Cavity Location by Muon Tomography

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Abstract

Muon tomography (or muography) is one of the most effective methods for locating unknown underground voids. If the geometric conditions are favorable for the measurements, no other geophysical method can compete with it, neither when resolution nor when simplicity is considered.

In the last years, thanks to the continuous R&D of our low-cost, portable muon detectors, as well as the improved data processing methods, we have completed several successful natural and artificial cavity exploration projects, demonstrating that location is possible even if the characteristic size of cavity is 5% of the rock thickness between the detector and surface.

Here we present case studies carried out in Hungarian underground sites, where we could find unknown cavities and verify the method by locating known artificial shafts and adits with high precision. Reaching these unknown caves is in progress either by conventional caving exploration techniques or by drilling.

Further measurements are ongoing by the new upgraded detectors. By decreasing gas consumption and supporting electric power by solar cells, we are able to measure even at remote locations without the need of any direct access, for durations of several months.

Introduction

Locating unknown underground voids is one of the most difficult geophysical tasks, despite the continuous improvements of different methods and data analysis techniques. It is even more difficult to obtain direct images of the underground structures. Muography is probably the most effective method for generating spectacular results, where not only the proof of the existence of an unknown cave or artificial void is possible, but we can obtain information about its size and shape, too. The main limitations are the geometrical constraint (the detector must be placed more or less under the rock body to be investigated), and the measurement time (the order of magnitude of which is months rather than days).

Instrumental

Our Group has developed a series of gaseous multi-wire particle detectors for muography applications, which are able to operate even in remote locations thanks to the low power consumption, and in harsh environment like a natural cave. We have different size detectors for the optimal operation for both natural environment in difficultly accessible places and for artificial adits where the larger detectors can reduce measurement time. More technical details and references are listed in a separate article (Hamar et al.: Multi-Wire Detectors for Underground Muography). The elaborated geodesy needed for the data evaluation has been carried out by modern, efficient tools (handheld laser scanner, airborne Lidar).

Results

Several field projects have been performed by our group in the last years, both in natural and artificial environment. Here we present the results of some of our ongoing measurements.

Castle Hill of Buda

The Castle District of Buda, in Budapest, capital of Hungary, is located on a ~60m tall hill next to the river Danube. This is a particularly exciting area because several kilometers of tunnels and adits have been excavated during the centuries under the densely built-up area, many of which are unknown, causing even civil engineering problems. However these unknown parts of the system are also important targets of archaeology. Under the Castle Hill there is the oldest Hungarian tunnel used for traffic. The auxiliary adits of the tunnel are ideal places for test measurements because the rock is marl with homogenous density up to the surface, and there are several other artificial tunnels and shafts with well-known geometry above the lowermost adits. Fig.1 shows the result of a test measurement from a tunnel 33m below the surface. From one measurement the direction of the anomaly and the extent of the anomaly in the muon's track direction can be reconstructed. For the exact location of an anomaly at least two measurements are necessary from significantly different viewing angles, but sometimes relevant information can be extracted from even one measurement. Here another tunnel and a connected chamber, the depth of which is about half way from the detector to the surface, can clearly be seen on the right of Fig.1. The sketch of the geometry is shown on Fig.2.

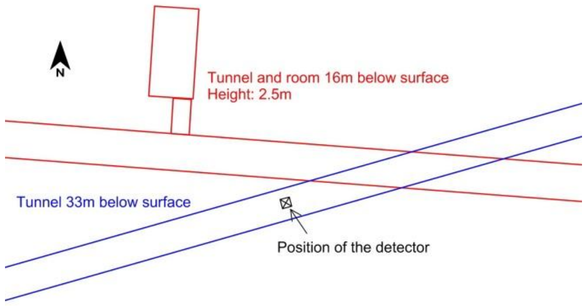

Figure 2: The layout of the test measurement under Castle Hill

It is also important result that there are not any significant unknown voids up to about 30 degrees from the zenith. There are some slight indications for other voids at higher angular distances but these will have to be verified by other measurements from different viewing angles.

