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Applications of Muon Absorption Radiography to the Fields of Structural Engineering

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A B S T R A C T

Muon radiography, also known as muography, is an imaging technique that provides information on the mass density distribution inside large objects. Muons are naturally produced in the interactions of cosmic rays in the Earth's atmosphere. The physical process exploited by muography is the attenuation of the muon flux, that depends on the thickness and density of matter that muons cross in the course of their trajectory. A particle detector with tracking capability allows the measurement of the muons flux as a function of the muon direction. The comparison of the measured muon flux with the expected one gives information on the distribution of the density of matter, in particular, on the presence of cavities. In this paper we discussing the Apllication of muon ray in the field of Structural engineering.

Keywords: machine learning; muon scattering tomography; non-destructive evaluation; Geant4; support vector machine; reinforced cement concert

Introduction

Reinforced Cement Concrete (RCC) structures have been the backbone of civil engineering for several decades. Reinforced concrete is an important building material in large-scale infrastructure: roads, bridges, tunnels, and buildings. Conventional concrete, despite having high compressive strength, lacks tensile strength which makes concrete brittle in face of shear and tension forces [1,2]. In the light of making concrete structures resistant to brittle and ductile mode failure, steel is added to the plain concrete. Steel due to its versatile properties can withstand these forces and, thus, is a perfect reinforcement for concrete [3]. It is however liable to damage due to corrosion, carbonation and chloride ingress. In order to avoid structural collapse, non-destructive testing methods are necessary to assess the quality of RCC structures. Additionally, knowledge of the type of defect and its precise location also improves the chances of averting the calamity. There are multiple Non-Destructive Evaluation (NDE) techniques that are typically used for imaging. These are ultrasonic tomography [4], infrared tomography [5,6], Ground Penetrating. Radar (GPR) [7], impact-echo [8]. These methods, however, have some limitations, which include the need for a high amount of heat for imaging non-conducting materials (active thermography), interference from environmental parameters, such as sunlight intensity (passive thermography), shadows of other bodies, wind, etc. Alternatively, radiological imaging methods (radiography) using X-rays and gamma-rays are very effective, but are not preferred due to their potential for biological hazards. Cosmic ray muon tomography is thus gaining traction for the imaging and monitoring of RCC structures. Since the beginning of 1950s, cosmic ray muons have found applications in tomographic studies of large civil structures owing to their highly penetrative and less-interactive nature [9–13]. Other than imaging structures based on the differential flux of absorbed and penetrated muons, multiple scattering suffered by the muons while passing through matter due to their interaction with atomic nuclei, has also been exploited to scan targets, the underlying physics of which is formulated based on their atomic number, weight, and density [14–16]. This innovative NDE technique has found applications in scanning nuclear-waste containers, possibly-smuggled special nuclear materials in cargo containers, monitoring gate valve conditions, pipe wall thickness [17–20], etc. In addition to these, monitoring and imaging defects in large concrete structures have also emerged to be a substantial utilization of muon imaging [14,16,21]. This article showcases MST [22] as an NDE technique to image RCC structure and puts forward a recipe to discriminate rusted portions of steel rebars using the Geant4 simulation toolkit [23]. Subsequently, a classification-based Machine Learning (ML) algorithm has been employed to enhance image reconstruction and improve rust identification among targets involving similar material densities (steel (7.87 g/cc), rust (5.25 g/cc), and concrete (2.3 g/cc)). For training and validation, the ML model has been applied to a scenario with four blocks of materials: aluminium ($Z = 13$), iron ($Z = 26$), lead ($Z = 82$), and uranium ($Z = 92$) to address different ranges of atomic number and density. The scattering positions and corresponding angles of the muons as they pass through the blocks have been obtained from reconstruction of muon tracks from the muon hits as recorded by the muon trackers in the MST setup. This work has been accomplished by the Geant4 simulation. Based on these parameters, radiographic image production has been carried out. Next, by employing a Pattern Recognition Method (PRM) [24], the materials in focus have been separated from the background (air). The ML technique, mentioned above is a Support Vector Machine (SVM) [25] classifier which has been used to detect rust on a rebar in a RCC unit. The working principle of MST has been detailed in Section 2 and the simulation model of the system has been described in Section 3. Discussion on image reconstruction of the target can be found in Section 4, followed by its analysis in Section 5. Finally, training the ML model on four blocks: Al, Fe, Pb, and U, and its implementation to segregate rust from the steel rebar have been reported in Section 6 along with its detailed analysis

What is Muon Tomography:

