Muon Tomography for Mapping and Monitoring Tailings Storage Facilities

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ABSTRACT

Tailings storage facilities pose an increasingly significant global challenge for mining companies. Given that tailings, the by-products of mine processing plants, demand meticulous management due to the potential hazards associated with storage facility failures, continuous attention is imperative. The repercussions of such incidents can lead to profound and enduring environmental damage in downstream regions. Therefore, consistently monitoring the structural stability of these facilities is paramount to ensure the safety and sustainability of both active mining sites and legacy mines.

This paper introduces an innovative approach using muon tomography to analyze the internal density structures of tailings dams. The research, conducted at the BHP Prominent Hill Mine site in South Australia, presents a pioneering method and technology for examining the internal density distribution of tailings storage facilities using muons. Muons, being a natural source of radiation capable of generating X-ray-like scans of large structures, offer a distinctive opportunity to gain insights into the inner structure of tailings storage facilities. Moreover, this technology holds the potential to serve as a foundational platform for future research in the development of early warning systems for detecting structural changes.

Keywords: tailings storage facilities; tailings wall monitoring, muon tomography, muography.

1. Introduction

Tailings Storage Facilities (TSF) undergo continuous long-term monitoring to assess stability and liquefaction risks. Current remote monitoring capabilities for TSF employ detection systems like extensometers, LIDAR, total station, taseometers, and seismic sensors. However, these systems have limitations in terms of range, coverage, and susceptibility to background noise. Additionally, challenges such as radiation licenses impeding deployment and high energy consumption restricting flexibility and longevity further impact their feasibility.

Addressing these limitations, muons, naturally occurring particles originating from cosmic rays in space, offer a promising solution for scanning large volumes of material. Muons penetrate through hundreds of meters of rock with well-characterized frequency and direction, making them a potential tool for comprehensive assessments. These particles are continuously generated by high-energy cosmic rays colliding with Earth's atmosphere at altitudes of approximately 15 kilometres, resulting in an average muon flux of about 1 muon per square centimetre per minute at sea level. The rate at which muons lose energy during interactions with matter is proportional to the density of the material they traverse.

The concept of utilizing muons for scanning was initially explored in 1955 for estimating tunnel overburden in the Snowy Mountains of Australia (George, 1955). Subsequent advancements in detector capabilities have enabled applications in mineral exploration (Bryman et al., 2015), volcano monitoring (Nagamine et al., 1995), tide/tidal wave detection (Tanaka et al., 2022), and even mapping of corridors inside pyramids (Procureur et al., 2023).

In this paper, we present a pioneering application of muon tomography for monitoring Tailings Storage Facilities, showcasing a world-first use case in this context.

2. Methodology

Muon tomography is a sophisticated imaging technique that leverages the natural flux of cosmic ray muons to probe the interior of dense materials, such as geological formations or structures within mines. Muons are elementary particles similar to electrons but with greater mass, and they continuously rain down from the outer atmosphere. As muons travel through matter, they undergo deflection and attenuation due to interactions with atomic nuclei, with higher-density materials causing greater attenuation. By deploying arrays of muon detectors and measuring the flux and trajectories of incoming muons from various directions, it is possible to reconstruct three-dimensional images of the internal structure of the target material. Advanced algorithms are then employed to analyse the recorded muon data and produce detailed images, providing insights into the density distribution and spatial features of the scanned object. This non-invasive imaging method offers capabilities for imaging subsurface structures in diverse applications, from geological surveys to archaeological excavations and nuclear security.

The primary sensing module is a muon detector designed in a 'telescopic' configuration, featuring multiple plastic scintillators that emit light upon interaction with muons. These emitted photons are then captured by silicon photomultipliers (SiPMs) arranged as single-pixel units (Krishnan et al., 2020). By employing optically isolated sub-detectors within a panel plane, the geometric estimation of intersecting muons' arrival direction becomes feasible. The telescopic detectors achieve angular resolutions better than five degrees, covering a field-of-view of approximately 17 × 17 degrees per pointing.

