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Innovative shaft inspection system for the Gotthard Base Tunnel

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ABSTRACT: Amberg was commissioned by the Swiss Federal Railways SBB to develop a measurement system and execute an inspection of the 800 m deep Sedrun shaft B at the Gotthard Base Tunnel. A special shaft module equipped with multiple sensors was built to acquire a reliable data base. The inspection and condition assessment were performed based on this data using an in-house inspection and data management platform. This paper presents the innovative measurement system developed and highlights the challenges encountered during this project.

Keywords: Shaft, Measurement, Inspection, Maintenance, Structural Health Monitoring

1 INTRODUCTION

Mobility is a cornerstone of our modern society. It enables us to travel, exchange goods and get in touch with each other. However, the structural infrastructure used for this purpose is subject to a natural ageing process. To assure a long service lifetime and the necessary integrity of such facilities, regular inspections, maintenance and renovation measures must be carried out, all of which involve costs. To make the best use of available financial resources and to ensure the longevity of these important facilities, it is crucial to develop effective maintenance strategies and to create a reliable data basis.

Inspection data provides information about the condition, performance, and potential problem areas of the infrastructure. They thus form the basis for strategic planning of measures and investments. However, depending on the structure and prevailing conditions, the collection of reliable data is not possible with standard tools and calls for new and innovative approaches.

This paper presents the specially developed measurement system developed for the inspection of the Sedrun shaft B at the Gotthard Base Tunnel and highlights the challenges encountered during this project. In the meantime, this system has also been used for the shaft inspection of other tunnel systems in Switzerland.

2 GOTTHARD BASE TUNNEL

The Gotthard Base Tunnel is a symbol of Swiss precision and innovative inspiration, 57 km long at the heart of the Swiss Alps connecting people through the generations to come. It is composed of an intrinsic complex system of tunnels, numerous crossovers, and access tunnels, as well as shafts.

The tunnel is subdivided into the five sections Erstfeld, Amsteg, Sedrun, Faido, and Bodio (north to south). The following Figure 1 shows a schematic overview of the tunnel system.

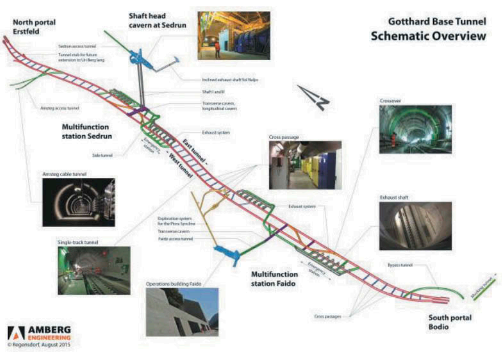

Figure 1. Schematic overview Gotthard Base Tunnel (*Source: Tunnelling the Gotthard, STS Tunnelling Society, 2016*).

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In the Sedrun section, an intermediate access is provided by a nearly one-kilometer-long access tunnel and two about 800 m deep vertical shafts leading down to the railway tunnel level. In the following, the focus will be led on shaft B in Sedrun (former known as shaft II).

Shaft B is located about 40 m from shaft A in a side niche. The shaft was constructed by raise-boring in the first stage and enlarged to a final excavation diameter of 7.0 m with a shaft boring machine in the second stage. Rock support was composed of wire mesh, rock bolts and shotcrete with steel fibre reinforcement and a layer thickness of 22 cm. The shotcrete serves as both rock support and permanent lining. In order to be able to fulfil its function as an exhaust ventilation shaft even in case of a fire, the shaft was additionally lined with an 8 cm thick shotcrete layer composing polypropylene fibres to ensure fire protection. In case of a fire, the smoke rising through the shaft is directed through an additional inclined tunnel out of the mountain, bypassing the cavern.

In the original concept of Sedrun section, shaft B was not included. The decision for building a second shaft was taken at a later project stage for reasons of construction operations, ventilation, and safety. During the ongoing railway operating phase, shaft B serves as an exhaust air shaft for ventilation in normal operation and in case of an incident. Since this function is crucial for operational safety, the structure must be included in the inspection and maintenance planning for the Gotthard Base Tunnel.

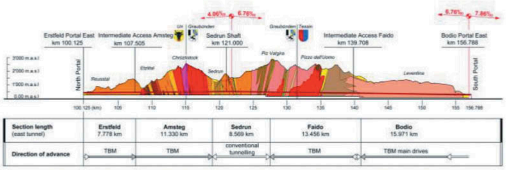

Figure 2. Geological profile of the Gotthard Base Tunnel, with localisation of the Sedrun Shaft (*Source: Tunnelling the Gotthard, STS Tunnelling Society, 2016*).

