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Interior Exploration of Unexcavated Ancient Burial Mounds by Muography Using MWPC Detector

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Abstract

Muography is a technique that employs muons in cosmic rays to facilitate visualization of the Earth's crust and underlying large-scale architectural structures. As a novel application of muography, we are investigating the interior of Kofun, ancient burial mounds in Japan. This report presents the preliminary results of muographic imaging of an unexcavated Kofun, which is believed to contain artifacts. A high-sensitivity Multi-Wire-Proportional-Chamber (MWPC) detector was employed as the measurement device, and 128 × 64 pixel muon transmission images were acquired. The images were compared with muon transmission simulations assuming the presence of a stone chamber inside. As a result, it was indicated that there was a possibility of an uneven area around the projected image of the virtual stone chamber. Although the lack of resolution did not allow the identification of artefacts with a high degree of confidence, it demonstrated the potential for using muography to explore the interior of the Kofun.

Key words: muography, cosmic ray fluoroscopy, muon, MWPC, Kofun, internal survey of buried cultural properties

I. Introduction

Investigations of historical ruins using muography have been ongoing since the early studies of the pyramids in Egypt (Alvarez *et al*., 1970). In recent years, remarkable results have been achieved, such as the discovery of an unknown chamber inside the pyramid of Khufu by muography using an atomic dry-plate (Morishima *et al*., 2017). In Japan, this method has been used to investigate the interior of Kofun, an ancient burial mound.

Excavation is the fundamental method for surveying ancient burials, but damage to cultural heritage is an issue. Therefore, non-destructive and non-invasive methods such as airborne laser measurement, magnetic exploration, ground-penetrating radar and electrical exploration have recently been used for preliminary surveys (Adachi, 2019). However, the measurement accuracy of these methods varies greatly depending on the surface geometry and internal state of the mound, and it is also difficult to fully understand the 3D structure of

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the interior. Muography, on the other hand, is a completely non-contact, non-destructive and non-invasive method for surveying the interior, and when used in combination with multi-point measurements, it is expected to be a surveying method that can even determine the 3D structure of the interior.

So far, muographic investigations on Kofun have been conducted using the atomic dry-plate method, but due to the problem of ambient noise and the difficulty of three-dimensional analysis, stone chambers and burials have not been identified (Ishiguro, 2018). Unlike pyramids, which are isolated structures in the desert that can be measured from interior corridors and reliefs, kofun must be measured from the outer perimeter, which requires consideration of detector installation conditions and measurement methods. In addition, since the tomb of the emperor is closed to visitors, muography, which allows remote measurement, may be the only means of investigation.

Tanaka *et al*. (2020) applied a multiwire proportional chamber (MWPC) muographic detector, which realizes a high signal-to-noise ratio and has achieved remarkable results in volcano fluoroscopy (Oláh *et al*., 2018), to investigate the internal fault conditions in the Imashirozuka-kofun burial mound in Osaka, Japan. This burial mound was collapsed by a large earthquake of the Fushimi Earthquake in 1596, and excavation studies have reported that no stone chamber or buried objects exist inside the mound (Kamai *et al*., 2008). The muographic measurements detected a fault line of internal slip caused by the earthquake, and the accuracy of their measurements was verified by matching them with historical records (Tanaka *et al*., 2020). However, its applicability to the detection of stone chambers and buried objects in the interior, which is required in the field of archaeology, remains unclear.

In this study, we conducted an internal measurement experiment using a MWPC detector on an unexcavated Kofun, which is believed to have a stone chamber inside, and obtained muon transmission images. Through comparison with simulation results, the applicability of muography as a non-destructive and non-invasive method for surveying the interior of buried cultural objects was discussed.

Fig. 1 A panoramic view of the Tsukuriyama-kofun burial mound, captured by drone. Points P1 and P2, indicated in the figure, represent locations where muographic measurements were conducted.

II. Ancient burial mound to be measured

Tsukuriyama-kofun, located in Shiomo-Shimo, Kita-ku, Okayama, Japan, was selected as a target for measurement. It is the fourth-largest rear frontal mound in Japan, measuring 350 m in length and 31 m in height. It is estimated to have been constructed in the early 400s (early 5th century). The identity of the burial remains has not been determined (Nishida, 2020). The mound is designated as a national historical site, but since it is not an imperial mausoleum, the mound is open to the public and is currently used as a burial mound park, attracting many visitors. Figure 1 shows a full view of the mound taken by a drone. The flat surface of the upper rear portion is said to have been constructed for the Battle of Bitchu-Takamatsu Castle in 1582.