To attain a limited 3D stereoscopic resolution of the muon flux detected across the embankment of a Tailings Storage Facility (TSF), two or more telescopic detectors are strategically positioned along the embankment. These detectors undertake multiple scanning sweeps over several weeks to analyse the muon flux variation with respect to the angle across the TSF embankment, as illustrated in Figure 1.

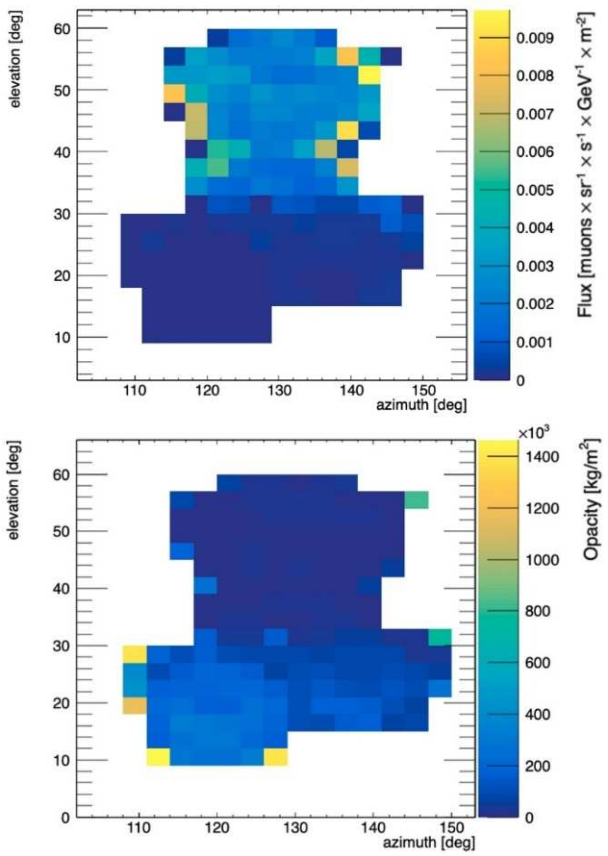

Figure 1. (Top) recorded muon fluxes for detector one. (Bottom) inferred opacities using derived flux-opacity relationships.

The observed muon flux is influenced by the elevation angle of observation and the opacity (or projected surface density), directly proportional to the muon path length within the TSF embankment material and the material's density. Employing a minimum of two observation points separated by a known distance offers a stereoscopic 3D constraint on the material within overlapping fields of view.

The self-supported telescopic muon detection system operates on solar power and relies on 4G for data transmission, allowing it to function autonomously without dependence on the mine's power and communication infrastructure. This autonomy streamlines various administrative and permission-related aspects with the host site.

To establish a correlation between the measured muon flux and observed opacity, numerical simulations were conducted using the PUMAS library (Niess, 2022) and the Pyrate software package (Scutti, 2022). The resulting relationship, which accounts for the correction associated with the observation elevation, is employed to convert the measured muon flux data into observed opacity values.

Assuming a geometry where the TSF can be subdivided into N 3D sub-blocks with uniform density ρ_j, the opacity Λ_i relative to a given muon path i inside the TSF is the sum of the products of individual path lengths Δl_{ij} and densities ρ_j for each sub-block j.

Simplifying assumptions about the interactions of muons with the medium of the TSF embankment are as follows. (a) Muons travel in straight lines for the energy ranges that predominate the ambient muon flux. (b) Muons are attenuated at a rate (Λ_i) proportional only to the density of the medium traversed (ρ_j) and distance traversed (Δl_{ij}) given as:

$$\sum_{j=1}^{N} \Delta l_{ij}\rho_j = \Lambda_i \quad (1)$$

Our algorithm for 3D muon tomography relies on the concept of Lines-Of-Sight (LOS), where various detectors' LOS intersect shared cells within the 3D block model space. This involves comparing the observed LOS opacities with those calculated using Equation 1. The calculation of LOS opacity is performed through a 3D regular grid traversal algorithm (refer to Figure 2), navigating through a pre-defined discretized geological model of densities.