Muon tomography, also known as muography, is indeed a technique that utilizes cosmic ray muons to create three-dimensional images of objects or structures. It takes advantage of the scattering of muons as they pass through materials, which provides information about the density and composition of the objects they interact with.Compared to X-rays, muons are much more penetrating and can pass through thicker materials without significant attenuation. This property makes muon tomography suitable for imaging dense or heavily shielded objects that may be challenging to visualize using traditional X-ray-based techniques like computed tomography (CT scanning).The flux of muons at the Earth's surface is relatively high, with a single muon passing through an area the size of a human hand every second. By measuring the trajectories and scattering patterns of these muons as they pass through an object, scientists can reconstruct a detailed image of the object's interior.Muon tomography has found applications in various fields, including archaeology, geophysics, and nuclear waste detection. It enables non-destructive imaging of large structures such as pyramids, volcanoes, or geological formations, providing valuable insights into their internal composition and structural integrity.

Muography has indeed been utilized to map the interior of large civil engineering structures. Its ability to penetrate thick materials and provide detailed imaging makes it a valuable tool for assessing the integrity and condition of such structures without the need for invasive techniques.

One notable application of muography in civil engineering is the examination of tunnels and underground cavities. By placing muon detectors around the perimeter or on the surface above the structure, scientists can measure the flux and trajectories of muons passing through the ground. Variations in muon flux and scattering patterns can then be used to create a tomographic image of the interior, revealing the presence of voids, anomalies, or potential structural issues.This non-invasive approach to assessing tunnels and other civil engineering structures offers advantages over traditional inspection methods, as it eliminates the need for costly and time-consuming excavations or disruptive measures. It allows engineers and researchers to obtain valuable information about the internal condition of structures, such as detecting voids, identifying areas of potential weakness, or assessing the effectiveness of repairs or reinforcement.Muography has been successfully employed in the examination of various structures, including tunnels, dams, bridges, and historical buildings. It provides a unique perspective on the internal composition and structural features, aiding in maintenance, monitoring, and decision-making processes related to civil engineering projects.Muon tomography, or muography, offers several

Advantages as a non – invasive technique for various application:

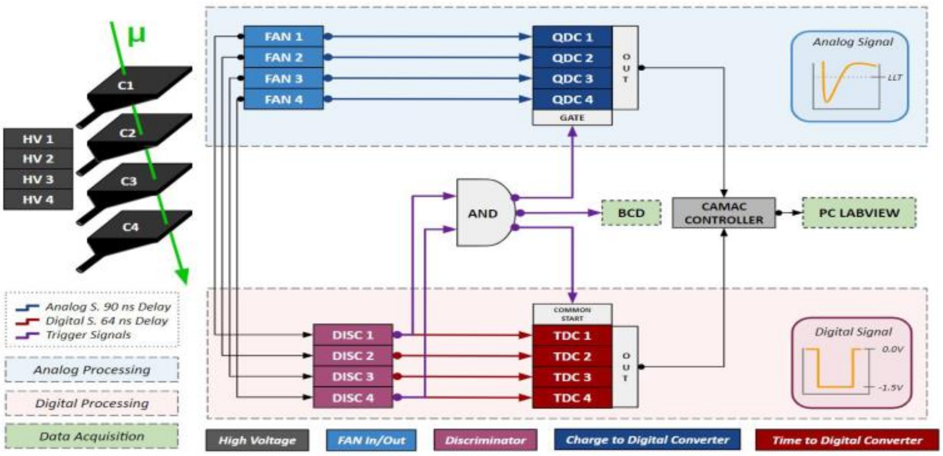

Fig.1 Electronic diagram for the UNIANDES muon telescope. The diagram shows the processing of analog and digital signals and summarizes the signal processing phase.

a) Penetration: Muons are highly penetrating particles, capable of passing through significant amounts of material. This allows muography to image through thick and dense structures that may be challenging for other imaging techniques, such as X-rays.

b) Non-destructive: Muography is a non-destructive imaging technique, meaning it does not require physical contact or alterations to the object being examined. This is particularly valuable when dealing with delicate or valuable structures, historical artifacts, or critical infrastructure where invasive methods may be impractical or undesirable.

c) Large-scale imaging: Muography can provide imaging on a large scale, encompassing entire structures or geological formations. It enables the assessment of structures such as tunnels, buildings, or volcanoes, allowing for a comprehensive understanding of their internal composition, structural integrity, and potential hazards.

d) Imaging through materials: Muons have the ability to pass through materials that are typically challenging for other imaging modalities, such as dense rocks, metals, or concrete. This makes muography suitable for imaging objects that are heavily shielded or have high-density components.

e) Continuous monitoring: Muography can be used for continuous monitoring of structures, providing real-time or periodic imaging data. This is particularly useful for tracking changes over time, such as deformation, movement, or structural degradation, and can help in early detection of potential issues or hazards.

f) Cost-effective: Muography can offer a cost-effective alternative to other imaging techniques, especially in situations where invasive methods or expensive equipment may be required. It utilizes natural cosmic muons, which are abundantly available and do not require the generation of additional radiation.

