ABSTRACT: The Swiss Weinberg tunnel was excavated from 2007 to 2011 using a tunnel boring machine (TBM). The railway tunnel is 4.8 km long and 11.2 m in diameter and mainly runs through hard molasse rock. 245 m before reaching the target shaft it transitioned to unconsolidated soft rock with only a few meters of overburden. Convergence measurements were required to mitigate the anticipated impact. As traditional convergence measurement methods were not a viable option, tShape was introduced for in-place deformation monitoring using SAA technology. Any deformation that moves the tShape array is accurately measured as a change in the shape of the array. Arrays were mounted on the inner lining right behind the TBM head. The web-based swissMon monitoring platform was used for automatic data acquisition, analysis and visualisation. swissMon determines transformation vectors using a 2D Helmert transformation. The transformation is applied relative to the centre of each of the measured points. Scale factor and rotation parameters can be either calculated separately or combined during the subsequent adjustment. This White Paper introduces tShape measurement technology and online data analysis. Based on the measurements taken at the Weinberg tunnel, it illustrates that even under difficult conditions tShape has proven to be a reliable system for automatic in-place deformation measurements inside tunnels.

1 Introduction

The Zurich Cross-City Rail Link construction project commissioned by the Swiss Federal Railways (SBB) started in 2007. At the heart of this project is a new underground station that is being constructed 16 m below the existing rail tracks underneath the Sihl River. Starting in 2014, trains will be able to enter and leave through the twin-track Weinberg tunnel, which has a diameter of 11.2 metres and was excavated using a tunnel boring machine (TBM). It underpasses the existing station, the Limmat River and parts of downtown Zurich and continues for 5 kilometres to Oerlikon. Tunnelling projects in urban areas like the one outlined herein require special supervisory measures to ensure compliance with safety requirements. A comprehensive monitoring system using state-of-the-art sensors and digital data transmission was established to identify potential hazards and to mitigate their impact. This White Paper introduces swissMon, the web-based monitoring platform used throughout the Zurich Cross-City Rail Link project to automatically record, analyse and display over 390,000 datasets generated by geotechnical and geodetic sensors on a daily basis. The White Paper illustrates the tShape in-place deformation monitoring setup. swissMon has now been in use for 5 consecutive years at Zurich Central Station, handling vast amounts of data 24 hours a day, 7 days a week, under tough construction site conditions and with exceptional results.

2 The Zurich Cross-City Rail Link Project

2.1 Project Overview

The Swiss Federal Railways (SBB) commissioned the Zurich Cross-City Rail Link, a 2 billion Euro infrastructure project. Starting in Altstetten, Switzerland, the 9.6 km long railway link underpasses Zurich Central Station and will continue as far as Oerlikon (see Figure 1).
Zurich Central Station is in the heart of the Swiss railway network and handles a constantly increasing commuter flow. Up to 300,000 passengers pass through Zurich Central Station every day. SBB expects that the daily number of passengers is going to be 500,000 by 2020. This volume will exceed the station's capacity and can not be accommodated using supporting measures, such as optimising train flow rates. Based on this estimate, SBB decided to significantly expand its existing railway infrastructure.

"Löwenstrasse", the second underground through station, is the heart of the Zurich Cross-City Rail Link. West of this station, the tracks cross two new bridges ("Letzigrabenbrücke" and "Kohledreieckbrücke") to Zurich Altstetten. To the east, the Weinberg tunnel connects Zurich’s Central Station with Oerlikon. The two new bridges between the Zurich Central Station and Altstetten will help to reduce traffic congestion west of Löwenstrasse.

The Weinberg tunnel will significantly increase the station’s capacity in the eastern section. From 2014, trains using the new “Löwenstrasse” through station (see Figure 2) will be able to pass directly through Zurich Central Station without having to change direction.

The new “Löwenstrasse” through station is being built 16 m below the Central Station’s platforms 4 to 9 and passes directly underneath the Sihl riverbed. As the existing station is already operating close to its full capacity, SBB had to ensure that construction would not impact the train flow. Hence, using a construction method for the new station designed to minimise impact on the existing traffic was one of the most important prerequisites. A top-down construction method was chosen for the underground structure. Heading east, trains will leave the through station and enter the Weinberg tunnel on two single tracks.

The first part of the tunnel runs below the 150-year-old Central Station landmark. Due to the complexity of the construction, an approximately 220 m long underpass had to be excavated using a manually operated tunnel boring machine. The remainder of the 5 km long tunnel was excavated using a Herrenknecht convertible S-451 Mixshield (a tunnel boring machine with a diameter of 11.2 m). Starting at Oerlikon, the TBM had to drill through molasse rock in open mode for the first 4.1 km.