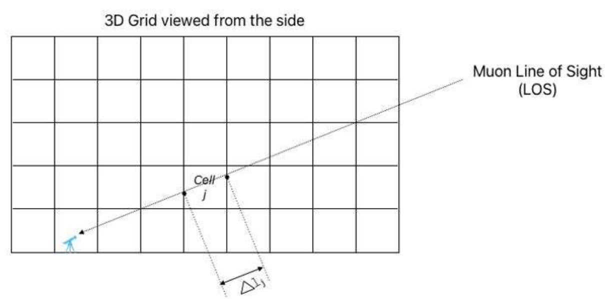

Figure 2. 3D Regular Grid Traversal Algorithm: with the opacity along a muon's line of sight (LOS) computed using equation 1.

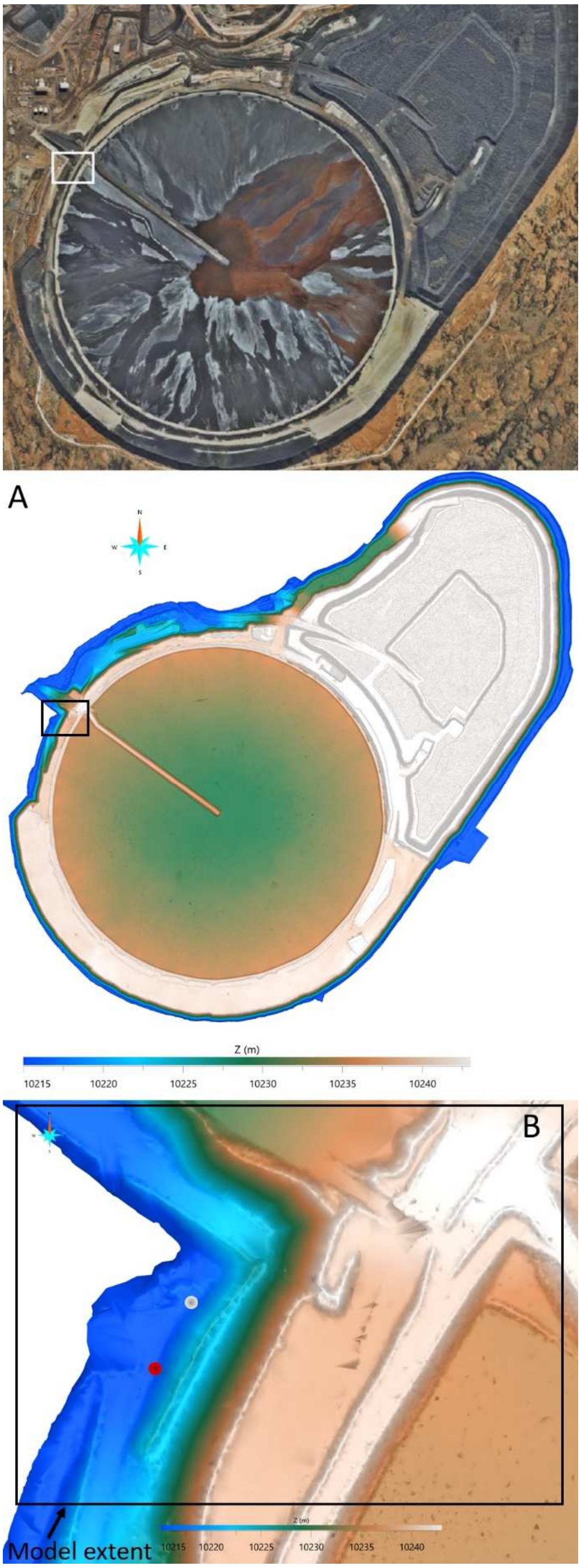

Figure 3. Top, aerial view of Prominent Hill tailings storage facility with white box showing modelled region. Centre and Bottom, Topography surfaces generated from LiDAR data (blue colours are low elevations, white colours are high elevations) for: (A) the entire Prominent Hill tailings storage facility (black box shows the location of the scanned region), and (B) the scanned region zoom in, with the two telescopic detector deployments as the white and red dots. These detectors are placed approximately 10 m from the beginning of the rise, spaced 50 m from each other.

