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Development of cosmic-ray imaging with nuclear emulsion films for safety assessments of levees

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Flooding associated with recent extreme weather events has caused levee failures in Japan, which has many steep rivers, resulting in extensive damage, such as inundation of residential and agricultural lands. Many levees have been built by adding fill to older ones, and the soil structure inside the levees is complex. The interior of the levees cannot be determined without modification to the ground surface. Conventional inspection methods (ex. GPR) can only inspect to a maximum depth of several meters and not reveal any hidden hazards, so reinforcement and other safety measures are usually taken only after an accident has occurred. Therefore, we wondered if it would be possible to detect the location of deformation inside the levee and evaluate the safety of the levee in order to prevent flood disasters, using the technology of cosmic-ray imaging with nuclear emulsion films that has been used to image the inner structure of nuclear reactors and pyramids. In this presentation, we report on the observation of the density distribution inside the levee by installing nuclear emulsion films in the culvert, which was started in the fall of 2021. Seven detectors were installed in a flume pipe approximately 70 m long, and this observation was throughout the year. Muon flux of all detectors reflects the overburn thickness, and penetration rate also clearly indicates the amount of accumulated material including peripheral equipments. In addition, we found that three spots of low density were consistent with the location and size of handholes buried in the levee from the data of six months.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023 38th International Cosmic Ray Conference The Astroparticle Physics Conference

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PoS(ICRC2023)540

1. Introduction

Compared to 50 years ago, the average temperature of the sea surface has increased by several degrees, which has led to an increase in weather phenomena that bring powerful windstorms, such as typhoons and hurricanes, as well as localized torrential rains. In addition, Japan's topography is characterized by steep mountains and rapid river flows, therefore, river flows are increased in a short period of time and are likely to lead to flooding and levee breaks. Those river features require strengthening of the levees, but the foundation ground and the soil structure of the levees, making it difficult to identify localized weak points in approximately 120,000 km of Japanese rivers. At present, efforts are being made to detect vulnerable areas by using ground-penetrating radar and borehole surveys to assess the conditions inside the levee, but the depth and extent of such exploration is not sufficient, making it even more difficult to assess the inside of the levees of large rivers. In this study, we conducted an evaluation of the density distribution inside a levee using the cosmic ray imaging technique [1, 2, 3], which has been used to reveal the density distribution of nuclear reactors and the internal structure of a pyramid. This technique is beginning to be used as one of the methods to evaluate the safety of levees by detecting holes made in the levees by animals [4].

2. Experiment and method

2.1 Nuclear emulsion films

The detectors we used for our observations were nuclear emulsion films [5,6]. It is one kind of photographic film that is sensitive to radiation. The main structure is made of a 500μm-thick plastic substrate with a 80μm-thick coating of photosensitive material on both sides, which is 200 nm silver bromide crystals dispersed in gelatin (Fig1. (a)). Unlike ordinary photographic film, the photosensitive layer is thicker, so radiation passing through the nuclear emulsion film is recorded as a three-dimensional trajectory. This is thin plate-shaped detector, and lightweight, compact, freely formable, and portable. It can record radiation tracks without a power supply, is packed in an aluminum-laminated sheet for light shielding, is waterproof and dustproof, and has a much greater variety of installation locations than other electronic detectors (Fig1. (b)). However, in high-temperature environments (more than 30 degree celsius), the rapid disappearance of recorded radiation tracks is observed, and the installation period is limited in such locations. It also has the same limitation in areas with high radiodensity because it does not have time resolution.

After the experiment, chemical development allows the recorded radiation tracks in emulsion films to be observed under a microscope as a sequence of silver particles. After the developed emulsion films are removed the precipiated silver particles on the surface and undergone a process of swelling with glycerin solution (Fig1. (c)), the three-dimensional information on the position and angle of the recorded the trajectries is read out by a high-speed automatic system (Hyper Track Selector) [7] (Fig1. (d)(e)). The positional resolution of the nuclear emulsion films is due to the size of the silver bromide crystal as a the detection element.

As the result, it has a high positional resolution of submicron and an angular resolution of submrad in the zenith angular direction.

Nuclear emulsion films continue to record charged particles after they are manufactured. Since they do not have time information, at least two films must be stacked in order to distinguish between signal and noise, and trails that linearly penetrate the two films are considered to be signals.

