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Mapping and monitoring tailings storage facilities with muography

Cartographie et surveillance des installations de stockage de résidus avec muographie

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ABSTRACT: Tailings storage facilities present a global and growing challenge for mining companies. The management of tailings, which are the by-products of the mine processing plant, requires careful attention due to the potential risks they pose if the storage facility were to collapse. Such incidents can result in severe and lasting damage to the environment in downstream areas. Therefore, it is crucial to continuously monitor the structural stability of these facilities to ensure the safety and sustainability of active mining sites and legacy mines. This paper introduces a novel approach where muon tomography is employed to analyse the internal density structures of tailings dams. This work was conducted at the Prominent Hill Mine site in South Australia. We introduce an innovative method and technology for examining the internal density distribution of tailings storage facilities using muons, a natural source of radiation that can create X-ray-like scans of large structures. Muon technology provides a unique opportunity to provide insights into the inner structure of tailings storage facilities and potentially serves as a foundation for future research on developing early warning systems for detecting structural changes.

RÉSUMÉ: Les installations de stockage de résidus représentent un défi mondial et croissant pour les sociétés minières. La gestion des résidus, qui sont les sous-produits de l'usine de traitement minier, nécessite une attention particulière en raison des risques potentiels qu'ils posent en cas d'effondrement de l'installation de stockage. De tels incidents peuvent entraîner des dommages graves et durables à l'environnement dans les zones en aval. Il est donc crucial de surveiller en permanence la stabilité structurelle de ces installations afin de garantir la sécurité et la durabilité des sites miniers actifs et des mines existantes. Cet article présente une nouvelle approche où la tomographie muonique est utilisée pour analyser les structures de densité internes des barrages à résidus. Ce travail a été réalisé sur le site de la mine Prominent Hill en Australie méridionale. Nous introduisons une méthode et une technologie innovantes pour examiner la distribution de densité interne des installations de stockage de résidus à l’aide de muons, une source naturelle de rayonnement capable de créer des balayages de grandes structures semblables aux rayons X. La technologie des muons offre une opportunité unique de mieux comprendre la structure interne des installations de stockage de résidus et sert potentiellement de base à de futures recherches sur le développement de systèmes d'alerte précoce pour détecter les changements structurels.

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

1 INTRODUCTION

Tailings Storage Facilities (TSF) are subject of long-term monitoring for stability and liquefaction assessments. Some remote monitoring capability for TSF is currently available with detection systems such as extensometers, LIDAR, total station, taseometers, and seismic sensors. However, their range and coverage of detection area are limited. Furthermore, background noise that inhibits detection ability, radiation licences that create barriers to deployment, and significant energy consumption of the systems either increase cost or restrict the longevity and flexibility of deployment.

The use of muons, naturally occurring particles from space, that impact a site and penetrate through hundreds of metres of rock with well-characterised frequency and direction, has long been considered a potential means to scan large volumes of matter.

Muons are continually being created by high-energy cosmic rays arriving from interstellar space and colliding with Earth's atmosphere at altitudes of about 15 kilometres. The average muon flux at sea level is about 1 muon per square centimetre per minute. The rate at which a muon loses energy as it interacts with matter is proportional to the density of the material it travels through.

Initially explored in 1955 to estimate tunnel overburden in the Snowy Mountains in Australia (George, 1955); detector capabilities have since greatly improved permitting 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 demonstrate a world-first use case of muon tomography in the context of TSF.

2 METHODOLOGY

The core detection unit is a 'telescopic' muon detector with several plastic scintillators that emit light when struck by a muon. This light is then received by mounted single-pixel silicon photomultipliers (SiPMs) (Krishnan et al., 2020). By utilising optically isolated sub-detectors within a panel plane, the arrival direction of intersecting muons can be estimated geometrically. The telescopic detectors provide angular coordinate uncertainty of less than five degrees within a field-of-view of order 17 × 17 degrees per pointing.

Two or more telescopic detectors are arranged along the embankment of a TSF to provide a limited 3D stereoscopic resolution of the muon flux detected across the extent of the embankment. Each detector observes multiple pointings over the course of several weeks to determine the muon flux as a function of angle across a TSF embankment (shown in Figure xxx). The observed muon flux depends on the elevation angle of observation and the opacity (or projected surface density), which is directly proportional to the muon path length inside the TSF embankment material and to the density of the material itself. Using at least two observation points separated by a known distance provides a stereoscopic 3D constraint on the material within overlapping fields of view.

The stand-alone telescopic muon detector system is solar powered with data transferred over 4G and can work independently of the mine power and communications infrastructure, easing many overheads and permissions from the host site.

Numerical simulations using the PUMAS library (Niess, 2022) and the Pyrate software package (Scutti, 2022) have been used to establish a relation between measured muon flux and observed opacity. This relation, which includes the correction for the elevation of observation, is used to convert the measured muon flux into observed opacity.

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. (1) Muons travel in straight lines for the energy ranges that predominate the ambient muon flux. (2) 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:

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

The basis of our adopted algorithm for 3D Muon Tomography is that of the Lines-Of-Sight (LOS) of different detectors intersecting common cells in the 3D block model space and by comparing observed LOS opacities against those computed by equation 1. The computed LOS opacity uses a 3D regular grid traversal algorithm (Figure 1) through an a priori discretised geological model of densities.

