Technical Report

Underground Muography at Buda Castle

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Abstract

The Buda Castle project is the largest underground muography project of the Wigner Research Centre for Physics (RCP) and one of the major ones worldwide. The project has been running for more than four years, and we have about two more years until completion. The research area is the southern part of the hill of Buda Castle, Budapest, where the present castle and the partly buried ruins of the ancient buildings are located. The goal is to find every unknown underground void (caves and tunnels) with a characteristic extent larger than $2 \times 2 \times 2\,\mathrm{m}^3$, as well as to find the zones with significantly lower density than the surrounding base rock (backfilled cellars, tunnels, rock debris zones, etc.). During the project we investigate the whole area which can be reached from the presently known underground facilities. Most of these facilities are at an ideal depth, about 50 m below the surface, and the corridor system available for measurements is dense enough to populate an appropriate measurement grid to make even 3D inversion for the uppermost 30 m of almost the entire castle area. Thanks to the wide range of detectors developed and built by the Wigner RCP, we can measure with good resolution and efficiency even from places that are difficult to reach. This paper will introduce the project and the first results obtained by 3D triangulation based on several dozens of already completed measurement points.

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1. INTRODUCTION

Budapest, the capital of Hungary is the most important tourist destination in the country. The city's major tourist attraction is the Buda Castle, which has been built on the south half of the top of a 50 m high hill next to the river (see Figure 1).

The first buildings of the oldest castle stem from the Middle Ages, while the current state has been developed after numerous phases of rebuilding and war demolishing. Thus, the castle is extraordinarily interesting from the archaeological point of view: several layers of ruins of ancient buildings are above each other, sometimes underneath the current buildings. There are also many void remnants, either in intact form or partly collapsed or backfilled. Finding these voids is not only interesting for the archaeologist, but it is also important to know their location and extent for the planners of the current reconstruction phase. The obvious density contrast of the voids even if they are backfilled with loose material, makes this research ideal for muography.

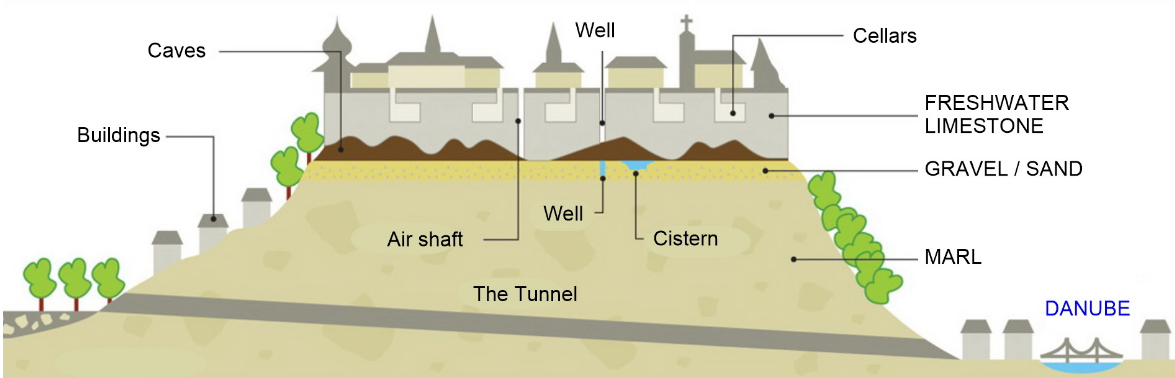

FIGURE 1: The cross section of the Castle Hill (source: nol.hu).

Before and during the Second World War and then later in the Cold War era, several underground infrastructures were built, mainly at the level of the foothill. These corridors and rooms, as well as the service passages of The Tunnel, i.e., the first underground place for transportation in Hungary, which was built in the middle of the nineteen century and crosses Castle Hill just under the castle area, are ideal places for the measurements.

2. INSTRUMENTATION

During the last 15 years various muography detectors have been developed by the Regard Group, the gaseous detector research and development group of Wigner RCP. These detectors are able to serve as a routine geophysical tool, robust but easily portable, high resolution and low consumption for both gas and electricity. In the Buda Castle project several different size MWPC [1] and CCC [2] type detectors have been used to adapt to the measurement requirements: rock length to be measured, desired resolution, constraints in deployment, etc. The most important parameter, angular resolution was generally better than 1 degree. One of the detector types during measurement can be seen in Figure 2.

FIGURE 2: “Mts50” MWPC type detector with $50 \times 50\,\mathrm{cm}^2$ active area in tilted measurement position.

3. THE MEASUREMENT CAMPAIGN AND DATA PROCESSING

The campaign, which aims to cover about 80,000 m^2 by detailed muography measurements, started about 4 years ago and is still continuing with varying intensity. The number of detectors involved in the campaign varied between 2 and 5. Up to this date (September 2023), the detectors have been set up on 40 different measurement points where considering the different directions altogether 80 muograms have been recorded. The average measurement time needed to collect $\sim 10^6$ muon tracks per muogram is roughly a month, so during about 2500 detector days, more than 100 million muon tracks have been measured. During the planning of the measurements, we tried to focus on the areas where there were no buildings on the surface, but we made a detailed investigation under two major buildings of the castle, as well. For this, we had to calculate via modeling the muon path lengths in the building material too, to take into account the effect of the “shadowing” of the additional material. This was also the case when the area in question was clean, but due to the slant muon paths, the buildings were partly in the line of sight.