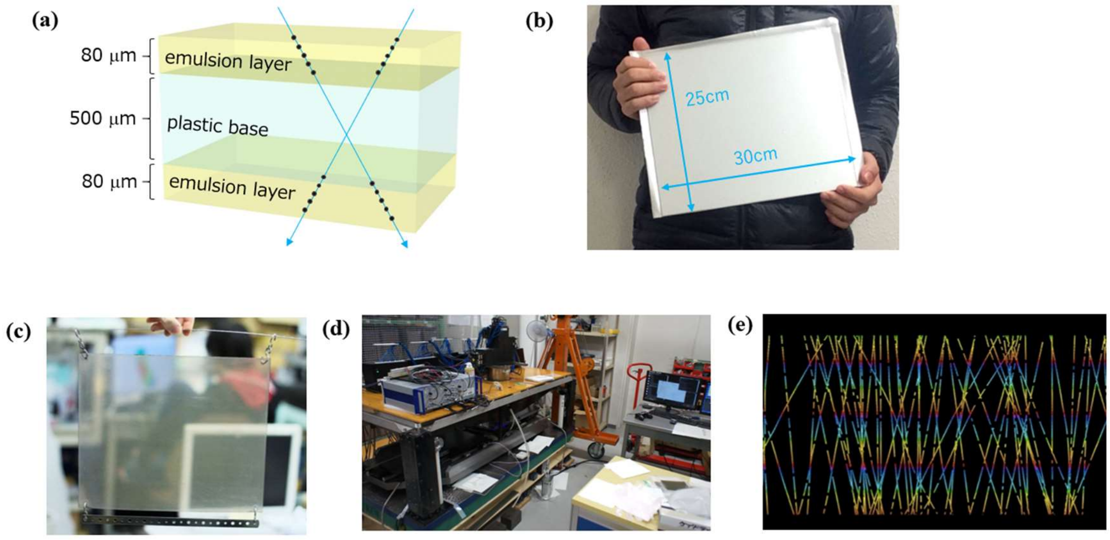

Figure 1: (a) Cross section of nuclear emulsion film (b) A packed film with aluminum-laminated sheet (c) A film after chemical development (d) A read-out system (Hyper Track Selector) (e) Reconstructed 3-dimentional tracks in emulsion film

2.2 Cosmic-ray imaging

Cosmic-ray imaging is a technique that uses muons, which have high penetrating power among secondary cosmic rays, to image the density distribution inside large structures like X-ray radiographs. It is possible to visualize the density distribution inside from bridges of meter class to volcanoes of kilometer class, which are difficult to visualize with X-rays and neutrons. Due to the characteristics of the nuclear emulsion films mentioned above, the incident angle of radiation on the photosensitive layer can recognize trajectories at almost all angles, but as a result of considering reading speed and other analysis conditions, we have set a range of ±45 degrees (90 degrees viewing angle) for our analysis.

As muons pass through materials, they lose energy and are absorbed as the amount of material in its path increases, and then amount of material could be estimated from the decreased number of muons. Compared the number of muons through the material with the number of muons in the case of nothing above the detector, and check the difference in the penetration rate for each angle. There are a number of models of muon fluxes on the ground, and these are constructed by extrapolating from several previous experimental data.

3. Observation and results

3.1 Observation inside the levee

The following three methods can be used to observe density distribution in levees with cosmic ray imaging. 1) Drill a borehole and install a detector in it. 2) Install a detector outside the levee. 3) Install a detector in ceiling of a culvert embedded in the bottom of levee. Consider these ; In the method 1), the borehole is drilled inside the levee, which may lead to weakening of the levee. Because the diameter of the borehole is small, the size of the detector must be reduced, which makes observations time-consuming. 2) is difficult to observe without selecting a observation season or preparing a shed or air-cooling system to install nuclear emulsion detectors, which are not temperature tolerant because it is located completely outdoors in this method. 3) is easy to install if the inside of the flume can be accessed by humans, and can be observed inside the levee around the culvert within a wide field of view, avoiding direct sunlight. However observation points are limited, installation is difficult because of water flow in the flume and can be affected and submerged by fluctuating water levels. In general, since the number of muons from the zenith direction is higher and decreases as the elevation angle decreases, it is better to install the detector horizontally to obtain a greater number of statistics. At filnally, we decided to select method 3) and started on observation inside a culvert embedded in the bottom of levee of the Shinano River in Niigata, Japan from November 2021 [Fig.2].