The objective of the algorithm is to determine the density distribution of the traversed medium (ρ_j) in a manner that minimizes equation 2.

$$\left\| \Lambda_i - \left(\sum_{j=1}^{N} \Delta l_{ij}\rho_j\right)\right\| \qquad (2)$$

The developed algorithm for solving equation 1 employs a Monte Carlo Markov Chain (MCMC) approach. Beginning with an a priori discretized geological model of densities to initialize values, the algorithm uses precomputed segment lengths of muon trajectories and reconstructed opacities from observed muon events. Through an iterative process, the algorithm stochastically perturbs the image, randomly selecting one cell at a time with the aim of minimizing equation 2.

This MCMC approach provides the flexibility to incorporate geological constraints during the model's convergence (Guillen et al., 2004), offering an advantage over approximate imaging methods like SIRT (Ren and Kalscheuer, 2020).

3. Survey

The Prominent Hill copper-gold mine in northern South Australia, houses a Tailings Storage Facility (TSF) within the Integrated Waste Landform (IWL), as illustrated in Figure 3. The TSF is a circular facility with a diameter of 1,750 meters, covering an area of about 2.4 km². It has undergone five embankment lifts since its commissioning in 2009, featuring a minimum 60-meter-wide waste rock dump rising 25 meters high. On the tailings side, a filter zone and a 6-meter clay liner were constructed concurrently.

Figure 4. Two muon detector telescopes mid-installation (note not their final placements), with the background muon counter as the small black box at its base.

Three detectors, as seen in Figure 4, were deployed to monitor the region of interest. The primary and secondary detectors, functioning as telescopes, dynamically scanned the region, while the third reference detector recorded the background muon rate. A total of 10 days' worth of events was collected for the scanned region shown in this work.

The muon flux observed across the embankment was converted to opacity using the PUMAS muon physics transport engine (Niess, 2022). The MCMC algorithm was then employed to invert regions with intersecting sightlines, generating a 3D apparent density. Kriging of discrete points produced a 3D volumetric apparent density, as shown in Figure 5.

The results of the muon-derived apparent densities, post-kriging, are found to be a heavily skewed distribution, with the 10th and 90th percentile found at 1.64 g/cm^3 and1.82 g/cm^3, respectively. While there are some outliers with unrealistically high apparent densities (over 10.0 g/cm^3), these make up a very small proportion of the scanned volume (0.3 per cent of the scanned volume falls between 3.0 g/cm^3 and 10.2 g/cm^3) and are considered to be numerical artefacts.

As shown in Figure 5, relatively high apparent densities (between 1.8 g/cm^3 and 2.2 g/cm^3) are robustly detected although their cause remains unclear. We suspect these values correspond to cemented backfill and basement waste which has been confirmed to have been used to build the TSF in the observed direction of the telescope. Apparent densities estimated from muon tomography have tended to be slightly higher (median of 1.68 g/cm^3) compared with the measured value (1.495 g/cm^3). We suggest the most likely explanation for this is that the median value has been influenced by these high values which would not have affected laboratory-measured value.

In general, however, there is little variability in the inferred values for the apparent density within the volume imaged, reflecting that essentially only one ‘rise’ was scanned that would reasonably exhibit a similar density throughout construction.

The resulting 3D volumetric region revealed a range of apparent densities, aligned with the expected wall material density. Notably, higher density regions (between 1.8 g/cc and 2.2 g/cc) correlated with known areas of cemented backfill and basement waste in the wall, indicating a plausible cause for these outliers.