Built in 1998, shaft B was already operational for almost 18 years when the commercial operation of the Gotthard Basis Tunnel started in December 2016. With its almost 800 m depth, carrying out inspection services is a real challenge in terms of accessibility and health and safety.

During the construction time of the tunnels a heavy-duty hoist and an emergency hoist were installed in the shaft. After completion however, all equipment was deinstalled. As a result, carrying out inspection services in a shaft of this length becomes a real challenge.

In 2019, a pre-inspection of shaft B in Sedrun was performed to conduct several data acquisition tests and gain experience about the shaft environment. It was carried out by staff from Amberg and SBB, who were lowered into the shaft B using the emergency equipment for shaft A.

Due to safety concerns in case of technical malfunctions, further inspections involving personnel in the shaft were forbidden. To overcome this, Amberg was asked by the Swiss Federal Railways SBB to develop an innovative solution for the inspection of Sedrun shaft B.

3 MULTI-CAMERA INSPECTION SYSTEM (MCIS)

To address the challenge given, the first step was to develop an automatic measuring system capable of gathering all the necessary data for an office inspection. To ensure a reliable data set it was defined that the measuring system needed to capture both photos and scan data and provide them with a precise vertical position - a second significant challenge. The third challenge arose from the requirement that the measuring system had to be attached to the crane using only a single rope, making it vulnerable to rotations. To answer these three challenges, the Amberg Multi-Camera Inspection System (MCIS) was developed.

In the following subchapters, the technical solutions for the three challenges highlighted above will be outlined in more detail.

3.1 *Inspection sensors*

Traditionally, Amberg uses laser scanners for inspection data. Hence, the high-performance laser scanner *Amberg Profiler 6012* was the best sensor for integration into the MCIS. This approach had several advantages, including independence from a light source and the elimination of focusing issues to measure the relative diameter of the shaft.

As an additional source of information, six standard single-lens reflex cameras were included in the MCIS to provide high resolution and coloured images of the shaft surface. Given that the radius of shaft B did not change significantly, fixed camera focus was possible. Moreover, six 24 MP full-frame cameras captured significantly more data than a single laser scanner. However, the usage of cameras also necessitated the attachment of a light source to the MCIS. This presented a challenge, not only in illuminating the 6.4 m diameter shaft but also in positioning the light sources carefully to create consistent illumination throughout the shaft surface. Otherwise, over- and underexposed photos would reduce the general data quality in the deep, dark shaft. In the end, 24 LED lights were attached to the system, 12 above and 12 below the cameras, to provide the more than enough illumination.

To power the MCIS, detailed considerations of the necessary electrical power for the 5 V, 24 V and 220 V devices had to be made. Especially the 24 LED lights consume the biggest amount of electrical power. At the current state, multiple battery packages enable the MCIS to acquire data for about 30-40 minutes, which was more than enough time to measure shaft B for two times.

3.2 *Positioning*

It was soon evident that the entire system needed to be time-triggered. The alternative of establishing a data link through cable or radio over the ca. 800 m deep shaft B in Sedrun proved almost impossible. Consequently, all MCIS subsystems had to be controlled by a single computer to generate relatively precise timestamps.

The solution to the second challenge was to measure the relative height of the MCIS by measuring the used length of the steel rope of the crane to lower the MCIS into the shaft. Here an exception to the "one computer controls all devices" concept had to be made since other direct methods were unreliable. The most effective solution involved attaching an optical odometer to the diverter pulley of the crane which could be controlled and observed by a second computer. The odometer logged the revolutions together with an absolute timestamp directly to an internal memory.

3.3 *Rotations*

To counter any rotations caused by the single rope hanging, a highly precise inertial measurement unit (IMU) was required. The *Amberg Measurement Unit 1030* (AMU1030) is designed specifically for measuring rotations and was therefore the ideal solution to master this challenge. This choice was also advantageous as the AMU1030 was already integrated into the *Amberg IMS5000* system, a trolley system used to scan railroad tracks, which also included the high-performance laser scanner *Amberg Profiler 6012*. This ensured the compatibility of the systems used.