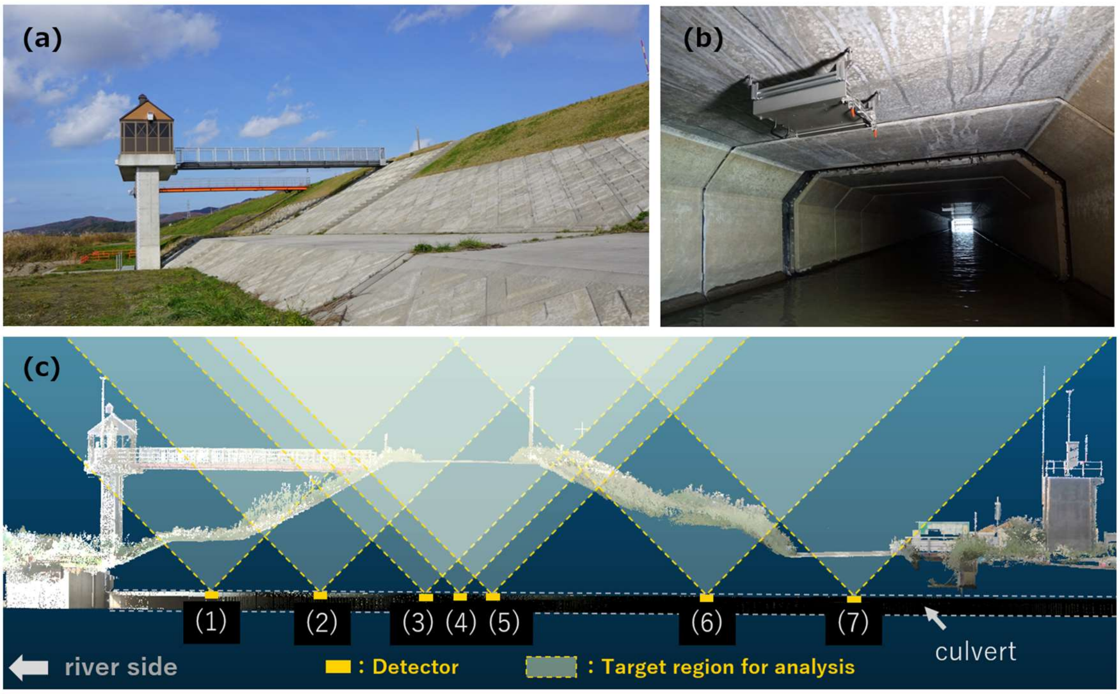

Figure 2 : (a) A picture of the levee which we installed the detectors equipped with nuclear emulsion films (b) An installed detector in the culvert. (c) 3-dimentional image of the levee from side view and position of seven detectors. Light yellow triangles show target region for analysis.

Detectors equipped with 25 cm × 30 cm nuclear emulsion films were installed at seven locations inside the culvert [Fig2], and they were replaced every one to four months to observe cosmic rays throughout the year. This culvert was newly constructed in 2020 and its length is about 70 meters, with about 60 units of box-shaped concrete structures whose inner cavities are 270 cm wide, 140 cm high, and 120 cm deep.

3.2 Result

In this section, the observation results are shown for about one month from November 2021, three months from December 2021, and two months from March 2022 will be discussed. Figure 3 shows the muon flux in tanθ space ($\tan\theta_x$ - $\tan\theta_y$) at each location during a one-month observation starting in November 2021. Approximately 1 million muon tracks were accumulated for one month at each detector with an effective area of 0.07 m^2. The muon fluxes increase or decrease with the overburden thickness of the levee. Dividing the value of the muon flux obtained at each location by the value for the free-sky case estimated from Miyake's formula [8] yields the "penetration rate". This corresponds to the accumulated amount of material that the muon has passed through; the larger the value, the less material. In detector (1) in Figure 3, the shadows of the three concrete pillars of the sluice control room above the culvert are clearly visible, and the steel plate bridge passing the road and the control room is faintly visible in a straight line. In detector (2), changes in the amount of material due to slope inclination are reflected in the penetration rate. Detectors (3), (4), and (5) have the thickest overburden and therefore have the lowest penetration rates.

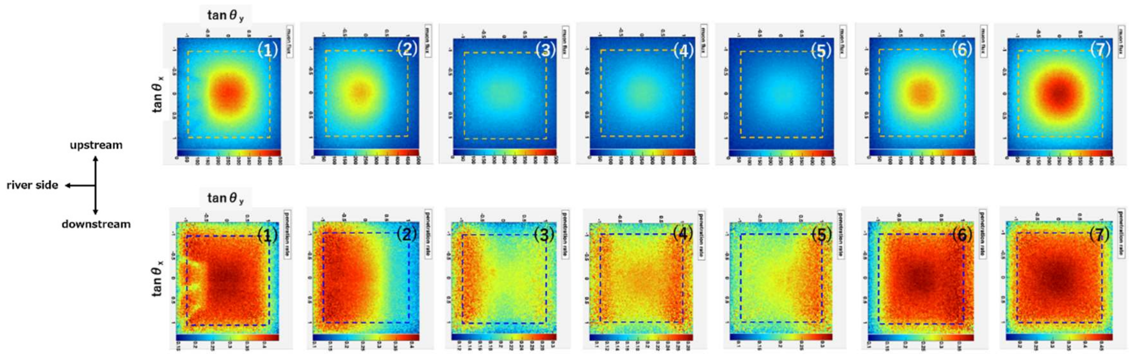

Figure 3 : (Top) Plots of muon flux (tracks/cm2/day/sr) without a correction of detection efficiency (Bottom) Penetration rate of the observation data without a correction of detection efficiency for about 1 month. $\tan\theta_x$-axis means the direction of the river flow and $\tan\theta_y$-axis means the direction of extension of the culvert.