During the final 245 m the TBM passed through unconsolidated soft rock and had to be converted for closed-mode operation in order to advance below the Limmat River. On November 22, 2010, the successful breakthrough to the target shaft was celebrated, completing the first important part of the new rail link, which will open in 2014.
2.2 Construction Monitoring

In order to identify potential hazards at a very early stage and to mitigate their impact, a comprehensive monitoring system using state-of-the-art sensors and digital data transmission was implemented to monitor the Cross-City Rail Link project. It is one of the world's largest monitoring projects, requiring a large variety of geodetic and geotechnical sensors. Table 1 provides an overview of the system's components.

<table>
<thead>
<tr>
<th>Automatic Measurements</th>
<th>Manual Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 80 total stations covering more than 3000</td>
<td>• Manual levelling covering more than 1000 targets</td>
</tr>
<tr>
<td>3D targets</td>
<td>• Inclinometer measurements</td>
</tr>
<tr>
<td>• 850 hydrostatic settlement cells</td>
<td>• Manual inclination measurements</td>
</tr>
<tr>
<td>• 50 inclination sensors</td>
<td>• Sliding deformeter measurements</td>
</tr>
<tr>
<td>• 30 in-place inclinometers</td>
<td>• Rod extensometer measurements</td>
</tr>
<tr>
<td>• Systems for water quality control</td>
<td>• Chemical measurements, etc.</td>
</tr>
<tr>
<td>• Piezometers</td>
<td></td>
</tr>
<tr>
<td>• Anchor force cells</td>
<td></td>
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<tr>
<td>• Strain gauges</td>
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<tr>
<td>• A meteorological station, etc.</td>
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Throughout the project, automatic measurements had to be taken every 30 to 60 minutes. Additionally, the customer requested online access to real-time measurement data.

The logistics required a monitoring platform that was adequate for the size of the Cross-City Rail Link project, and the site-specific design needed to address data transmission as well as data processing needs. In addition, the construction methods used also involved challenges with the regard to the measurement techniques used.

Based on these requirements and to allow for an estimated data volume of up to 500,000 datasets per day, the decision was made to develop swissMon, a cutting-edge deformation monitoring platform. The structure of swissMon is completely modular and therefore adapts to any type and size of project.
It includes interfaces for all relevant geodetic and geotechnical sensors. Due to its modern architecture, new sensors and features can easily be integrated as long as a digital interface is available. For analogue sensors external hardware is needed for analogue-to-digital conversion.

- **Sensor unit (tMon):**
  On-site sensor control, automatic analysis and validation of field data.

- **Database unit (tLis):**
  Data storage, complex trigger tests, input of manual measurements, alerting

- **Web unit (tWeb):**
  Data visualisation, access to project documents, data downloads.

This architecture enabled data acquisition during any part of the project and next to real-time data visualisation on the swissMon platform.

### 3 Automatic Convergence Measurements inside the Tunnel

#### 3.1 Boundary Conditions

245 m before reaching the target shaft, the TBM drilling the Weinberg tunnel transitioned from molasse rock to unconsolidated soft rock with only a few meters of overburden (see Figure 3). During urban tunnelling projects, ground subsidence must be avoided, which involves a particular challenge. Therefore, special equipment, such as mixed-shield TBM's must be used to maintain constant soil pressure during and after tunnel construction. When operated properly and when the underground conditions are known, the risk of surface subsidence and voids can be reduced.

During the advance of the TBM, all important parameters have to be monitored carefully, one of them being the deformation (convergence) of the excavated tunnel. For the most part, deformations occur very shortly after rock face advances. This must be taken into account, so that deformation measurements can start at the earliest possible stage.

![Figure 3. TBM Trajectory, Geological Situation and Design Features Used to Avoid Settlement](image)

Geodetic deformation measurements with highly precise total stations are a state-of-the-art method to determine convergence. This method requires an unobstructed line of sight inside the tunnel. Its use in connection with TBMs is very limited, because the drilling machines take up most of the tunnel’s cross-section. The TBM and the trailing support decks used at the Weinberg tunnel had a total length
of nearly 150 m. For this reason, convergence measurements could not be performed using geodetic methods (see Figure 4).

![Figure 4. Setup inside the Tunnel during TBM Advance in the Crucial Phase](image)

In a second step, renowned geotechnical systems, such as the Bassett Convergence System (BCS) were evaluated for suitability. The BCS monitors the movement of reference points that are mounted on the tunnel lining. A system of articulated arms links each reference point to the next, forming a series of virtual triangles. A tilt sensor is mounted on each arm. Spatial displacement of the reference points moves the arms and results in tilt reading changes. Unlike optical systems, the BCS is specifically designed for tunnels and has no line-of-sight requirements (DGSI 2011).

Since the system operates almost in real-time and has proven reliable during various projects, this solution was studied in detail. However, an analysis of the geometrical shape of the TBM showed that the distance between the clearance outline and the tunnel lining was less than 40 mm, preventing the use of the BCS.

Since the use of traditional methods was not a viable option, tShape was introduced as an innovative solution for in-place deformation monitoring.

### 3.2 Technical Details of the tShape Installation

Relying on the modularity of swissMon, tShape uses Measurand’s SAA technology to obtain its data. The SAA is a chain-like array of MEMS-based accelerometer sensors and microprocessors that fit into a small casing with a diameter of 30 mm.