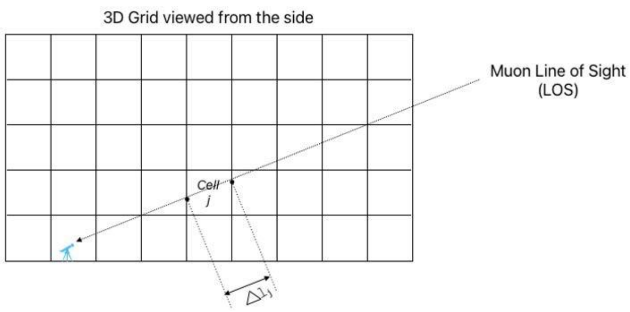

Figure 1. 3D Regular Grid Traversal Algorithm; with the opacity along a muon's line of sight (LOS) computed using equation 1.

The algorithm aims to find the density distribution of the medium traversed (ρ_j) such that equation 2 is minimised:

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

The algorithm developed to solve equation 1 is based on a Monte Carlo Markov Chain (MCMC) approach. Starting with an a-priori discretised geological model of densities to populate the initial guess for values of the image precomputed segment lengths of muon trajectories for the action, and reconstructed opacities derived from the observed muon events, an iterative method stochastically perturbs the image - one randomly selected cell at a time - looking to minimise equation 2.

This approach allows for geological constraints to be applied to the evolution of the model during its convergence (Guillen et al., 2004). The ability to use geological constraints is an advantage the MCMC approach offers over approximate imaging methods such as SIRT (Ren and Kalscheuer, 2020).

3 SURVEY

The Prominent Hill copper-gold mine is located approximately 640 km northwest of Adelaide in northern South Australia. Prominent Hill has one TSF impounded within the Integrated Waste Landform (IWL), shown in Figure 2. The TSF is a singular, circular facility containing tailings generated from processing ore from the open pit and underground mines. It has a diameter of 1750 m covering an area of about 2.4 km^2.

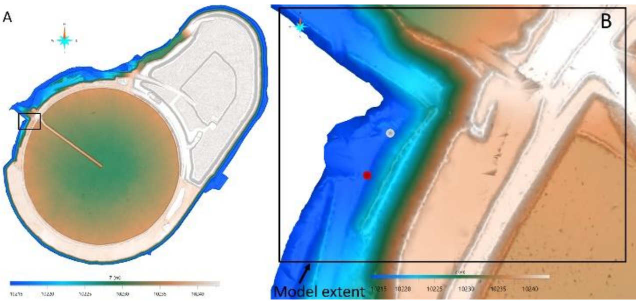

Figure 2. Topography surfaces generated from LiDAR data (blue colours are low elevations, white colours are high elevations) for: (A) the entire Prominent Hill tailings storage facility (black box shows the location of the scanned region), and (B) the scanned region zoom in, with the two telescopic detector deployments as the white and red dots.

Construction of the TSF has been ongoing, with five embankment lifts occurring since commissioning in 2009. The TSF embankment is a minimum 60 m wide waste rock dump rising 25 m high. On the tailings side of the embankment, a filter zone made up of finer waste rock, typically 3 m wide, was built concurrently with a 6m clay liner adjacent to the tailings.

Three detectors (seen in Figure 3) were used to monitor the region of interest identified in Figure 2. The primary and secondary detectors were telescopes used to scan the region dynamically. These detectors are placed approximately 10 m from the beginning of the rise, spaced 50 m from each other. The third reference detector was a simple muon counter recording the background rate.

The primary and secondary detectors were powered by an independent solar array with a single communication link used for data transfer and power distribution. Data acquisition and 4G gateway then arbitrated the data from all three detectors and forwarded data to the cloud.

Figure 3. Two muon detector telescopes mid-installation (note not their final placements), with the background muon counter as the small black box at its base.

Each detector observed multiple pointings over the course of nearly ten days to determine the muon flux as a function of angle across the TSF embankment.

The muon 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 the MCMC algorithm. These discrete points were then kriged to create a 3D volumetric apparent density, as shown in Figure 4.

The results of the muon-derived apparent densities, post-kriging, are found to be a distribution heavily skewed to the expected wall material density, 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 numerical artefacts.

As shown in Figure 4, 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).

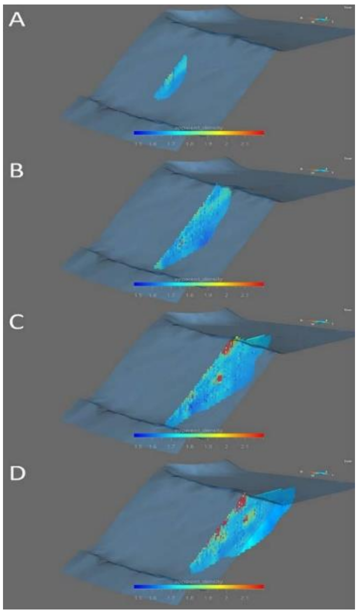

Figure 4. Apparent densities kriged throughout the scanned volume, shown as a progressive slice from North (A) to South (D). Cooler blue colours indicate low apparent densities, warmer red colours indicate high apparent densities. The transparent blue surface is the topography of the TSF. Note that only the rock fill embankment has been scanned.

4 CONCLUSIONS

Although only a limited area of the Tailings Storage Facility was scanned in this short deployment the utilisation and efficacy of muons for cheaply scanning large volumes, with no site disruption or installation requirements is clear. Muon technology provides a unique opportunity to provide insights into the inner structure of tailings storage facilities and potentially serves as a foundation for future research on developing early warning systems for detecting structural changes.

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