4 SHAFT MEASUREMENT AT THE GOTTHARD BASE TUNNEL

4.1 *Data acquisition at shaft B*

The data acquisition for inspecting the shaft B occurred on the 11th and 12th of July 2021, around midnight when a free slot in the train traffic schedule was available. In coordination with Amberg, the SBB provided a special crane with over 800 m of rope and a case for the MCIS installation. Before the measurement, everything was installed and tested on-site. Just before entering the shaft from its top, the MCIS with all its subsystems was initiated, and autonomous data recording commenced.

Figure 3. MCIS before entering the shaft B.

The *Amberg Profiler 6012* scanner rotated at 100 revolutions per second, capturing 10,000 points per rotation, resulting in a data acquisition rate of 1 million points per second. Simultaneously, the AMU1030 recorded the MCIS rotation for post-processing correction.

Using the odometer, it was possible to measure not only the depth but also the travel speed, which aimed to maintain a target speed of 0.5 m per second with an accuracy of +/- 0.05 m/sec throughout the entire shaft depth. The speed value was transmitted directly to the crane operator to adjust the speed if necessary.

The camera system was controlled by the measuring computer via a trigger box, capturing simultaneous images from all six cameras at 3-second intervals. Consequently, a series of pictures was taken every 1.5 m, providing a 360° imaging of the shaft. The lenses were manually focused, and each had a focal length of 15 mm, ensuring sufficient overlap for later panoramic image creation.

Within less than an hour, the entire shaft was measured twice, creating over 150 GB of data. The data was stored on a hard drive on site.

4.2 *Data post processing*

After data collection, the first step in post-processing was synchronizing all the timestamps from each different sensor. Since most sensors were controlled by the MCIS computer, only the separate odometer data required synchronization with the MCIS timeline. Scan data and camera data were generally post-processed independently.

Figure 4 below shows the data processing workflow.

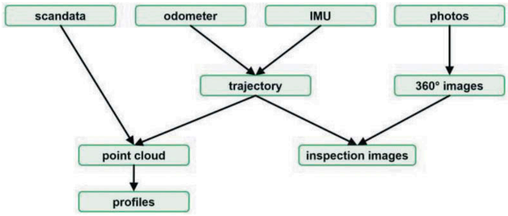

Figure 4. Data processing flow chart.

The odometer data was applied to the scan data to render a tube out of the measured thousands of scan lines during the data acquisition. Subsequently, IMU data was applied to the scan data to correct for rotation movements during data collection. This resulted in a point cloud representing the shaft's geometry accurately from a relative perspective, enabling the extraction of profiles and other data for inspection and other purposes.

The camera data was also post-processed in a similar manner to the scan data. Photo corrections, such as exposure, vignetting, and white balance adjustments, were applied to achieve homogeneous pictures of the shaft surface. Since all photos were taken simultaneously from each camera in sets of six, 360° panoramic images were created using photo-stitching techniques. The final step involved vertically sorting and cropping each panorama picture to generate a complete picture of the vertical shaft surface. Figure 5 below shows the 360° panoramic image at the shaft head: The blue objects are the safety barrier which were installed around the open shaft. Right below the red shaft cover is visible. Under the shaft cover a chamber is visible on the right-hand side. This is the "exhaust" that leads the air to the turbines. The lower part of the images shows the shaft surface with marked defects in blue and red.

Figure 5. 360° panoramic image of the shaft surface.

Based on the referenced point cloud, horizontal profiles of the vertical shaft were created in the software *Amberg Tunnel*. These profiles were centred to the least-square centre point of the measured profile points to best fit the theoretical circle-shaped reference profile for deformation analyses.

5 SHAFT INSPECTION

5.1 *Scope of an inspection*

According to the Swiss standard SIA 469 (1997), an inspection is defined as the determination of the condition of a structure by targeted (usually visual), simple examinations with evaluation of the same.

As a standard procedure, this determination is achieved by a manual inspection of the structure with the aid of adapted access platforms, including simple on-site surveys as crack width measurement and the search for hollow sounding areas with a hammer. All the information collected on site is then displayed in a structural defects map.

In case of an office inspection as performed for shaft B in Sedrun, the quality of the data acquisition is essential for a visual identification of any structural defects. This is assured by using different types of sensors on the MCIS for the acquisition of complementary information for a better inspection and assessment of the structure.

5.2 *Amberg inspection cloud*

For conducting condition assessments, a special inspection and data management software was developed in house – the *Amberg Inspection Cloud* (AIC). This online platform is a comprehensive image-based inspection platform for planning, managing, capturing, and reporting on visual surface conditions. It is designed to act as a single source of information for inspection data allowing for easy visualisation of defects and statistical analysis for every defect category. When uploading inspection data from different points in time, the software allows for a direct defect comparison and thus identification of any development of a defect over time.

