CONTINUOUS EXPLORATION AHEAD OF THE TUNNEL FACE BY TSWD - TUNNEL SEISMIC WHILE DRILLING

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Ewald Brückl, Vienna University of Technology, Vienna, Austria
Werner Chwatal, Vienna University of Technology, Vienna, Austria
Stefan Mertl, Vienna University of Technology, Vienna, Austria
Alexander Radinger, Pöyry Infra GmbH, Salzburg, Austria

Abstract

Seismic measurements using the VSP principle have been carried out for over 20 years to investigate the rock ahead of a tunnel face and made a contribution to reduce the risks during construction for conventional tunnelling, as well as for tunnelling with a Tunnel Boring Machine (TBM). However, reflecting horizons intersecting the tunnel axis obliquely cannot be imaged at their intersection with the tunnel. This circumstance imposes a major uncertainty on the prediction of the geological situation ahead of the tunnel face. A possibility to image all reflecting horizons, regardless of their orientation, at least near to their intersection with the tunnel axis is offered by continuous monitoring with the drilling head of a TBM as the seismic source (Tunnel Seismic While Drilling - TSWD). In this study we present continuous TSWD data from a gallery drilled in limestone and dolomite of the Northern Calcareous Alps, Austria. This gallery intersects a deeply incised valley, filled with sediments. The two main goals for the processing were the derivation of high signal to noise seismograms from the pilot and receiver signals and the removal of the first arrivals from the data in order to uncover reflected phases, even from reflectors very near to the TBM drilling head. Both goals were achieved satisfactorily and the main geological structure was well resolved. Geophysical issues which need further investigation are addressed. The results of our study suggest that substantial risk reduction could be achieved by continuous TSWD. However, the high production rate of modern TBMs imposes a major challenge on real time monitoring, processing and prediction.

Introduction

Deeply incised valleys, karst cavities, fault zones and other unexpected degradations of rock quality can substantially affect safety and efficiency of tunnel construction. While conventional tunnel construction is relatively flexible towards deteriorations of rock quality, similar circumstances can lead to persistent interruptions and expensive remedial measures during tunnelling with a Tunnel Boring Machine (TBM) (e.g. Pircher, 1987). Seismic measurements using the Vertical Seismic Profiling (VSP) principle have been carried out for over 20 years to investigate the rock ahead of a tunnel face and made a contribution to reduce the risk of construction for conventional tunnelling, as well as for tunnelling with a TBM (e.g. Brückl et al, 2001; Dickmann, 2008). However, only reflecting horizons which intersect a straight tunnel axis orthogonally are imaged at their true intersection with the tunnel axis. This circumstance imposes a major uncertainty on the prediction of the geological situation ahead of the tunnel face (Brückl et al., 2008).
Walk-away VSP could be used to image reflecting horizons at their true intersection with the tunnel axis even if their orientation is not orthogonal to the tunnel. While it is no problem to deploy a wide spread of source locations at the surface around boreholes in walk-away VSP surveys, it would require a major effort to place the receivers in deep boreholes drilled radially to the tunnel axis in order to realize a walk-away VSP geometry in a tunnel. Only in rare cases such expenditure would be reasonable.

A more effective method to image all reflecting horizons at least near to their intersection with the tunnel axis is continuous monitoring with either the source, or the receiver, or both located at the current position of the drilling head. Construction with a TBM allows the drilling head of the TBM to be employed as a seismic source (Petronio and Poletto, 2002). This method is based on experience from SWD - Seismic While Drilling (e.g., Poletto and Miranda, 2004) and has been called TSWD - Tunnel Seismic While Drilling (Petronio et al., 2003). In this study we describe a continuous data acquisition by TSWD and investigate the potential of this method to image reflecting horizons close to their intersection with the tunnel axis. First results were already presented at the 57th Geomechanics Colloquium in Salzburg, Austria, October 2008 (Brückl et al., 2008).

**TSWD data acquisition in the Hieflau gallery**

The Hieflau gallery with a total length of 5.6 km is situated in limestone and dolomite of the Northern Calcareous Alps in Austria (Fig. 1). It is part of the enlargement of an existing hydropower plant. The TBM was of the type Robbins DS-TBM 194-272-2 with a diameter of 6.2 m.

![Figure 1: Longitudinal section of the geological and geometrical settings for the gallery of Hieflau; position of receiver and transverse gallery Hartelsgraben, as well as source locations (cutting head of the TBM with pilot sensor) are shown; inset shows the location of Hieflau in Austria on small scale.](image)

A most essential part of the TSWD data acquisition system is the sensor for recording the vibrations of the TBM’s cutting head during drilling. We will name this sensor “pilot sensor” within the
scope of this paper. We assume that this signal propagates from the drilling head to the shaft of the main bearing. Therefore we fixed two 3C accelerometers on the non-rotating part of the main bearing to record this pilot signal. The recording unit for the pilot signal was placed in a special casing about 10m behind the cutting head at the TBM control station.

