or (4). As the penetration distances can be obtained through measurements or drawings, the average densities of the permeability path can be calculated by dividing the surface densities with penetration distances. The muon flux obtained from (1) and (4) will have almost the same values for identical surface densities, but Minato's equation applies well in a swallow underground, whereas at a depth of several hundred meters, Miyake's equation works better.

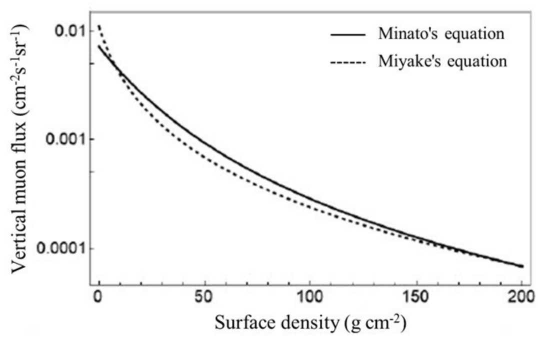

Fig. 2. Relationship between vertical muon flux and surface density.

2.3 Muon Detection Method

Cosmic-ray muons can be detected using radiation. This method uses substances that emit light when charged particles called scintillators pass. Scintillators are frequently used for the detection of gamma rays in radioactive substance analysis. In methods using scintillators, a combination of scintillators is called a detector. There are many substances that function as scintillators; however, in many cases, plastics are generally used because of their weight and convenience of processing. The light emitted from the scintillators is converted into electrical signals through a photomultiplier. Muons can be counted in order to read such signals in the pulse signals. The coincidence-counting method is another approach; this method only counts muons that synchronously pass two scintillators. As this method measures the muon flux in a range of solid angles generated by two scintillators, the average density in that direction can be calculated.

In addition, a detection method using nuclear emulsions is also available. Nuclear emulsions are a type of photographic film that visualizes the orbit of elementary particles by recording and fixing them through silver bromide crystals. By reading the track with a microscopic system to establish a digital database, the angle distribution of the muons can be obtained.

Noise particles, that is, cosmic rays other than muons, can be almost perfectly discriminated by inserting a stereotype between multiple dry plates to trigger scattering. There are several advantages of using nuclear emulsions: they do not need a power source, are highly dustproof and waterproof, and yield high-resolution results. The disadvantage is that nuclear emulsions are not available in real time because the method accompanies the development process in order to obtain data.

The coefficients of cosmic rays have statistical distributions (Minato, 1986; Myake et al., 1964; Bogdanova et al., 2006). Similar to radioactive decay, the generation of cosmic rays is a random phenomenon in time-base. To calculate the surface densities from the muon flux, statistically sufficient precision is required. Coefficients of cosmic rays must follow a Poisson distribution. Denoting the coefficients of the muons as N, the standard deviation σ can be expressed by the following Equation (5).

$$\sigma = \sqrt{N} \tag{5}$$

Accordingly, the coefficient of variation of N can be expressed by Equation (6).

$$\epsilon = \frac{\sqrt{N}}{N} \times 100(\%) \tag{6}$$

When calculating the surface densities from the muon flux, it is essential to reduce the coefficient of variation and improve precision.

3. Experiment

3.1 Muon Tomography Simulation

To use muography in geophysical exploration technology, it is necessary to be able to distinguish between various types of pipes buried, cavities and groundwater in the ground. GEANT4 simulation can be used to determine whether muons are sufficiently captured for the material to be measured. GEANT4 is a simulation program that calculates interactions and paths that occur when radiation particles pass through a material and visualizes them in a 3D image (Agostineli et al., 2003). The basic concept of simulation is based on the Monte Carlo method, and is an open source created for particle physics and nuclear physics research. As shown in Fig. 3, this process was simulated using GEANT4 for a scenario including various materials in a ground region of 7m depth. After the X-size structure was fabricated, water, iron, and air with different densities were placed in the Y-size. The distance between each material was set to 200cm. The simulation conditions generated a total of 16,500,000 muons with 3 GeV of energy, and it was assumed in Fig. 4 that the detector moved in the x-axis direction. The density of each material was set as shown in Table 3.

