

# Muon tomography applied to assessment of concrete structures: First experiments and simulations.

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## Abstract

Non-destructive techniques for reinforced or prestressed concrete inspection such as ultrasound or radar have found regular, successful practical application but sometimes suffer from limited resolution and accuracy, imaging artefacts or restrictions in detecting certain features. Until the 1980s X-ray transmission was used in case of special demands and showed a much better resolution than other NDT techniques. However, due to safety concerns and cost issues, this method is almost never used anymore. Muon tomography has received much attention recently. Novel detectors for cosmic muons and tomographic imaging algorithms have opened new fields of application. As a first step towards practical application in civil engineering and as a proof of concept we used an existing system to image the interior of a reference reinforced 600 kg concrete block. Even with a yet not optimized setup for this kind of investigation, the muon imaging results are at least of similar quality compared to ultrasonic and radar imaging, potentially even better. In a second step, we have performed simulations to assess the potential for a set of important testing problems such as grouting defects in tendon ducts. The next steps include the development of mobile detectors and optimizing acquisition and imaging parameters.

**Keywords:** Muon tomography, concrete, reinforcement, tendon ducts

## 1 Introduction

The availability of the European road and rail transport infrastructure is an essential prerequisite for mobility and growth in the EU and world-wide. Bridges and tunnels along this infrastructure are the costliest but also the most vulnerable assets. EU road infrastructure is getting older and suffers from aging issues with a large part of it already approaching the end of its lifespan. According to the European Union Road Federation, in 2018, the network had a length of 5.5 million km and a value of 8000 billion Euros, the latter declining [1]. In Germany, 10 % of the bridges (bridge deck area considered) under federal administration were rated with a condition “less than sufficient” [2]. They are subject to serious deterioration, due to the increase of freight volumes (and traffic) with as well as vehicle weights. Traditional approaches for assessing the condition of transport infrastructure are based on structural inspections (visual, tap test) at fixed or adjustable time intervals. They are not fully adequate for an efficient inspection and monitoring of the transport infrastructure assets, which after all amount to about 40% of the total European assets [1]. Only an efficient inspection, preferably permanently under flowing traffic will give infrastructure owners and managers the right picture to prioritize their maintenance operations.

There are already a number of Non-Destructive Testing (NDT) methods that provide engineers with tools to inspect aging infrastructure [3][4][5][6]. Standard technologies for structural assessments by locating objects, voids, flaws and other features in 3D are ultrasonic methods and ground penetrating radar. These techniques have revolutionized NDT in civil engineering (NDT-CE) but still suffer from limited resolution and other limitations. Until the 1980ies, X-

ray radiography has also been used on site, due to its superior resolution and accuracy. However, it is hardly ever used today due to restrictions on radiation safety and associated cost. So, what can be done when you want to do an X-ray, but don't want to use an active X-ray source? Muography, a technique which uses a special type of cosmic rays for imaging density contrasts, is known since the 1950ies [7]. Over time, several other ideas to use muography for imaging natural man-made objects have been envisaged or tested, including volcanoes [8][10] and an ancient Egyptian pyramid [9]. Recently, based on a more accurate imaging method ("muon tomography") and the development of new high-resolution detectors, the investigation of freight containers or radioactive waste packages got attention [10][11]. The application to detailed examination of reinforced concrete structures has been investigated [12]. This paper summarizes the results of an evaluation experiment using a reference specimen in a laboratory detector [13] and shows a potential application to detect grouting flaws in tendon ducts based on simulations.

## 2 Muon tomography

### 2.1 Principle

Muon tomography is a technique, which is used to reconstruct 3D density maps of volumes using the Coulomb scattering of muons. By measuring the tracks of muons as they enter and exit the volume, an estimate of the average magnitude of scattering occurring in discrete volume elements can be calculated. Due to their high average energy of several GeV, i. e. 10,000 times that of typical X-rays, and due to the way muons interact with matter, they are highly penetrating and can pass through tens and hundreds of meters of rock (or concrete). The primary advantages of using muon tomography over other methods are this penetration depth and the fact that it is entirely passive while also being non-destructive. The comparatively long time it takes to make a measurement using cosmic-ray muons, can be considered its main detractor; millions of muons are required to create a high-resolution image and the flux of muons at sea level is around 170 Hz/m<sup>2</sup>. This means that in practice data needs to be collected continuously for days or even weeks. The flux of muons also has a strong angular dependence, mostly limited to +/- 30° to the vertical, which leads to a better imaging resolution in the horizontal plane than in the vertical direction.

