Rapid seismic data acquisition in a TBM road tunnel excavation with segmental lining

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ABSTRACT: Dedicated tunnel reflection seismic is a reliable geological exploration tool. In this method, 24 boreholes are prepared along a tunnel wall, which serve as seismic sources. In four additional boreholes, tri-axial seismic sensors are installed. By recording P- and S-waves propagating through the rock mass, seismic velocities are obtained, and an estimation of rock mechanical properties is possible. Changes in these properties allow for better understanding of the rock mass condition ahead of the face and timely identification of hazardous zones. Experiences on using reflection seismic during the construction of a double-shield TBM road tunnel in Switzerland are presented. Data acquisition was carried out by the tunnel contractor and data processing and evaluation by specialists in tunnel seismic. With 17 seismic measurements, a forecast of the rock mass was made over a length of 2,200 meters. Furthermore, the disturbance-free seismic data acquisition could be tested using an innovative next-generation hardware.

Keywords: in-tunnel reflection seismic, geological forecast, rock mechanical parameters, site characterization.

1 SEISMIC INVESTIGATIONS IN MECHANISED TUNNELING

Non-destructive geophysical site investigation while tunnelling is a reliable tool for long range predictions. The Tunnel Seismic Prediction (TSP) technology copes very well this task since it provides reliable results up to 150 m ahead of the face. In addition, it provides high resolution and allows for the estimation of mechanical properties of the rock mass based on the seismic wave velocities. Therefore, by carrying out comprehensive 3D geological predication using TSP, geological uncertainties can be managed in favour of all parties involved (Dickmann & Krueger 2014). The technology is based on the seismic reflection method, that is well established and proven and is widely used for hydrocarbon explorations.

Over the past decades, TSP has been applied to several hundred hard rock tunnel projects worldwide excavating with a selection of Tunnel Boring Machines ranging from open gripper to single and double shield machines. The presence of a segmental lining is not necessarily a limitation since the required seismic source and sensors are deployed into the rock via boreholes. Such small diameter boreholes can be drilled in the segment junctions or in the grouting and erector holes, which are common in most segments.

1.1 The TSP layout and recording procedures

In tunnel seismic, seismic signals are produced by a series of 24 shots containing small explosive charges with a quantity of usually 20 to 100 g. These charges provide a very good signal-to-noise ratio and signal conditions that are very suitable for recording and processing. Four receivers, consisting of highly sensitive tri-axial sensors, are contained in protection tubes whose tips are firmly cemented into boreholes in both sidewalls (Figure 1a).

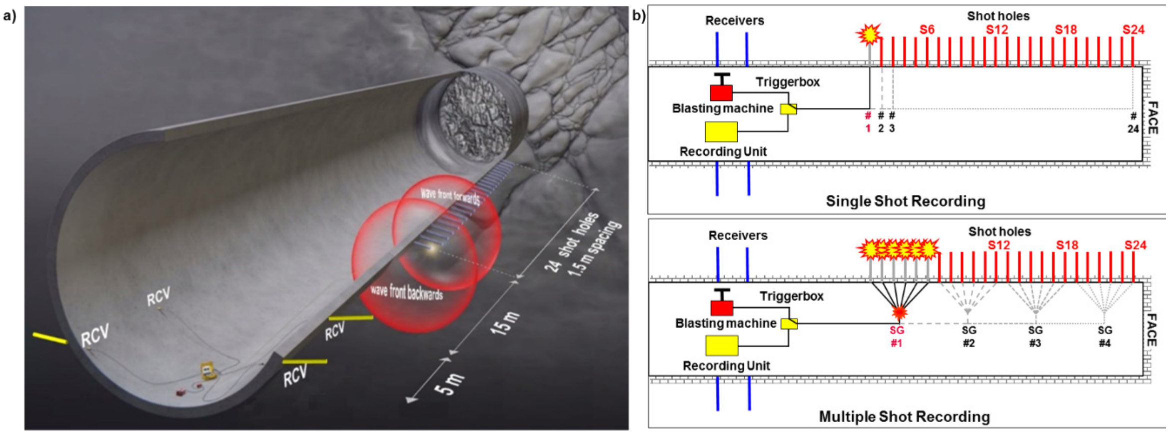

Figure 1. a) Standard TSP layout including recommended distances between boreholes. b) Type of seismic data recording procedures: SSR and MSR schemas (top and bottom, respectively).