Fig. 5 shows the number of muons specified for each material as a result of the experiment. It was confirmed that scattering occurred in iron, which has a relatively high density, so the number of measured

Table 3. Type of scintillator in model

Scintillator	BC-408 scintillator
Size	50 x 50 x 0.5 cm^3
Density (g/cm^3)	1.06
Light output (photons/keV)	10
Reflectivity	1.6

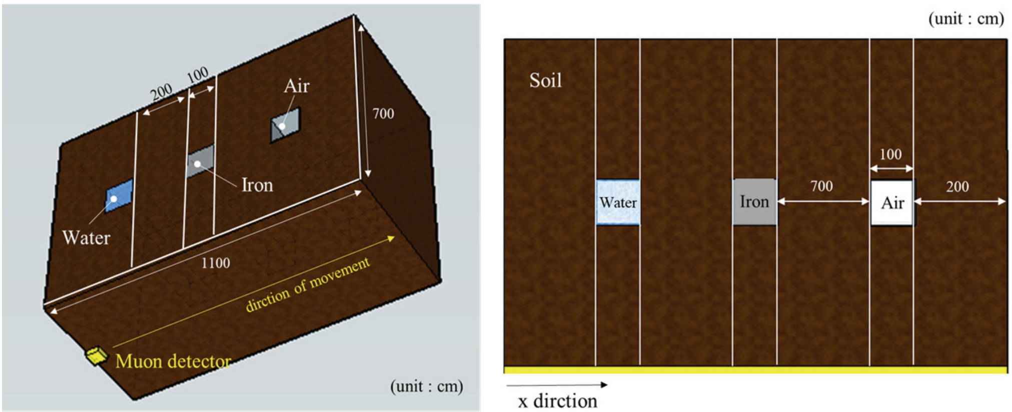

Fig. 3. Geometry of model ground.

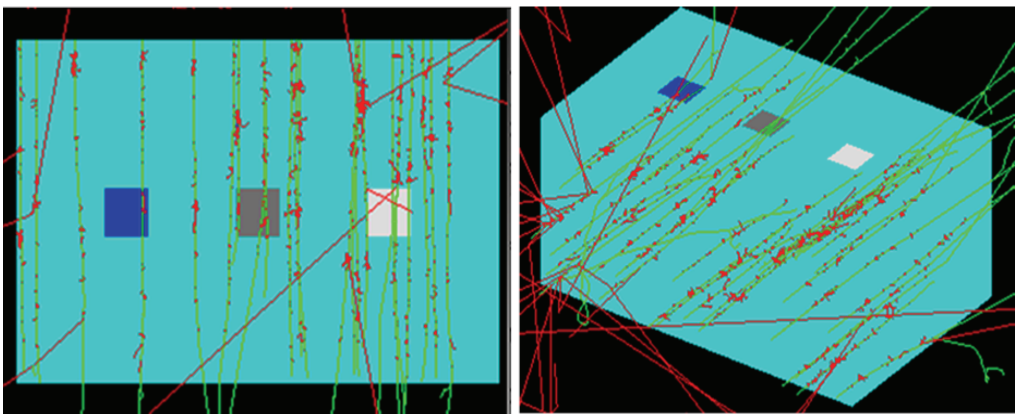

Fig. 4. Example of GEANT4 simulation for model ground.

muons was small, whereas permeation was high in water or air with low density. Thus, it is judged that the material can be distinguished by the muon coefficient based on the density difference.

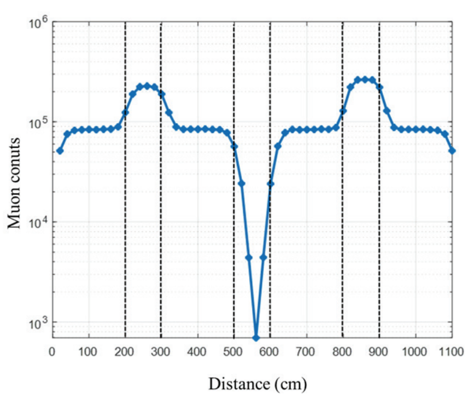

Fig. 5. Results of simulation.

Numerical experiments were executed to examine the photosensitive area of the new type of detectors. The relationship between the photosensitive area and measurement time for 5 m of earth cover is shown.