Note, that the term tomography is used in differently in muon imaging and X-ray radiography related literature. In NDT standards for X-ray imaging, the term tomography refers to 360° ray coverage. Setups with limited ray coverage (e. g. due to limited access from two sides) are called laminography. However, we are staying with the term tomography for the muon imaging method in this study to be consistent with related literature.

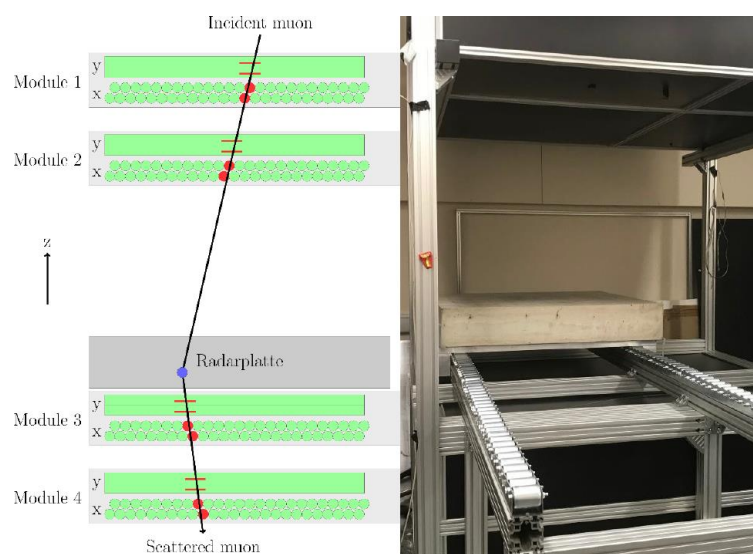
### 2.2 Experimental setup

The Lynkeos Muon Imaging System (MIS) consists of four detector modules each containing two orthogonal layers of scintillating fibres from which a space point can be determined (Figure 1). Two modules placed above the volume are used to reconstruct the incident muon tracks and two below for the outgoing, scattered tracks.

The active area of the MIS modules is 1 m by 1 m allowing objects having smaller cross sections to be imaged. The horizontal resolution of the MIS is limited by the 2 mm diameter of the scintillating fibres used in the detectors; these are triangularly packed in two sublayers allowing

an effective resolution of less than 2 mm where muons pass through neighbouring fibres. The vertical resolution of the reconstructed image is of the order of 4 cm due to the angular acceptance of the detector being limited to near vertical tracks.

The image reconstruction for the muon tomography data used in this paper has been performed by the MLEM (maximum likelihood expectation maximization) method [13] and back projection method [14]. The volume between the top and bottom detectors is divided into voxels. The value attributed to each voxel is calculated based on the average measured scatter of the set of muons which pass through the voxel. The voxel value is expected to increase with the density of the volume it relates to.



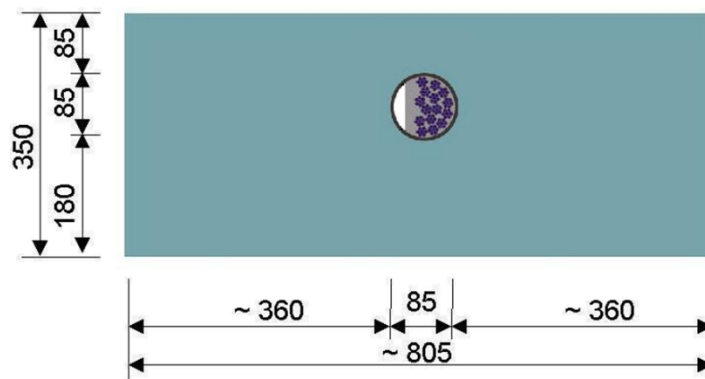
**Figure 1:** Principle (left) and experimental setup (right) of muon tomography

### 2.3 Simulations

Further studies of applications of muon tomography imaging on the reinforced concrete samples were carried out using the Geant4 [15] simulation toolkit. Our past study has shown that the Geant4 simulation results agree well the experimental results [14]. For the current study, Geant4 version 10.07 was used. The physics list used in the simulation was G4EmStandardPhysics\_option3 (Option 3), which uses the Urban MSC model [16] to describe the muon multiple scattering process. To avoid the infrared divergence, it is required to set up secondary particle production thresholds, which means that no secondary will be generated below the thresholds. This threshold should be defined as a distance, or range cut-off, which is internally converted to an energy for individual materials. These cut values were set to be 10 mm for all particles, and all the other parameters of Geant4 were using default values. Because Geant4 doesn't have a high quality built in cosmic ray muon generator, an external muon generator called "Efficient COsmic MUon Generator" (ECOMUG) [17] was used to generate the muon events. To make the simulation as close to the experiment as possible, the tracking detector geometry was constructed according to the actual detector geometry used in the experiments. For each muon event, the Geant4 simulation can provide various information for the particle hit, including the precise hitting positions. However, to make the Geant4 simulation comparable to the experimental data, the information used in the muon track reconstruction