The interior structure of Tsukuriyama-kofun has not been studied in detail until recently, and there is little documentation other than local legend regarding the existence of a stone chamber inside (Sumiya *et al*., 2022). In a posterior frontal circular mound built at the same time as this mound, the stone chamber is

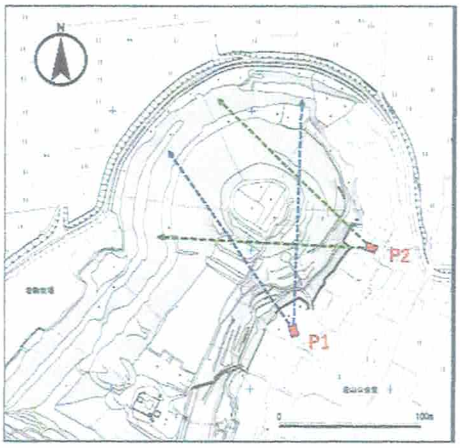

Fig. 2 Locations and range of measurement. Two positions, designated P1 and P2, were selected for muographic measurements, with the instrument oriented towards the posterior circular mound. The measurement range of the instrument was 1000 mrad (57.3 degrees). A contour map of the burial mound, used with permission from the Okayama City Board of Education (2014).

pit-like, and a cubic space of several meters is formed near the upper surface of the posterior circular part. Therefore, we decided to measure the cross-section of the posterior circular part by muography.

III. Measurement method

1) Equipment

The same MWPC system used by Tanaka *et al.* (2020) for the measurement of the Imajozuka-kofun mound was used for the muographic measurements. Six MWPC detectors, each measuring 80 × 80 × 6 cm in length, width, and thickness, were installed at equal intervals inside the apparatus. The external dimensions of the apparatus were W233 × D164 × H149 cm, and the total weight was about 1000 kg.

The muon arrival direction through at least four of the six detectors was calculated and measured over a range of 1000 mrad (57.3°) horizontally and vertically. The elevation and azimuth counts were converted to pixel luminance values and arranged horizontally and vertically to create a 128 × 128 pixel muon transmission image. A detailed description of the instrument can be found in Oláh *et al.* (2018).

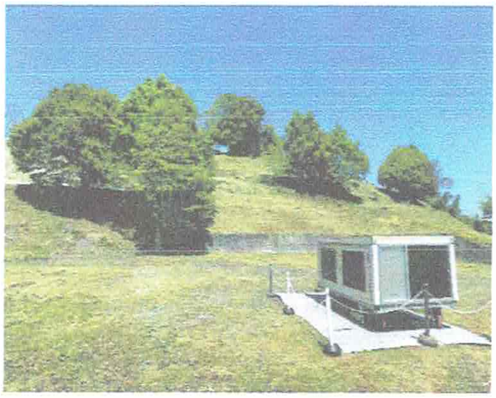

Fig. 3 Measurement device installed at location P1. The device was placed horizontally, oriented toward the central axis of the mound in the posterior circle.

2) Measurement points and installation period

The measurement device was put horizontally within the site of the burial mound. The installation direction was toward the center of the posterior circle at two locations of P1 and P2 in Fig. 2. The installation periods at each point were P1: 2021.4.24-2021.11.1) and P2: 2022.1.29-2022.6.18). These two positions are also marked in Fig. 1, while Fig. 3 shows the measurement equipment at P1.

IV. Results

1) Muon transmission images

The muon transmission images at P1 and P2 are shown in Figs. 4 and 5, respectively; the measurement time for P1 was 93 days (2021.6.20-2021.9.20) and for P2 127 days (2022.1.29-2022.6.4). The resolution of the device's output image is 128 × 128 pixels, but the lower half of the image is a transmission image of muons reaching from behind, so in this study we used the image of the mound in the upper half of the image (resolution: 128 × 64 pixels).