4. Conclusions

This work represents a world-first use of imaging a Tailing Storage Facility (TSF)with muon detectors.

A short-duration deployment was undertaken at the Prominent Hill TSF, with several days of muon events captured by two telescopic muon detectors arranged to provide a limited 3D stereoscopic resolution.

The muon rate, or flux, detected across the extent of the embankment was converted to an opacity using an open-source muon physics transport engine, PUMAS (Niess,2022). Regions in which opacities, or equivalently projected surface densities, had intersecting sightlines were then inverted to produce a 3D apparent density using a proprietary Monte Carlo Markov Chain algorithm. These discrete points were then kriged using the standard industry package SKUA-GOCAD to create a 3D volumetric apparent density.

Within that resulting 3D volumetric region, a range of apparent densities was inferred, heavily skewed to the expected wall material density (10th and 90th percentile found at 1.64 g/cm^3 and 1.82 g/cm^3 respectively). Relatively higher density regions (between 1.8 g/cm^3 and 2.2 g/cm^3) correspond to known areas of cemented backfill and basement waste in the wall.

Although only a limited area of the Tailings Storage Facility was scanned during this short deployment, the utility and effectiveness of muons for economically scanning large volumes without site disruption are clear. Muon technology presents a unique opportunity to gain insights into the internal structure of tailings storage facilities, potentially laying the groundwork for future research on developing early warning systems for detecting structural changes.

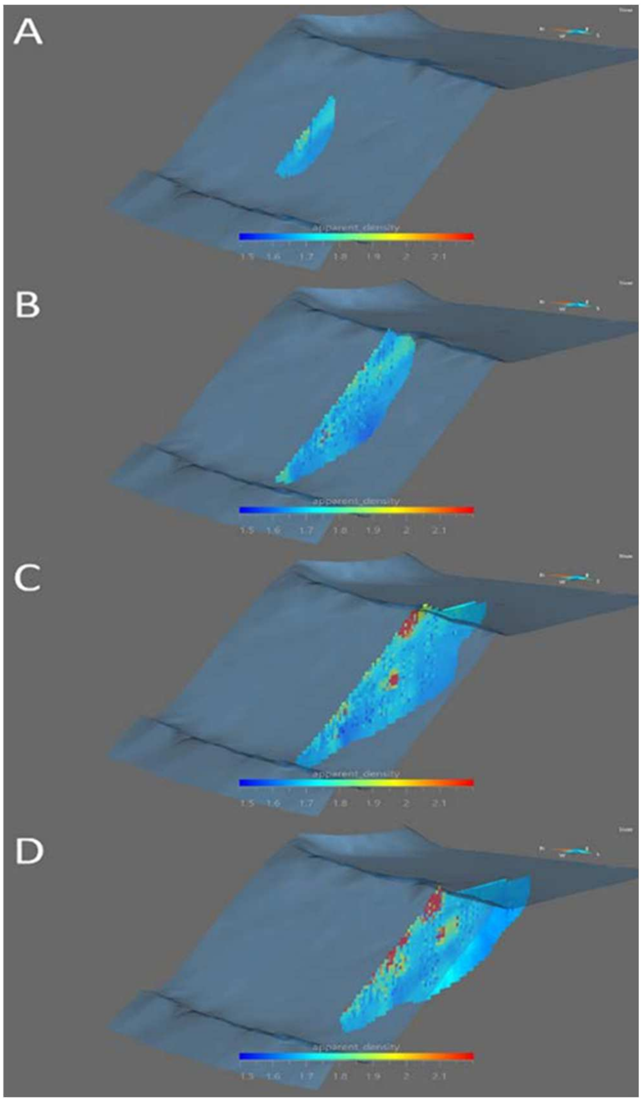

Figure 5. Apparent densities kriged throughout the scanned volume, shown as a progressive slice from North (A) to South (D). The transparent blue surface is the topography of the TSF.

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