Two data recording procedures are available: Single Shot Recording (SSR) and Multiple Shot Recording (MSR). In SSR, each shot is fired individually in a hole resulting in 24 ignitions. In MSR, shots are fired sequentially within a predefined group of holes using detonators of different delay in each hole. In this case, the number of firings depends on the number of groups; for example, four firings for the scheme as shown in Figure 1b on the bottom (six shot holes per group). The procedure to be used will depend mainly on the following aspects: type of detonators available, time available for data acquisition, condition of the rock mass along and surrounding the shot alignment, and expertise of the TSP crew. In any case, the MSR procedure allows for much faster data acquisition and significantly reduces the time it takes for the TSP crew to access the layout area.

2 SITE DESCRIPTION

The Kerenzerberg Tunnel, part of the N03/70 national road between Weesen and Murg, Canton St. Gallen, Switzerland, is a 5.7 km long road tunnel that has been in operation since 1986. It is located in the central east area of the country about 70 km south-east from Zurich representing the fifth longest road tunnel of Switzerland (Figure 2).

As part of a safety upgrade of the existing tunnel, the construction of a 5.5 km long safety tunnel was planned (Schönlechner et al. 2022). The new tunnel will run parallel to the existing road tunnel and will serve as an escape tunnel in case an incident occurs in the existing road tunnel. A series of cross-connections and interconnected air tunnels will link both tunnels, which will also help with the rehabilitation work in the main road tunnel. The tunnel was excavated with a TBM with a diameter of approx. 7 m. The consortium KER450 (Strabag AG, Pizzarotti SA, Heitkamp Construction Swiss GmbH and Jäger Bau GmbH) has been commissioned to drive the tunnel. An initial section of about 250 meter was excavated by the drill & blast method. Excavation of the tunnel was done without complete interruption of the daily operability of the existing tunnel.

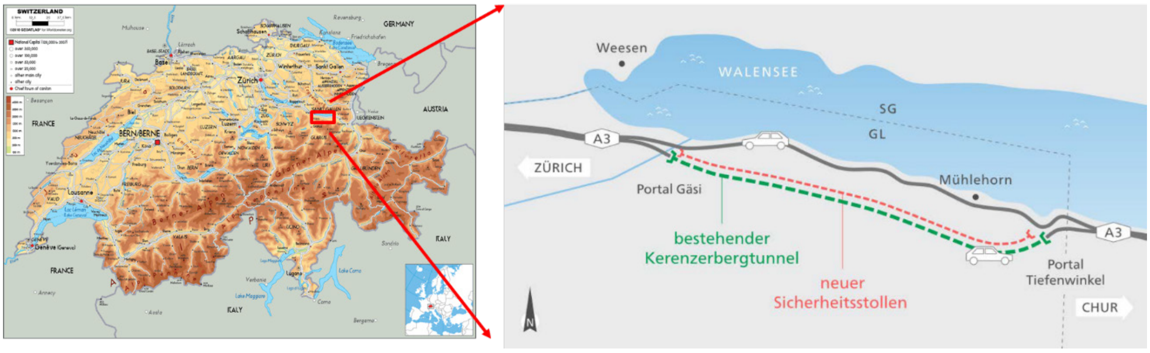

Figure 2. Project location (modified from www.worldometers.info and www.astra.admin.ch).

2.1 *Local geology and Investigation targets*

The geology of the Kerenzerberg Tunnel is from a tectonic point view situated in the “Helvetic cover” and there are three main sections: The section 1, “Gäsi Salleren”, is mostly dominated of different limestone formations with intermediate thin marl layers. In this section there is karst predicted which is a main reason for the use of seismic prediction. The section 2, “Salleren-Breccia”, is a mix of cataclastic rocks. This section is characterized by tectonic movements and foldings. Section 3, “Quinten-Formation”, is dominated of thick-bedded limestone formations.