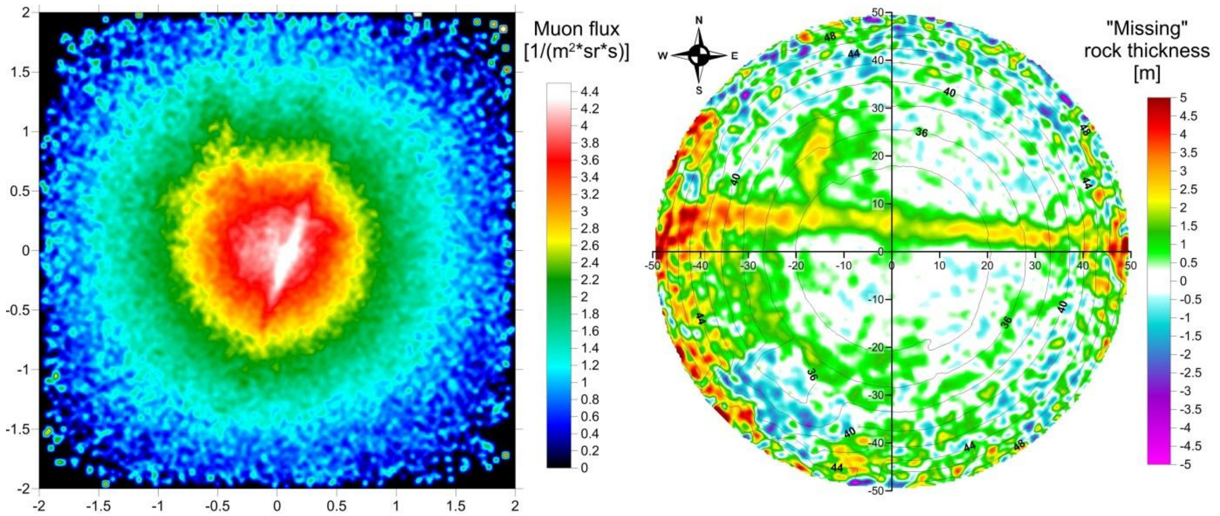

Figure 1: Left: the measured muon flux in detector coordinate system. The detector's rotation from the geographical North is about 110 degrees clockwise. The units on the axes are the tangents of the angles from the symmetry planes of the detector.
Right: the missing rock thickness in geographical coordinate system. The units on the axes are the angular distances from the zenith (0;0) in degrees. The continuous contour lines show the distance from the detector to the surface.

Királylaki cave

There are also a lot of natural caves under Budapest, with the total length of more than 50km. Another project of us aims to find new parts of Királylaki cave, few kilometers to the North of Caste Hill. The natural cave's entrance is in the middle of some 500m long tunnel system, so the measurements were performed from artificial tunnels. Fig.3 shows some results of the measurement series taken for about a year. This part of the tunnel is located under a steep hillside so the lowest detector to surface distances are about 30 degrees to the East from the zenith, as indicated by the black contour lines. The missing rock thickness pictures clearly show a series of fissures, viewed from different angels. The height of one of these fissures is at least 6m, with 10-15m length and 3-4m width. Reaching this fissure, which is likely to be connected to the known system, is planned by drilling from the tunnel.