Mechanically, SAA is an array of rigid segments connected by joints that permit bending in any direction, but that are stiff in torsion. Standard segment length is 305 mm, which dictates spatial resolution. The hollow segments each contain three orthogonal MEMS accelerometers. Every eighth segment includes a microprocessor. A typical array of 104 segments with a length of 32 m can be stored on a reel, ready for insertion. The waterproof coverings have been tested to 980 kPa (equivalent to a 100 m water column).

The 3D shape of SAA in a near-vertical casing is determined from static accelerations of X and Y accelerometers. In near-horizontal mode, the Z accelerometers are used to determine 2D shape in a vertical plane. The accelerometers sense tilt angles according to:

\[ \text{Signal} = C \cdot g \cdot \sin(\text{tilt}), \]

where \( C \) is a calibration constant and \( g \) is the acceleration of gravity. The special joints enable a solution for \( x, y, \) and \( z \) coordinates at each joint, using rotational transforms relating the orientation of one segment to the next segment (Danisch et al., 2007).
For convergence monitoring in the Weinberg tunnel, a total of 4 sections were equipped with tShape systems. The array was installed on the inner lining covering the upper 120° of the tunnel’s full section. To avoid damaging the system, the arrays were inserted into a 32 mm PVC pipe (see Figure 5). The pipe was fixed to the lining using clamps bolted to the concrete to ensure that any deformation affecting the casing is accurately measured as a change in the shape of the array.

For sensor control and on-site data analysis a tMon unit was installed in the tunnel close to the monitoring sections. For power supply and data transfer the system used the technical facilities on the TBM.

3.3 Data Analysis and Visualisation

Unlike conventional convergence measurements no control points can be used in connection with tShape, because all measurement points within the tShape array lie within the deformation range. This fact needs to be taken into account for data processing. In addition, the data processing design needs to meet the following requirements:

- Pre-selection of the points to be displayed in the convergence measurement results
- Transformation to global (national) coordinates
- User-defined transformation control points
- Statistical modelling of control points during the adjustment

tShape measurements are generally recorded in three dimensions. Conventional convergence measurements are usually done in two dimensions. Therefore, one of the dimensions can be fixed when using tShape.

The fixed dimension needs to be within the tunnel’s cross-section plane. The shifts or deformations affecting the individual points can be determined using a 2D Helmert transformation. The parameters of the over-determined transformation can be estimated using a least squares adjustment.

The following formulas are used:

\[
X^T = X_0 + m \cdot \cos \omega \cdot x - m \cdot \sin \omega \cdot y,
\]

\[
Y^T = Y_0 + m \cdot \cos \omega \cdot x - m \cdot \sin \omega \cdot y,
\]

Where:

- \(X_0, Y_0\) is the translation in x and y direction
- \(m\) is the scale factor
- \(\omega\) is the rotation
The transformation is applied relative to the centre of gravity of each of the measured points. The scale factor and rotation parameters can be either calculated separately or combined during the adjustment. A translation is calculated in each case.

Figure 6. Sample Transformation Residuals Plot (Control Points)

The required number of control points varies depending upon the number of transformation parameters. The maximum number of points is defined by the number of available measurement points in the tShape array. Control points can be weighted during the adjustment to optimise the quality of the adjustment result. The adjustment provides a means of assigning a lower weight to less reliable points.

Figure 7. Convergence Measurement Plot Created from tShape Data Displayed in swissMon

swissMon determines the transformation parameters based on the aforementioned formulas. Subsequently, all the points in the measurement array are transformed using the transformation parameters and integrated into the national coordinate system (see Figure 7). The output data is
supplied in the same format as the input data. The transformation residuals are plotted in order to ensure data control (see Figure 6). In addition, a log file is created, which also allows for the interpretation of the translation output results.

3.4 Monitoring Results

So far, the system design is working as planned and no significant deformations were recorded during the crucial tunnelling phase. Figure 8 below provides an example of the system’s performance. The Figure depicts a timeline for measurement points that were placed on the first lining ring in the top part of the tunnel a few meters from the TBM head. In August 2010, maintenance had to be performed on the TBM. During maintenance the hydraulic pressure on the lining was released. This produced a slight deformation (convergence) of less than 5 mm. As soon as the TBM was back in operation, the lining was pushed back into position. This process was monitored in detail by the system.

![Figure 8. Results of the tShape Measurements Recorded inside the Weinberg Tunnel](image)

4 Conclusion

The tShape system was set up as previously described to monitor convergence during TBM advance. The measured data corresponded to the predicted output. The system delivered reliable results. Any anomalies were detected and corrected using the generated log file. Even under difficult conditions, tShape has proven to be a reliable system for automatic in-place deformation measurements inside tunnels.

5 References

SBB 2010. Brochures and Datasheets for the Project Sections issued by Swiss Railway Company SBB (www.durchmesserlinie.ch)


DGSI 2011. Technical Data Sheet of the Bassett Convergence System