Due to the occurrence of various limestones in different formations, especially in section 1, and the prediction of several faults, TSP technology was used with the main task of timely detection of karst zones (e.g. presence of cavities) that could intersect the tunnel cross-section and thus pose a major risk to the tunnel drive. In addition, exploration of water bearing bodies and instability zones, particularly near the expected fault zones, were important targets.

2.2 *TSP layout in the TBM environment*

The 220-meter long TBM started the excavation in the west portal (Portal Gäsi) at around Stationing 250 m. The first 250 m were excavated by conventional tunneling method, drill and blast. In order to test the applicability of the TSP method, a pilot seismic campaign was done before the excavation with the TBM started. The standard TSP layout as depicted in Figure 1a was used for this pilot measurement. Due to the presence of the TBM shield (~20 m length) and in order to place the layout as close as possible to the tunnel face, the number of shot holes was reduced to 20.

For the remaining campaigns, performed along the TBM excavated area, the TSP layout was adjusted to use the grouting holes of the segments for placing both the shot and receiver holes. Figure 3 shows the distribution of the boreholes along the TBM. As can be seen, the layout was prepared in the upper part of the tunnel section as it was easily accessible at this level and the machine’s drill rig was available to prepare the required boreholes. The distance between two consecutives grouting holes was 1.65 m which is about the standard required distance (1.5 m). The layout had a length of about 52 m. Distance to tunnel face varied between 15 to 20 m.

3 INTEGRATION OF TUNNEL SEISMIC INTO THE PROJECT’S CYCLE

The strategy for integrating tunnel seismic into the project aimed at 1) involving few site personnel in the seismic activity and 2) minimizing the downtime needed for data acquisition. For the first aim, a crew of two site engineers were trained in data acquisition. Data processing and evaluation was done by tunnel seismic experts remotely. Once the data was acquired, it was forwarded to the processing center via the cloud, including the geometry details. Results were handed out within 3-4 hours after data reception. For the seismic source, a blasting machine, electric and non-electric detonators and detonation cord with a detonation velocity over 6,000 m/s were used.

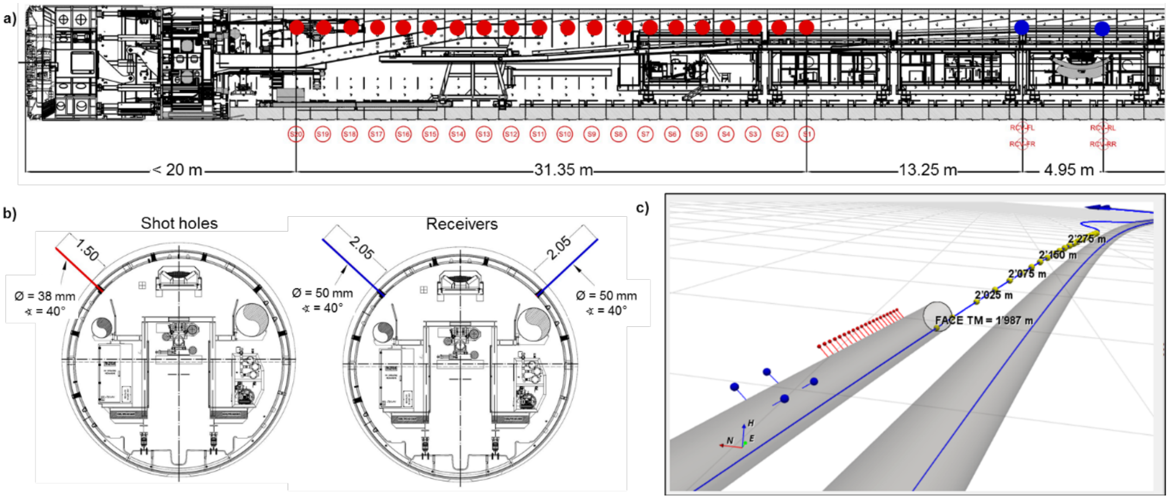

Figure 3. a) TSP layout (shot holes-red and receivers-blue) upon the TBM scheme. b) TBM cross-section showing the orientations and depth of shot and receiver holes. c) TSP layout as reproduced in the Amberg TSP Ease software. The existing road tunnel was reconstructed in the software as well.