includes only the serial numbers of the tracking detector elements that were hit by a particle and the energies deposited in each of the detector element. The algorithm used to reconstruct the muon track from the above information was the same as used for processing the experimental data. Unlike the experimental data, the simulated muon tracks have no alignment errors, and does not include noises from cross talk between different channels. To introduce these noises into the simulated data, Gaussian position noises were deliberately added to the reconstructed hitting positions.

A concrete example with dimensions of 805mm (length), 600mm (breadth), 350mm (depth) was simulated with Geant4. The cross section of the concrete sample is shown in figure 1. A tendon duct with a diameter of 85 mm is in the centre region of the concrete sample. The tendon duct pipe was filled with steel cables and concrete. To simulate a tendon duct defect, a void is created by removing some concrete. For this study, four different settings were simulated. The first has a void located on the left side of the tendon duct while the steel cable located on the right side, as shown in the figure 1. The second scenario has no void and the steel cables located on the right side. The third has a void on the top of the tendon duct pipe and the steel cable located at the bottom; and the fourth one has no void and the steel cable at the bottom. As shown in figure 1, the void is 2cm wide at the widest position, and it goes through the whole length of the tendon duct.



**Figure 2:** Cross-section profile of the concrete sample used in the Geant4 simulation.

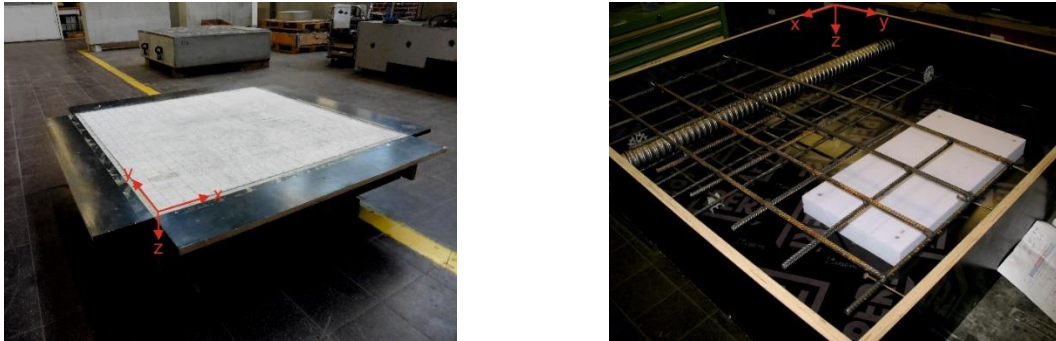
### 3 Evaluation experiment

A first of a kind experiment was conducted using a reference specimen produced by BAM for NDT training and validation purposes (“Radarplatte”, Figure 3). The size of the object is 1.2 m x 1.2 m x 0.2 m. It contains four potential targets: a Styrofoam plate mimicking reduced thickness or a void, an empty tendon duct and top and bottom rebar meshes with diameters down to 8 mm.