The data was normalized to the azimuthal distribution of the sky muon orbit, which is unaffected by man-made structures or surrounding terrain. The height of the mound at the elevation of the survey point P1 was 21 m,

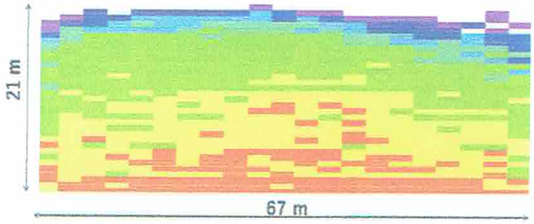

Fig. 4 Measurement result of muon transmission image at location P1. The measurement period was 93 days. The figure shows distribution of muon count numbers reached the detector through the mound. To decrease influence of noise, five pixels were binned in the horizontal direction, therefore, one pixel corresponds to 39.1 × 7.8 mrad in visual angle. The intensity of pixels were obtained as a gray scale image (normalized between 0 to 1) and they were colored in hue order 0 to 360 degrees.

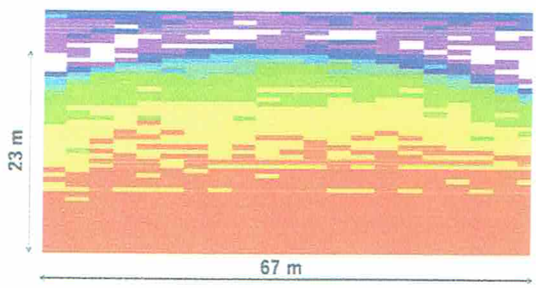

Fig. 5 Measurement result of muon transmission image at location P2. The measurement period was 127 days.

and at P2 it was 23 m. The horizontal distance from the detector to the top of the mound was approximately 100 m, and the elevation angle at the top of the mound was 12.4 degrees (0.22 radians). Since the aspect ratio of the mound, i.e. the ratio of width to height, was relatively large, about 5:1 (57.3°:12.4°), binning was performed with 5 pixels (0.039 radians) in the horizontal direction only.

The transmission images have been colored in hue in proportion to the number of muon counts. The distance from the detector to the center of the mound is about 100 m, and the size of the bin at that point is equivalent to 425

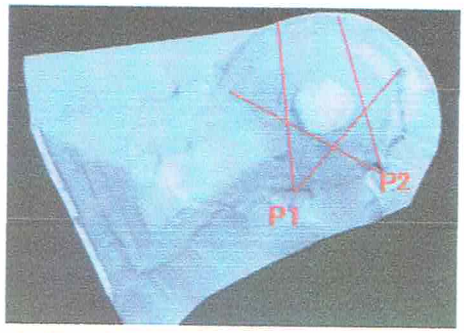

Fig. 6 3D model of the burial mound. P1 and P2 are measurement locations. A surface model was created from the contour map and converted to a voxel model and used for muon transmission length calculations.

cm wide and 85 cm high.

2) Interpretation of muon transmission image by simulation

A three-dimensional model of the mound was constructed for the analysis. First, a 3D surface model shown in Fig. 6 was built from the contour map of the mound (Okayama City Board of Education, 2014) and then it was converted into a voxel model using C/C++ code developed independently. To obtain transmission length of muon, ray-casting algorithm was used to count number of the voxels along the rays to the detector's viewing point. For this simulation, we used the PCL (Point Cloud Library) by Rusu and Cousins (2021). Due to the lack of information on the internal structure and density distribution of the Kofun, we supposed that inside of the mound is homogeneous. The distribution of muon transmission lengths at point P1 is shown in Fig. 7a. Here, the calculated length data was normalised to the maximum length, and then coloured in reverse order of hue for values between 0 and 1. In other words, the red areas indicate long transmission distances, and the blue areas indicate short transmission distances. The results of this colouring match the muon transmission image obtained from the measurement shown in Fig. 4.

In order to interpret the results with regard to the presence of buried objects, we set a stone chamber in the 3D surface model of the burial

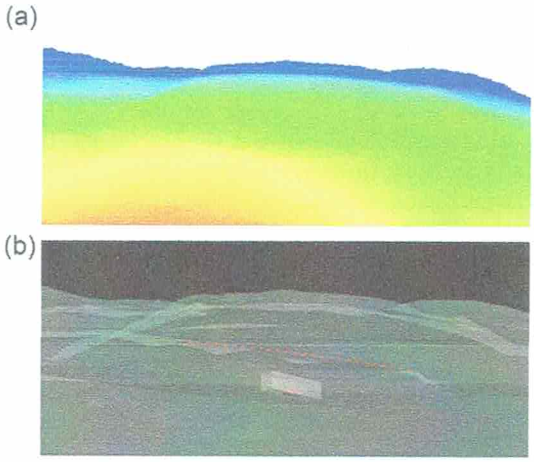

Fig. 7 Results of muon transmission length calculation (a) and projected image of a hypothesized stone chamber inside (b) at location P1. The size and location of the stone chamber was set at 8m long, 2m wide, 2m high and 1.5m deep from the top of the mound. The surface of the top flat area is shown with a red dashed line in (b).