In particular, plots of detector (3), (4), and (5) appear to have spot-like areas with a smaller density than the surrounding areas in Figure 3. Figure 4 shows about six months of data from november 2021 to the end of Aplir 2022 for these three locations. The black, blue and light blue arrows in each figure indicate identical low-density areas. The location of the intersection of the two points was determined by triangulation, and it was found to be on the surface of the levee, close to the boundary between the top of the levee and the slope. Since this area has a tanθ~0.1 and the distance from the top to the detector position is about 10 m, the cross-sectional area of the low-density area near the surface of the top is estimated to be about 1 m × 1 m. Given that the difference in the amount of material from the surrounding area is about 10%, if this low-density area is a cavity, it is estimated to be about 1 m in depth. After this data analysis, we received a blueprint around the levee from the administrator and confirmed that the handhole locations and hole sizes for the cable runs were nearly identical.

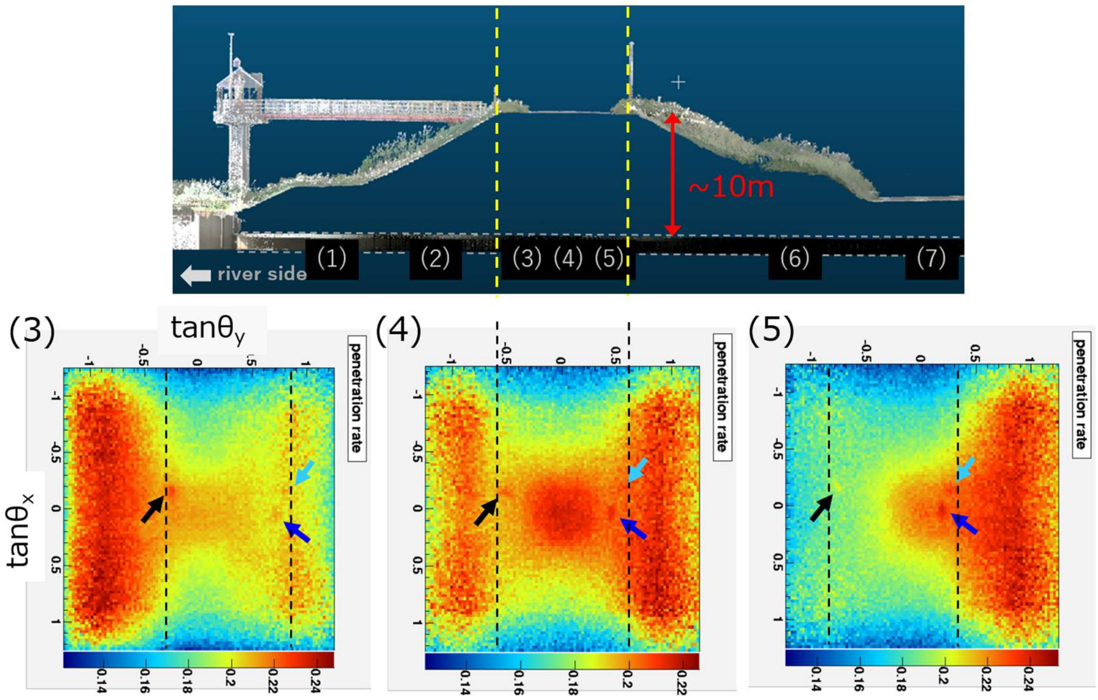

Figure 4 : Plots of penetration rate for 6 months observation. Black and yellow dotted lines show the boundary between the top of the levee and slope face. Black, blue and light blue arrows show lower density spots.

4. Conclusion

We considered the possibility of applying cosmic ray imaging as a method of assessing the safety of levees in order to prevent levee failures. Seven nuclear emulsion detectors were installed in the culvert embedded in the bottom of levee of the Shinano River in Niigata, Japan to observe cosmic rays penetrating the inside of the levee throughout the year. From about six months' worth of data, we found three spots with lower densities than the surrounding area, and we confirmed that these coincided in size with the location of handholes for levee management.

Acnowledgment

This work was supported by JSPS KAKENHI grant number JP21K04608 and JP21H05087. We thank Shinanogawa River Office, Hokuriku Regional Development Bureau, Ministry of Land, Infrastructure and Transport and the members of Niigata University, Taichi MOTEKI, Yuki TADOKORO, Yuki OHARA, Naoki Oizumi, Shohei SEKI, Hiroaki KARISAWA, Hiroki SAITO, Tasuku SUMIYA, Akane SUZUKI, Tsubasa SHIOYA, Daichi OKAWARA, Keita SHIMIZU

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