The receiver sensors (two 3C borehole geophones) with 15 Hz natural frequency were installed in 5 and 10m deep boreholes at the right and left side wall of the gallery at tunnel station 1673 (Fig. 1). The three components of the geophones were axial, tangential and radial to the tunnel axis.

From May to October 2008 nearly continuous monitoring of the pilot and receiver signals generated by the TBM drilling head was carried out between tunnel stations 1927-2644. In this region, at tunnel stations 2176-2208 the tunnel construction intersects a geological feature of special interest, the buried gorge Hartelsgraben, which is filled with fluvial and/or glacial sediments. Furthermore, the main gallery goes through the transverse gallery of Hartelsgraben at tunnel station 1953 (Fig. 1).

Seismic data were recorded by REFTEK 130 units. The sampling rate for the pilot and receiver signals was 1000 Hz and the data storage capacity was 8 Gigabyte. Data were retrieved from the acquisition units on a weekly basis, but because of technical problems some data gaps occurred. Due to logistical reasons the recording units could not be synchronized with GPS time, which causes undefined seismic velocities. We assume a P-wave velocity of 6000 m/s for the limestone and dolomite. The lack of exact information on the P-wave velocity of the rock does not pose a fundamental obstacle in testing the potential of the method to image all reflecting horizons very close to the tunnel axis.

Processing

Figure 2 shows a data sample of the TBM signal and the simultaneous record of the axial component (direction of the tunnel axis) of the 3C borehole geophone. One can see that the envelopes of the pilot- and receiver signals correlate well. The frequency content of the pilot signal is limited by the sampling rate and the corresponding anti-aliasing filter. The major energy of the receiver signal is found in a frequency range below 200Hz.

Figure 2: Raw data recorded by the TBM sensor (above) and the receiver sensor (below) at tunnel station 2000; 18 min recording together with spectrogram; 50 Hz notch filter and equalization of the amplitudes in the frequency range was applied; right side shows a seismogram and its frequency spectrum generated from 30 s of continuous recording.
The standard method to derive interpretable seismograms from this data is the correlation between the pilot- and the receiver signal (e.g., Poletto and Miranda, 2004). We applied an alternative method, which is based on the assumption that the pilot signal is a source wavelet convolved with a random sequence of spikes. Equal time windows with a length of 30 seconds are cut out of the pilot and the receiver data. We calculate the minimum delay transform of the pilot signal and apply this filter to the receiver record (Brückl et al., 2008). In order to remove a possible mixed delay character of the source wavelet we applied a delayed spike deconvolution preceding the minimum delay transform of the pilot signal. Power line contamination (50 Hz) is suppressed by predictive deconvolution. Thereafter, each trace can be interpreted as generated by a shot or an impulse source at the tunnel face and recorded by the receivers.

The production of seismic traces for time steps of 30 seconds corresponds to source distances in the range of a few centimetres. To have the seismic traces in well-defined intervals, the traces are stacked to a bin size of 1m, which again improves the signal to noise ratio. Prior to this step, seismic traces with a low signal to noise ratio are eliminated.

**Figure 3a** shows the seismic traces between the tunnel stations 1925-2750 calculated by this method for the axial component of the borehole geophone in the left borehole at 10 m depth. The maximum amplitude of the direct P-wave is positive and we pick the first arrival travel time at this maximum. Thereafter these travel times are used to align the first arrivals at time zero. The first arrivals show very continuous wavelets. At stations around the Hartelsgraben these wavelets are slightly disturbed. A second, less strong arrival may be an S wave, but more probably a Rayleigh wave (Bohlen et al., 2007). In case we assume \( V_p = 6000 \text{ m/s} \), the velocity of the R-wave would be \( V_r = 3100 \text{ m/s} \).

**Figure 3:** a) P-wave aligned seismic traces for the axial component of the left receiver with a source interval of 1m between the tunnel stations 1925-2750; P- and R-wave arrivals are marked by arrows b) Reflecting wave field for the same receiver and component; alignment to the arrival time of the P-wave was performed.
A crucial processing step is the removal of the first arrivals as well as the R-wave (at short source-receiver distances) in order to extract the reflected signals. This is done by aligning the wave type to be eliminated and then subtracting an average wavelet, which is generated by mixing 51 traces. The preceding application of an amplitude normalisation with the amplitude of the first arrival for each trace is essential for this procedure. After the suppression of the first arrivals, reflected signals become clearly visible, almost to the arrival times of the direct P-wave, or to zero time in the presentation given by Figure 3b.

We detected further strong signals at times larger than the R-wave arrivals, which were recorded by the tangential and radial components of the receivers. These signals indicate phases, which travel from the TBM to the reflecting horizons as P- or S-waves, and are reflected as P- or S-waves, and finally converted to an R-wave at the tunnel face (Bohlen et al., 2007; Lüth et al., 2008). Figure 4 shows these phases after the alignment of the traces to the R-wave arrivals. In this study we do not analyze the potential of these phases for exploration ahead of the tunnel face.