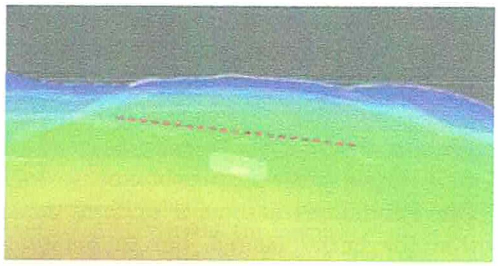

Fig. 8 Overlay of the muon transmission length image and the virtual stone chamber image at location P1.

mound inside, and a projected image of the stone chamber was obtained (Fig. 7b). The size and location of the stone chamber was based on burial mounds built in the same period and was set at 8 m long, 2 m wide, 2 m high and 1.5 m deep from the top of the rear circle. In addition, a cube measuring 2.39 m long, 1.1 m wide, and 0.75 m high was placed inside as a model of the sarcophagus.

The simulation result of muon transmission was obtained by superimposing both Figs. 7a and 7b, as shown in Fig. 8. Comparing with the measured image at P1 (Fig. 4), the possible existence of a heterogeneous area in the center where the assumed stone chamber is located.

In the case of internal survey of the earth's crust using muography, AI-based super-resolution and 3D processing based on the results of multi-point measurements are used because of the large dimensions of the internal composition. However, in the case of ancient burial mounds, the overall resolution is insufficient because the dimensions of the internal artifacts are only 1-3 m at most. There is also a lack of training data for deep learning analysis, as in the case of X-ray CT images in the medical field.

V. Discussion

One of the features of the MWPC detector used for this measurement is that the muon flux intensity arriving at the detector can be obtained as digital image data with minimal noise effects. By combining measurement result with muon transmission length simulation, it is expected to be possible to identify internal stone chambers and buried objects. However, in this measurement, the size of the pixel was comparable to that of the stone chamber to be detected, due to limitations in the resolution of the equipment and the installation location, making it difficult to identify buried objects only by image processing such as super-resolution and stochastic noise reduction.

With regard to the identification of buried structures, Balázs *et al.* (2023) developed a method to identify the interior three-dimensional structure by tomographic techniques from images of two measurement points. They solved an inverse problem using Bayesian inference from coarse muographic images measured at two locations and reconstructed the three-dimensional structure with high accuracy. They also included density differences and cavities in their calculations. In this study, we also considered reconstructing the interior three-dimensional structure from the measured data at P1 and P2 locations using their method, but the calculation was difficult due to the lack of signal-to-noise ratio. In order to improve the S/N ratio of the measurement results, we are now evaluating the reliability of the muon flux from the output signal of each MWPC unit and continuing the analysis by extracting only the signals related to the passage of muons.

The simulations assume a uniform density within the burial mound, but in reality the density varies from place to place, and strictly speaking, the material of the stone chamber and the volume of the cavity must also be accurately estimated (Balázs *et al.*, 2023). For this reason, we are considering measuring mounds with known interiors. One of the secondary mounds of the Tsukuriyama-kofun, the Senzoku-kofun, was partially collapsed due to theft water erosion, and the interior stone chamber was completely reconstructed (Nishida, 2020). By comparing the measurement results of the Senzoku-kofun with the simulation results, we plan to evaluate the data analysis method and reliability of the data.

In this measurement experiment, the large dimensions of the device limited the installation site. Therefore, we plan to develop a smaller, lighter, and more scalable device. By installing this device in many locations near the burial mound, higher resolution can be expected (Hamar *et al.*, 2022). In particular, for small tombs such as the aforementioned Senzoku-kofun, the use of a compact and lightweight measuring device will be essential.

VI. Conclusion

Results of muographic measurements on an unexcavated ancient burial mound were presented. Correspondence with muon transmission simulation results with a temporary stone chamber space inside indicated the possibility of the existence of a non-uniform area inside. There was a need to improve the signal-to-noise ratio and resolution of the instrument to identify buried artifacts, and ways to address this issue with current equipment were discussed. The results of this study will be useful for future non-destructive and non-invasive investigation techniques of buried cultural properties using muography.

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