After data collection, the muon flux was calculated using a sophisticated tracking algorithm developed by our group. The flux was converted to density length using Guan’s parametrization [3], and the results were cross-checked with Reyna’s method [4]. The minimum energy required for the conversion was obtained from Lesparre’s parametrization [5]. The theoretical rock lengths were obtained by conventional surveying of the detector positions and lidar data of the surface. At this stage, the “missing rock thickness” was the final result which was calculated by dividing the density lengths by the average density value, then subtracting the resulting “true” rock lengths from the theoretical ones for every direction. This simple method was very effective, thanks to the homogeneous density of the rock almost up to the relatively flat surface.

4. RESULTS

4.1. Test Measurement under a Known Void

In order to test the capabilities of the method in this area, first, a test measurement was carried out under a known tunnel. The straight tunnel and a connecting room were 16 m below a flat surface, while the detector was placed into another tunnel, 33 m below the surface. After five weeks of data collecting, the shape of the tunnel and the room, as well as their heights, are clearly visible on the missing rock length polar plot (Figure 3). Looking at the partial results, it turned out that three to four weeks are sufficient as a data collecting period in this area, which means that the known objects can be identified by pixels containing 3 sigma deviation from homogeneous rock estimation.

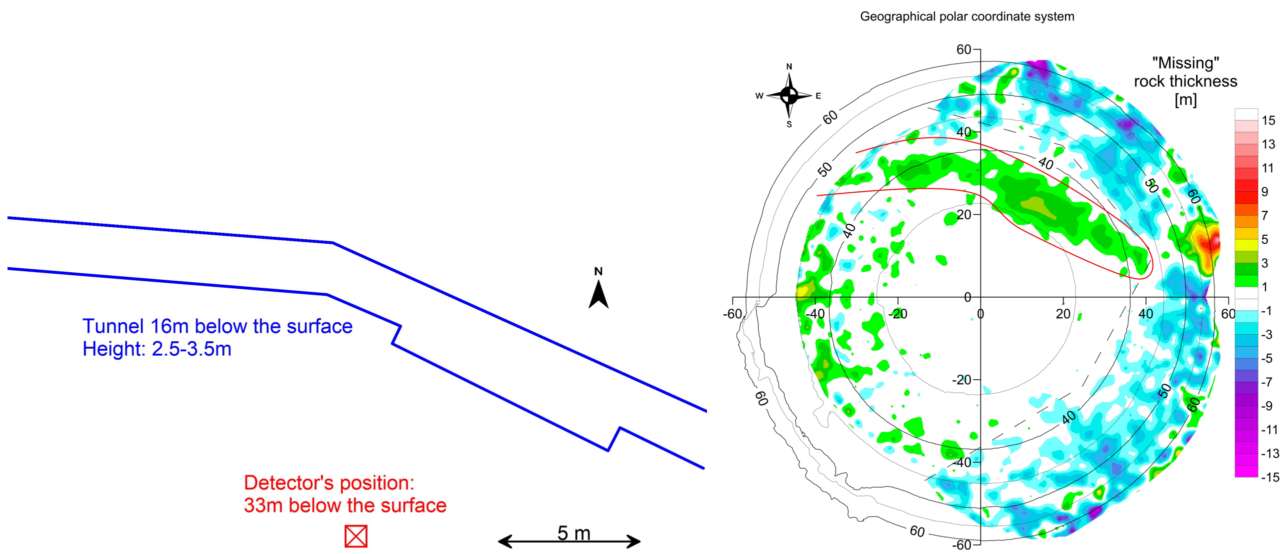

FIGURE 3: The layout of the detector and the known tunnel (above). The net "void thickness" map in the geographical system (right), the area within the red line indicates the effect of the tunnel. The uncertainty of the missing rock thickness varies from ∼1 m (zenith) to ∼2 m (50 deg). The continuous contour lines are the detector-to-surface distances. There are buildings on the surface whose effect can be seen to the right of the dashed line. The additional building material causes negative missing rock values.

4.2. Appearance of Building Walls

There were several measurements where the detector was placed directly under one of the main walls of the castle. Figure 4 shows that the structures of the walls as well as the heights (toward the line of sight) are very clearly depicted, although muons had to travel at least 40 m of bedrock under the walls before reaching the detector.

4.3. First Result by Triangulation

During the data acquisition period, some of the most significant anomalies were found by triangulation. First, the individual muograms were analyzed, and then, characteristic anomalies were identified in other muograms observing the same volume but from different angles. If an anomaly consistently appears in all the measurements in which measurement cones should have contained it, it has been confirmed as real. Several typical low-density anomalies have been identified, mostly close to the surface. They are probably the remnants of the cellars dug in the Middle Ages that were backfilled later during the building of the present-day castle (Figure 5). The detailed mapping of this area by 3D inversion is the task of the second half of the project.