Limitations of Muon Tomography:

It also has limitations. It typically provides low-resolution images and requires sophisticated data analysis techniques for accurate interpretation. Additionally, muography is affected by atmospheric conditions and can be sensitive to background noise, which may require careful calibration and data processing. Overall, muography's unique capabilities make it a valuable tool for imaging and monitoring large-scale structures, providing insights into their internal composition and structural characteristics in a non-invasive and cost-effective manner.

In the field of structural engineering, muography can provide valuable insights and advantages for assessing the condition and integrity of various structures.

Specific Advantages of Muon Tomography:

Here are some specific advantages of muography in structural engineering:

a) Non-destructive assessment: Muography allows for non-destructive assessment of structures, meaning it can provide valuable information about the internal condition of a structure without the need for invasive testing or physical alterations. This is particularly useful for evaluating the integrity of historical buildings, bridges, or other structures where preserving the original structure is essential.

b) Detection of internal anomalies: Muography can identify internal anomalies within structures that may not be visible from the exterior. It can detect voids, cavities, cracks, or other defects that may compromise the structural stability or pose a risk. This enables engineers to identify potential issues and take appropriate measures for repair or reinforcement.

c) Evaluation of structural health: By continuously monitoring structures using muography, engineers can assess the health and performance of a structure over time. This allows for early detection of structural changes, such as deformation or movement, which can help prevent catastrophic failures and guide maintenance strategies.

d) Assessment of underground structures: Muography is particularly beneficial for assessing underground structures, such as tunnels or underground cavities. It can provide valuable information about the condition of these structures, detect voids or areas of weakness, and help optimize maintenance and repair plans.

e) Cost-effective and efficient: Muography can offer cost-effective and efficient imaging capabilities compared to traditional techniques. It utilizes cosmic muons, which are naturally occurring and readily available, eliminating the need for expensive equipment or the generation of additional radiation.

f) Complementary technique: Muography can complement other structural assessment techniques, such as visual inspections, material testing, or geotechnical investigations. It provides a unique perspective on the internal condition of structures, enhancing the overall understanding and evaluation of their structural health.

It's worth noting that muography, like any imaging technique, has its limitations. It provides relatively low-resolution images, and interpretation requires expertise and sophisticated data analysis techniques. Additionally, external factors like atmospheric conditions can affect the accuracy of muographic imaging. Nonetheless, muography has proven to be a valuable tool in structural engineering, offering unique insights into the internal condition of structures and assisting engineers in making informed decisions regarding maintenance, repair, and safety measures.

Non-destructive assessment is a critical aspect of structural engineering that involves evaluating the condition, integrity, and performance of structures without causing any damage or alteration to the structure itself.

Non-Destructive Testing with Muon Tomography:

Muography, along with other non-destructive testing (NDT) methods, plays a significant role in this process. Here are some key points about non-destructive assessment in structural engineering:

a) Preservation of structural integrity: Non-destructive assessment techniques allow engineers to evaluate the health of structures without compromising their structural integrity. This is particularly important for historical buildings, monuments, or structures with cultural significance, where preserving the original form is crucial.

b) Detection of hidden defects: Non-destructive assessment methods, including muography, can detect internal defects, such as cracks, voids, corrosion, or delamination, which may not be visible from the exterior. These hidden defects can weaken the structure and lead to failure if left undetected and untreated.

c) Early detection of deterioration: Non-destructive techniques enable the early detection of deterioration or degradation processes in structures. By identifying signs of deterioration at an early stage, engineers can implement timely maintenance and repair strategies, preventing further damage and extending the lifespan of the structure.

d) Monitoring structural behavior: Continuous or periodic non-destructive monitoring allows engineers to track the behavior of structures over time. By collecting data on factors like deformations, vibrations, or structural movements, they can assess the performance of the structure and identify any anomalies that may require attention.

e) Cost-effective maintenance planning: Non-destructive assessment methods aid in optimizing maintenance and repair plans by providing accurate information on the condition of a structure. This allows engineers to prioritize repairs based on the severity of defects, allocate resources efficiently, and minimize unnecessary interventions.

f) Reduced downtime and disruption: Non-destructive assessment techniques often require minimal or no disruption to the operation or functionality of a structure. This is particularly beneficial for structures like bridges, tunnels, or buildings that need to remain operational during the evaluation process, avoiding significant downtime or inconvenience.