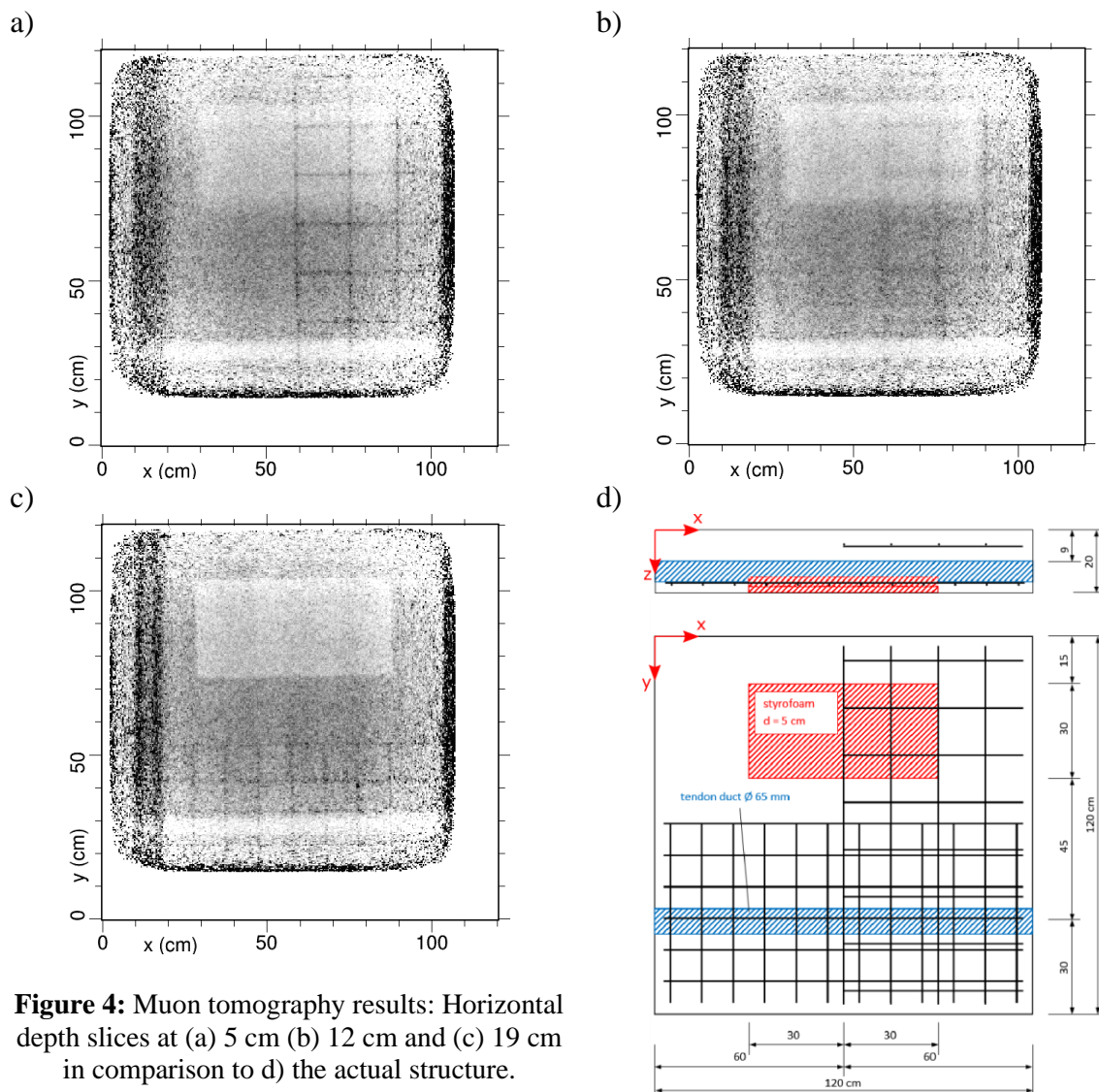
The experiment was carried out at the facilities of University of Glasgow using a muon tomography system provided by Lynkeos Ltd (Figure 1, right). The object has been in the detector for 1203 hours and the trajectories of about 23 million muons have been traced and used to reconstruct images. Horizontal cross-sections slicing the reconstructed 3D volume at different depth are shown in. Note, that the detector size is 1 m x 1 m, thus not capturing the full size of the object.

From the images it is obvious that all 4 targets can be detected, indicating a sub-cm resolution in the horizontal detection. However, the vertical resolution is limited due to the characteristics

of the muon's trajectories, resulting e.g., in the tendon duct and the Styrofoam plate appearing in the upper slice at 5 cm while being located in reality much deeper.



**Figure 3:** Test object “Radarplatte”, Current state (left) and before casting (right)



**Figure 4:** Muon tomography results: Horizontal depth slices at (a) 5 cm (b) 12 cm and (c) 19 cm in comparison to d) the actual structure.

## 4 Potential of application to tendon duct investigation

With the method described in section 2.3, 60 million muon tracks were simulated for each simulated scenario. With these data, tomographic images were reconstructed using reconstruction method described in reference [14].