5. FURTHER PLANS

We are planning to continue the measurement series for at least two years more to reach a full coverage of the area at Castle Hill which can be measured by muography from the accessible underground facilities. This area contains not just the Buda Castle area but also the North part of the hill where there are also suitable underground locations for the measurements. In addition to reaching the maximum available coverage, we will focus on areas of particular interest and try to decrease the limit of detection of voids down to even 2-3 m^3. However, this limit can be reached only with longer measurement times and favorable geometrical conditions.

Furthermore, we are also planning tomographic reconstruction by 2+1D slicing method (tomographic reconstruction in multiple 2D planes if measurements are situated along a straight line) [6] and also with direct 3D inversion for the areas where this is

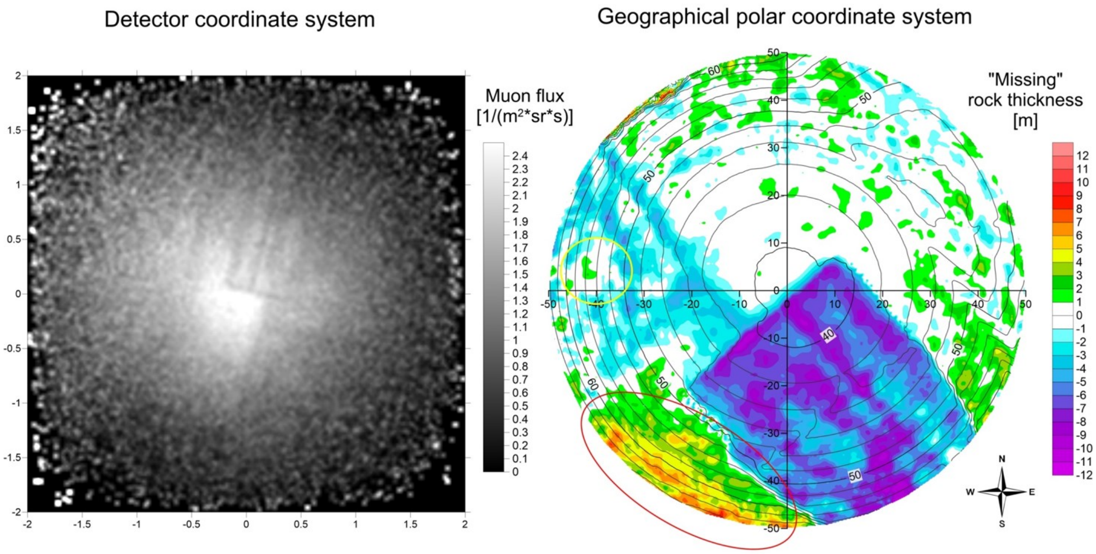

FIGURE 4: Muon flux in the detector system (left) and missing rock thickness map in the geographical system (right). The effect of the additional material on the surface of the walls of the castle is clearly seen in both figures. The red oval shows the area of possible voids under one of the castle yards. The contour lines on the right are the detector-to-surface distances.

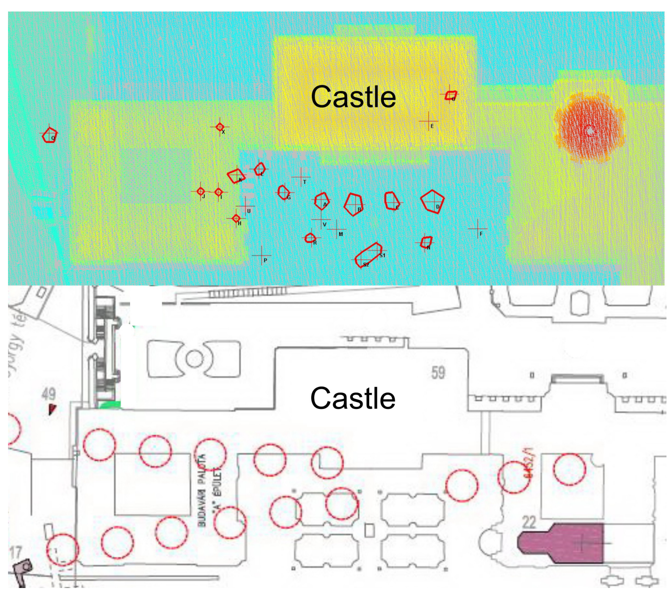

FIGURE 5: The significant near-surface low-density anomalies indicated by red polygons (above) on the elevation-colored point cloud map of the Castle. The causes of the anomalies are mainly the backfilled remnants of medieval cellars. The previous expectations of the location of the buried cellars based on archaeological considerations are indicated by red circles (below). Object No. 49, the entrance section of a medieval cellar, was also found by muography.

geometrically possible. Some parts of the area under investigation are ideal for 2+1D inversion as the measurements are in line, but most of the area needs real 3D tomography.

Besides the muography measurements we are planning to physically reach the new voids either by drilling or by full archaeological excavation.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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