Figure 4: Reflected wave field of the R-wave: aligned tangential and radial component of the left receiver for the tunnel stations 1925-2300; possible TWTs of reflections of the beginning of the buried gorge Hartelsgraben are marked with the wave type PP, PS and SS making the assumption that this interface is perpendicular to the tunnel axis

**Interpretation**

The data shown in Fig. 3b represents the basis for a prediction of geological boundaries and fault zones ahead of the current tunnel face. We perform a mapping of this data from the original space (tunnel station, time) to (tunnel station + prediction distance, prediction distance = velocity*time/2). This transformation manages that signals from interfaces crossing the tunnel axis perpendicularly are mapped at constant tunnel stations, presuming the velocity has been estimated correctly (Fig.5).

The most prominent signal in Figure 5 correlates with the Hartelsgraben, the only geologic structure, which represented a severe construction risk. We assume that the TBM drilling head, like a drill-bit, represents a single force source which generates compression P-waves in forward and dilation P-waves in backward direction of the tunnel (Poletto and Miranda, 2004). The boundary from the compact rock to the Hartelsgraben represents a decrease of the acoustic impedance and therefore the incident compression P-wave is reflected as a dilation P-wave, having the same polarity as the direct P-wave at the receiver location. Reflections from Hartelsgraben gallery can also be identified and correlated at the very beginning of our data (tunnel stations < 2000 m). Correlation of the reflected wave field with the wavelet of the first arrival supports exact location of the discontinuities (Fig. 6). From this
data we estimate the location accuracy of significant discontinuities crossing the tunnel axis to be about +/- 5 m.

**Figure 5:** Mapping of reflected wave field of the axial component for the left and right receiver for the tunnel stations 1925-2750; the interpretation of the reflections at the beginning of the buried gorge Hartelsgraben and the template of expected dip of this reflection oriented 30°, 60° and 90° to tunnel axis is inserted.

The reflection band correlating with the Hartelsgraben is not exactly orthogonal to the tunnel axis in **Figure 5**, indicating an oblique intersection of the boundary to the Hartelsgraben with the tunnel axis. A template (inset in **Figure 5**) shows the expected slopes of the reflection band for different angles of intersection. By the use of this template we estimate an intersection angle of 60° or even higher. In order to determine the orientation of the boundary to the Hartelsgraben unequivocally, the particle motion recorded by the 3C borehole geophones could be used. These studies are currently in progress.

**Figure 6:** Correlation of a stacked trace (prediction distances 20 - 30 m, left and right receivers) with the first arrival wavelet; maxima correlate with the Hartelsgraben gallery and the beginning of the Hartelsgraben (grey bars at tunnel stations 1953 m and 2176 m).
Conclusions

Seismic data were nearly continuously acquired by the TSWD method in the Hieflau gallery, covering a section of about 700 m length. The pilot signal was taken from the main bearing of the TBM drilling head, the receivers were situated in 5 – 10 m deep boreholes in a cross section about 250 m behind the first TBM drilling head station (tunnel station 1927). An alternative method to conventional correlation was successfully applied to convert 30 seconds long recordings of the pilot and the receiver signals to standard seismograms. The compressed seismograms contain signals with frequencies up to 170 Hz and the signal to noise ratio was excellent up to the maximum source-receiver distance of about 1 km. The wavelet of the first arrival has a nearly constant shape regardless of the source-receiver distance and it was not influenced by the very different geologic conditions. Because of this favourable circumstance, the first arrivals could be removed almost completely from the data and reflected signals could be traced from about 200 m to less than 10 m ahead of the TBM drilling head. This new achievement implies a significant reduction in prediction uncertainty.

The Hartelsgraben is a deeply incised valley which intersects the gallery otherwise running through compact limestone. It can be clearly identified in the reflected wave field (Fig. 5). Another, known reflector is the Hartelsgraben gallery which crosses the Hieflau gallery nearly orthogonally at the very beginning of our monitoring section. It can also be seen clearly in the reflected wave field. These two discontinuities, representing a significant reduction of the acoustic impedance, were located with an error of about +/-5 m by correlation with the first arrival wavelet (Fig. 6).

The data presentation used for Figure 5 offers an easy way to decide if a discontinuity recognized in the reflected wave field intersects the tunnel axis nearly orthogonally or obliquely. The detection of the particle motion recorded by the 3C borehole geophones could help to unequivocally estimate the orientation of such a discontinuity.

In the future, continuous applications of the TSWD method require the problem of timing to be solved, either by relative timing between the pilot sensor and the receivers, or by absolute timing (e.g. GPS). Our study did not intend to supply prediction in time. Modern TBMs can drill about 50 m per day under favourable geologic conditions. This imposes a major challenge on real time monitoring, processing, and prediction. However, the problems which need to be solved to achieve this goal have more of a data transmission and logistic character and are beyond the scope of this study.

References

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