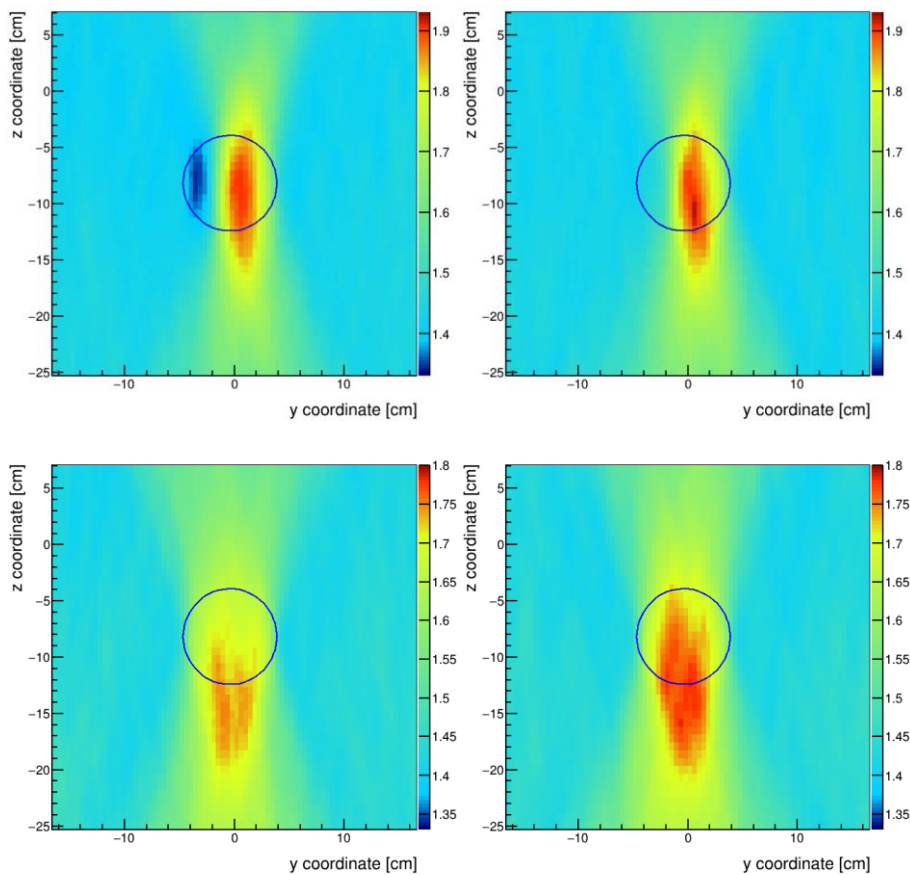
In figure 5, 4 cm vertical slices through the reconstructed images of concrete samples are shown. In the image on the top left side of figure 5, a void with a size about 2 cm by 4 cm can be seen clearly, which is shown as a blue spot in the centre region, where the steel cable is shown as an orange/red region. The image on the top right side of figure 2 is the scenario without a void, only the steel cable can be seen. The images shown on the bottom row are for concrete samples with the steel cables located at the bottom of the tendon duct; while the bottom left side image has a void at the top of the tendon duct and the bottom right one has no void. Unlike the images in the top row, where the void can be seen clearly as a blue spot, although the intensity at expected void region is reduced, the difference is not big enough to show as an isolated blue spot. The reason for the reduced capability for these settings is caused by the combination of the limited opening angle of the muon imaging detector and the special angular distribution of the cosmic ray muon. With the increase of the opening angle of the muon imaging detector, more muons come from the side, the capability to image a void on the top/bottom side will increase. However, due to the natural angular distribution of incoming muons, its capability in the vertical direction is still expected to be worse than in the horizontal direction.

## 5 Summary and outlook

The research presented in sections 3 and 4 shows the potential of muon tomography application in the assessment of civil structures. The evaluation experiment has proven the sub-cm resolution in the horizontal direction by detecting rebar with 8 mm diameter. The successful detection of a Styrofoam plate and a hollow tendon duct have demonstrated the capability to detect larger voids.

The simulations have been carried out to evaluate the capability to detect smaller voids in tendon ducts. Such kind of voids are occurring in civil engineering practice and pose a threat to the structure's capacity as they increase the risk of corrosion of prestressed cables in those ducts.

To be able to use this technology in practice we would have to improve the detection technology in terms of mobility, cost, robustness and directivity. Detailed validation studies on the methods capabilities, limits of detection and accuracy would have to follow. By doing this, we will add a fascinating technology to NDT-CE, capable to fill some gaps in the toolbox currently available.



**Figure 5:** Vertical slices of reconstructed muon tomographic images. Top left: a void on the left and steel cable on the right inside the tendon duct. Top right: no void and steel cable on the right. Bottom left: a void on the top and steel cable at the bottom. Bottom right: no void and the steel cable at the bottom. The blue circle indicates the tendon duct.

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On behalf of the first author, this paper is dedicated to his colleague Dr. Christiane Maierhofer, a pioneer in modern NDT-CE, recently deceased, one of the persons who had shown him that NDT-CE is an attractive field of research, worth switching the career by 180 °.

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