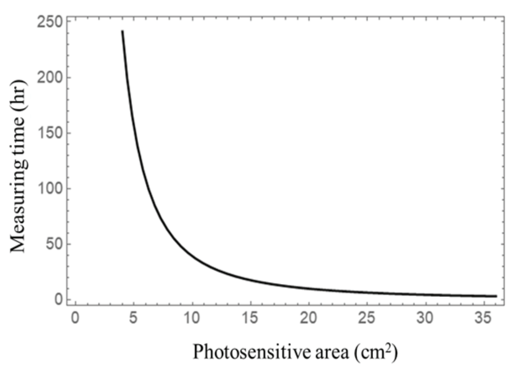

Fig. 6. Relationship between measuring time and photosensitive area.

Here, the measurement time was defined as the time required to obtain the required number of muons. The required number of muons was set to 10,000 in consideration of the variation coefficient. As shown in Fig. 6, the measurement time decreased as the photosensitive area increased. From the experiment, the measurement time was approximately 15 hr.

4. Discussion

To adopt existing surveys using muons for observing the inner state of the ground, several considerations are needed. To observe the inner state of the ground, detectors should be installed in deep places on the ground. On this account, detectors should have sizes that will not damage the ground. However, existing scintillator-type detectors have low transportability owing to their height (approximately as tall as a human adult). In the case of nuclear emulsions, it has advantages such as high resolution and not requiring a power supply. However, they are not suitable for consecutive investigations, as the nuclear emulsion itself must be recollected in order to obtain data.

The spatial resolution of the surveys using muons is determined according to the coefficients of the muons. In other words, for a given measurement time, the resolution improves as the photosensitive area of the lateral extractor increases. In existing surveys using muons, measurement times of several days or several weeks are required to obtain sufficient resolution. Considering that the inner state of the ground slowly changes, shortening the measurement time is a subject that must be further investigated. To solve such problems, new types of detectors have been developed. These new detectors improve the transportability and degree of freedom of the shape by using scintillation fibers in the detection parts of muons. It is expected that the photoelectron conversion part can improve the light reception efficiency and reduce measurement time through substitution with a multi-pixel photon counter (MPPC), which is an optical semiconductor.

New types of detectors using scintillation fibers and optical semiconductors for ground detection were introduced. As new types of detectors are developed for use inside deep ground, it is necessary to examine the durability and waterproofness of detectors. In addition, the possibility of dislocation of the location or angle of the detectors may be considered. To calculate the surface density of the muon flux, the incidental angle of the muons is an important factor; therefore, a method to fix the location and angle of the detectors should be considered. This will be examined through experiments using model ground.

5. Conclusion

Muography has already been shown to be useful in a variety of fields, including volcano imaging, archeology, underground structure and tunnel detection, monitoring of carbon capture storage sites, rock mass density measurements, cargo scanning, imaging of nuclear waste and reactors, and monitoring of historical buildings and blast furnaces. Muon radiography can be used to monitor any large structure, such as a bridge, wind turbine, or dams. Muons are naturally created, free to use, and have a broad energy spectrum; additionally, muons are heavy, penetrating particles that are also safe to employ. Muons have a steady flux and a lifetime of 2.2 microseconds, and they can be absorbed or attenuated. On Earth’s surface, the total muon flux from all angles is around 1 muon per square centimeter per minute. In the atmosphere and underground, muons travel at different angles or directions, and many cosmic-ray-induced muons have a high energy, so they suffer little from scattering effects even in high-density materials. As a result of a simple numerical experiment, it was possible to sufficiently distinguish the density of each material as a result of the density investigation of pipelines, cavities, and water buried in the ground. Depending on the density differences, measurement times ranging from a couple of weeks to a couple of months are needed at that depth. But, due to sufficient muon flux, it is judged that it can be used for geophysical exploration. Also as an imaging method that can analyze the internal structure of the rock masses, muography is thought to be applicable as a technology to monitor faults and weak zones damaged by blasting in mine. Some open pit mines are severely threatened by hidden cavities under benches which are always inaccessible and unmapped. The first thing to be well considered is safe and precise cavity detection, as the conventional detection methods cannot output a clear cavity vision. The muography measurement system can be said to be a future technology that can easily detect the location and shape of cavities in rock mass. Thus, a complete safety evaluation system for such cavity will be established to ensure safe operation above.

However, there are still things to be improved to be used for geophysical exploration. It will be possible to develop into a physical exploration technology suitable for various field underground space and mine tunnel through the detector design and field experiments suitable for geophysical exploration such as the miniaturization, durability, and flux distribution survey with varying zenithal angle in the ground.

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