Figure 4. Left: Installation of receiver, Right: Shot holes with protective mats made from discarded conveyor belt material.

3.1 Roadmap to rapid seismic data acquisition

The most important aspects of seismic data acquisition in the tunnel are, in addition to minimizing the time required, sufficient quantity and quality of data for further processing. First, at least 18 shots should be recorded. The quality of the data depends on several factors that can be controlled by the field crew. Minimal work downtime during data acquisition can be ensured provided that this activity is integrated into the tunnel excavation process. The optimal balance between all these aspects is achieved understanding how the rock reacts to the seismic excitation and being in constant exchange between field personnel and data interpreters.

Table 1 summarizes operative aspects for data acquisition of all campaigns. In the first campaign (training), a hybrid data acquisition procedure with five single shots followed by four shot groups was used. The first shots allowed the evaluation of the seismic response and the calibration of the charges to be used in the groups. After conducting about five campaigns, a sufficient understanding of the seismic response had been gained. For the next campaigns, the field crew decided for two shot groups, each with 10 shot holes. The time needed for data acquisition was significantly reduced from 74 to 115 min. to 3 to 8 min. As can be seen, the explosive charge and charge scheme was kept constant after TSP6, facilitating the execution of data recording.

The MSR procedure was a key factor for optimizing data acquisition. The field crew developed a unique procedure using only one detonator type in all shot holes. In the usual MSR procedure, detonators with different time delays are used, whose ignition is started together, and which then ignite the explosive charge according to their delay (Figure 1b, bottom). In this modified way, only one type of nonel-detonator with 1 s delay was used, which, starting from the ignition in the first shot hole, initiates the ignition in the next shot hole and so on.

Table 1. Campaign information. TM: Tunnelmeter, SG: Shot Groups, S: Shot hole, PL: Prediction Length.

Campaign	TM	SG	S per SG	Total S	Charge (g)	Time (min)	PL (m)
TSP1	251	9	1-1-1-1-1-5-5-5-2	20	16-150	115	124
TSP2	351	5	1-3-5-5-5	19	40-150	114	126
TSP3	479	6	5-5-2-1-5-6	21	40-120	74	99
TSP4	600	4	5-5-5-6	21	40-100	15	106
TSP5	748	4	5-1-4-10	20	40-140	8	122
TSP6	896	2	10-10	20	40-120	5	110
TSP7	1,041	2	9-9	18	40-120	3	153
TSP8	1,248	2	10-10	20	40-120	8	150
TSP9	1,398	2	10-10	20	40-120	4	150
TSP10	1,554	2	9-9	18	40-120	3	135
TSP11	1,693	2	9-9	18	40-120	6	157
TSP12	1,845	2	10-10	20	40-120	5	145
TSP13	1,987	3	10-9-1	20	40-120	12	132
TSP14	3,177	3	10-7-3	20	40-120	8	160
TSP15	3,341	2	10-10	20	40-120	5	158
TSP16	4,071	2	10-10	20	40-120	6	98
TSP17	4,232	2	10-10	20	40-120	3	70

3.2 *Summary of seismic results and forecast of rock mass condition*

Forecasts of the rock mass along approximately 2,200 m was delivered. Figure 5 depicts P- and S-wave seismic velocities and dynamic Young's Modulus (Vp, Vs and Edyn, respectively). Edyn is a key parameter for drawing inferences about the rock stiffness. Along a large section of the investigated range (TM 350 to 1,690), high seismic velocities are found which are in very good agreement with typical values for competent Limestones reported in the literature. Hence, high Edyn values > 50 GPa are estimated, which allow to infer occurrence of rock mass with increased rock stiffness and favorable for the excavation. In TSP1 and campaigns TSP12 to TSP15, between TM 1,850 and TM 3,341, decreasing values of Edyn between 30 and 50 GPa are estimated indicating less rock stiffness. Lowest values were obtained in the last two campaigns, with both velocities and Edyn significantly lower than 20 GPa. This was associated with fractured to highly fractured rock mass.