More than an inspection tool, the AIC is a conservation management tool as it complements existent data bases of the owners with detailed information about the condition of the structure, showing potential areas of concern. As the data of the inspections over time is centralized and built up on a reliable basis, it becomes possible to predict future needs more accurately.

5.3 *Defect mapping*

Before starting the inspection and defect mapping, the project had to be set up in the AIC. This not only includes the upload of the images but also the definition of the defect catalogue in accordance with the client's standard. For the detailed assessment the shaft was divided in different zones of about 10 m length each.

According to the plans, the shaft was built with a different diameter on the approx. last 9 m at its top at the connection to the shaft cavern, but no dimensions were given. This change of the diameter could be clearly seen and measured from the point cloud data, allowing for an update of the technical data of the structure.

The mapping of defects in the AIC is performed by an experienced inspector based on a visual inspection of the acquired images. Due to the high-resolution and quality of the data generated by the MCIS, structural defects such as sub-millimetre cracks can be detected. Most importantly, structural defects can be distinguished from any aesthetical or construction caused phenomena.

Figure 6. Detail of the background image generated by the MCIS.

The structural defect map was delivered to the client digitally in the AIC with no further treatment of the data such as CAD drawings being necessary.

5.4 *Condition assessment*

According to the Swiss standard SIA 469, art. 3.22, 3.23 and 3.24., the condition assessment must include an evaluation of the condition of the structure and the determination of any measures to ensure the required safety (structural safety, serviceability, and operational safety). In addition, a forecast of the development of the condition is required.

The defect mapping introduced above is one essential information for the condition assessment. Nevertheless, the data acquired by the MCIS allows for additional analysis.

Based on the georeferenced point cloud, a deformation analysis can be performed. Compared to the perfect circular nominal profile, the measured profile is influenced by slightly changing shotcrete thickness and the roughness of its surface, as much as by the geology that was traversed. The comparison

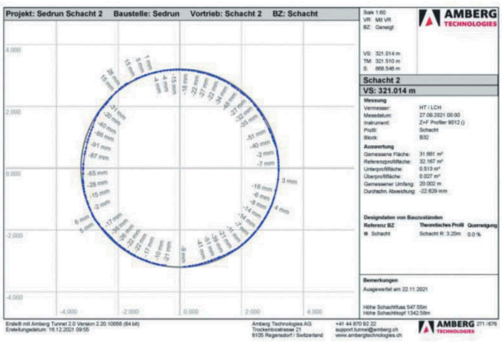

Figure 7. Results of the deformation analysis.

between the circular nominal profile in the calculated centre and the measured profile at shaft B shows profile differences along the shaft. Figure 7 below shows the result of the deformation analysis at position 321.014 m measured from the bottom. The blue dotted line represents the point cloud, the grey circle represents the nominal shaft profile.

In fact, deformations are not only assessed based on the profiles from the deformation measurements. Deformations due to force redistribution in the rock mass or due to water ingress cause certain damage patterns in the lining, which can be detected by mapping the damages on the images that were taken during the data acquisition. The inspection based on the panoramic images is therefore also decisive for the assessment of the deformations.

The differences between the designed circular profile and the measured one along the shaft were locally up to 100 mm. This would indicate significant deformations. In fact, such deformations would cause cracks in the shotcrete lining. Since no such cracks were found during the defect mapping, it can be concluded that the profile differences are not caused by local deformations but are either due to the construction or any material changes (e.g., calcite concretions).

As a result of the inspection, no severe damages were identified and therefore no structural measures are required. For further inspection it is recommended to collect complementary information about the shaft to refine the condition forecast. This might include a water analysis and some core drilling to obtain further information on the condition of the concrete. All this information will be also useful for planning structural measures in the future.

6 CONCLUSIONS

In this paper an innovative measurement system developed for the inspection of the Sedrun shaft B at the Gotthard Base Tunnel is presented.

The Multi-Camera Inspection System (MCIS) is a data acquisition module equipped with multiple sensors that can be used to collect reliable and high-quality data for inspection purposes.

For the Sedrun shaft B, the digital workflow based on panoramic images and point clouds enabled maximum condition information with minimum risk to people and impact on tunnel operations.

Since its first mission was successfully carried out at the shaft B in Sedrun, the MCIS system has also been used for the shaft inspection of several other tunnel systems in Switzerland.

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