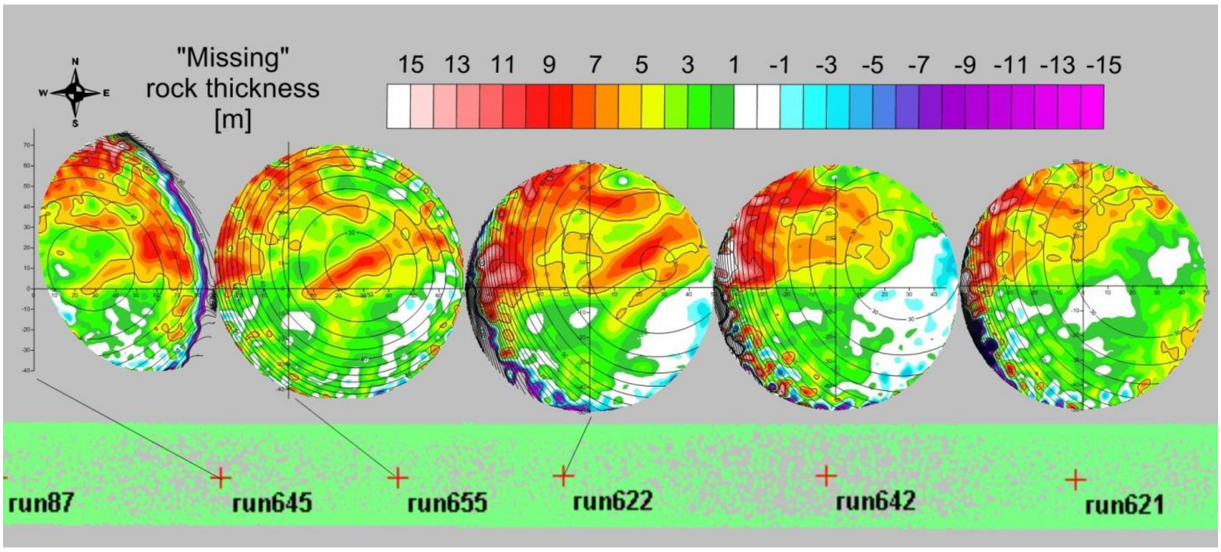

Fig. 3.: The missing rock maps of five measurements. The reddish colours show significant voids between the tunnel and the surface. The axes of the maps show the angular distances from the zenith in degrees, the cyclic black contour lines indicate the detector to surface distances. The run numbers show the relative places of the measurements in the tunnel (green point cloud), the distance between the measurement places was 10-15m.

Sátorkőpusztai cave

This cave, which is about 40km from Budapest, is one of the most beautiful caves of Hungary, despite the considerable loss of gypsum crystals in the middle of the last century. Finding unknown parts here in the original condition would be particularly important outcome. Here the measurement possibilities are limited due to the narrow passages of the cave, so a smaller size detector and extended measurement times have to be used. The preliminary results are very promising, there are zones where the missing rock thickness is almost an order of magnitude larger than the measurement uncertainties (Fig. 4, 5), so we can state that new cave sections have been found. However, due to the complex geometry of the known and the expected new cave, further measurements are needed to gain the exact location of the new sections.

Figure 4: The detector in the lowermost chamber

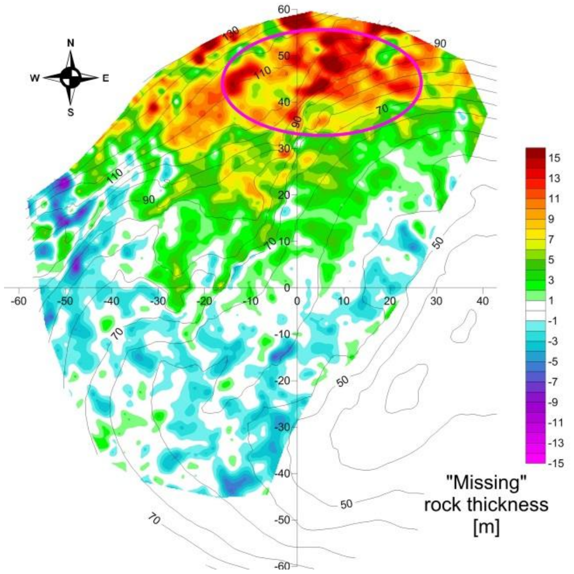

Figure 5: The missing rock map of one of the measurements at Sátorkőpusztai Cave. The pink oval shows the most promising area, where the missing rock thickness at some places is more than 15m, compared to the detector to surface distance of 80-110m.

Summary

We demonstrated here that muography is a very efficient tool for locating unknown caves or artificial voids. If the main geometric constraint can be overcome, the method not only can locate an unknown void but also gives information about the size and the shape of it, which can help to verify the results using the *a priori* knowledge of the target's geology. The physical exploration of these new voids is usually difficult, but we are continuously trying to reach the discovered sections either by conventional caving techniques or by drilling.

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