Examples of other non-destructive assessment techniques used in structural engineering include visual inspections, ground-penetrating radar, ultrasonic testing, infrared thermography, magnetic particle testing, and acoustic emission testing. Each method has its specific advantages and limitations, and their selection depends on factors such as the type of structure, accessibility, and the nature of the defects being investigated.

Overall, non-destructive assessment techniques, including muography, are invaluable tools for structural engineers to assess the condition of structures, detect hidden defects, and ensure the safety and longevity of the built environment.When using muon rays for the assessment of structures, there are several methods and techniques that can be employed. Here are some common methods of assessment using muon rays:

g) Muon Radiography: Muon radiography involves capturing images of the structure using the trajectories of muons as they pass through it. Muon detectors are placed strategically around the structure, and by measuring the flux and scattering patterns of the muons, an image of the structure's interior can be reconstructed. This method provides a 2D or 3D representation of the density distribution within the structure.

g) Muon Tomography: Muon tomography is an extension of muon radiography that generates detailed 3D images of the interior of a structure. By capturing multiple radiographic images from different angles, scientists can reconstruct a volumetric model of the structure, providing a comprehensive view of its internal composition.

h) Differential Muon Tomography: This technique utilizes the differences in muon flux at various locations around the structure to create detailed images of density variations within the object. By comparing the muon flux at different detector positions, it is possible to identify regions of differing density, such as voids, cavities, or areas with higher or lower density materials.

i) Muon Scattering Analysis: Muon scattering analysis focuses on studying the scattering patterns of muons as they interact with the structure. By analyzing the deflection angles and energy loss of the scattered muons, valuable information about the structure's composition and density can be inferred. This method is particularly useful for identifying materials with different atomic numbers.

j) Muon Tracking: Muon tracking involves monitoring the trajectories of individual muons as they traverse the structure. This technique enables the measurement of small-scale movements or deformations in the structure over time. By tracking the positions of muons and analyzing any deviations from their expected paths, engineers can detect structural instabilities or changes in the structure's geometry.

It's important to note that the specific method used for assessing a structure with muon rays depends on factors such as the objectives of the assessment, the size and geometry of the structure, and the available muon detection equipment. Different combinations of these methods can also be employed to obtain a more comprehensive understanding of the structure's internal characteristics.

Muon-based assessments offer non-invasive and penetrating imaging capabilities, providing valuable information about the density distribution, structural integrity, and potential anomalies within various types of structures.

Conclusion:

With reference to above study we can conclude that the Muon Tomography is very usefull in the eara of Until now researchers have mostly utilised well-established geophysical methods such as seismic tomography, electric resistivity tomography, ground penetrating radar and others to gain insights into the Earth's interior. In recent years a new method originating from particle physics, muon tomography, has been used more frequently to collect data on geological features at a few tens to hundreds of meters distance to the surface.

1. This new technology synergises well with the established geophysical methods as their advantages and drawbacks balance each other. Muon tomography offers the possibility to measure structural properties (like the density distribution) within the object in question, while not having to go near dangerous or inaccessible places.

2. Naturally, there are also scenarios where the established geophysical methods yield much better results. One of the most serious limitations of muon tomography, for example, is the fact that detectors always have to be placed below the target and can only inspect the material above. To be able to take the decision whether this new technology might be useful for one's research, well-founded knowledge on the possibilities and limitations of muon tomography is needed.
3. However, the know-how on this technology is in most cases located in particle physics laboratories. With this work, we present a starting point for prospective users with a geoscientific background to become familiar with muon tomography. The summaries of important aspects should help interested readers to form a solid overview.
4. The aspects in the previous chapters are not meant to be exhaustive. They consist, however, of a few important cornerstones that we think are important to get an idea on the whole topic of muon tomography. The guidelines are also intended to point the prospective users into the right direction. The showcase of different applications is thought to be an inspiration for readers.
5. Knowing about the potential uses of muon tomography, one can employ this technology in their own research field. The possible applications of this technology are still far from exhausted.
6. Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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