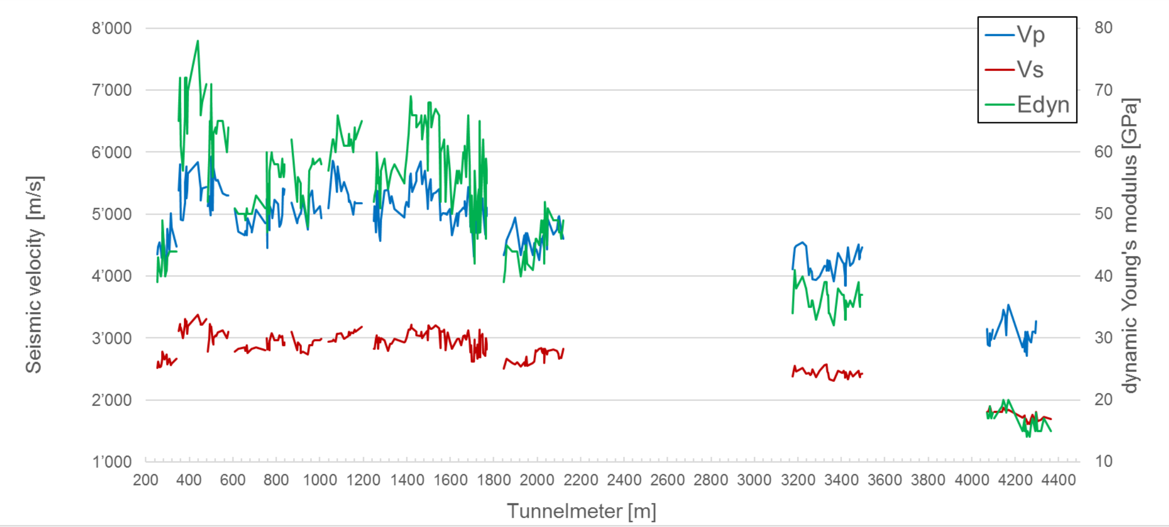

Figure 5. P- and S-wave velocities and dynamic Young's modulus obtained along the investigated section.

4 TEST OF NEXT GENERATION HARDWARE

While TBM tunnelling was in progress, the opportunity was taken for a test run during which the innovative TSP wireless system was installed and put into operation together with the innovative TSP impact hammer (Figure 6). The new TSP generation offers a layout especially for mechanical tunnelling in which the measurements can take place continuously and always for a very short moment when the machine is at a standstill. An impact hammer is used to generate the seismic waves, which is mounted at a fixed location in the area of the inner/outer telescopic shield. As soon as the machine stops after its advance stroke, the hammer moves sideways against the rock and begins to strike the rock. The trigger box connected to the hammer sends every exact strike time to the tablet-PC, which in turn sends a signal to the transceivers, now recording all the data. All transceivers, the trigger box next to the hammer and the tablet form an autonomous Wi-Fi network with their own router. If sufficient data is collected, it can be evaluated regularly and at short intervals to provide a continuous geological forecast.

Figure 6. Left: Set-up of TSP 603 wireless components in segmental lining environment. Right: The TSP Impact hammer mounted in the shield area will replace the explosives as a seismic source in future.

5 CONCLUSIONS AND OUTLOOK

Tunnel seismic prediction was performed along a large section during the excavation of the safety gallery of the Kerenzerberg road tunnel in Switzerland. In addition to obtaining information on the rock characteristics ahead of the tunnel face, an important objective was to determine the possible occurrence of large cavities and water intrusion due to karst formations. A total number of 17 seismic measurements were done providing a rock mass forecast over a length of about 2.2 km.

The TSP technique was fully integrated into the excavation cycle. Data was acquired by trained site staff of the contractor-JV while data processing and evaluation was in charge of seismic experts. After a short training period, the tunnel crew was able to optimize the data collection and significantly reduce the time required. Twelve of the measurements were taken in less than ten minutes; the fastest in 3 minutes, which is a world record for this type of data acquisition.

In general, high seismic velocities and elastic moduli were observed along most of the forecast area indicating competent rock material. Lower values were reported in a few campaigns, mostly related to areas with formation changes and fault zones, which in most cases corresponded well with the faults indicated in the geological forecast of the project's baseline report. TSP was also able to show on the predicted sections that there was no potential hazard due to large karst phenomena.

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