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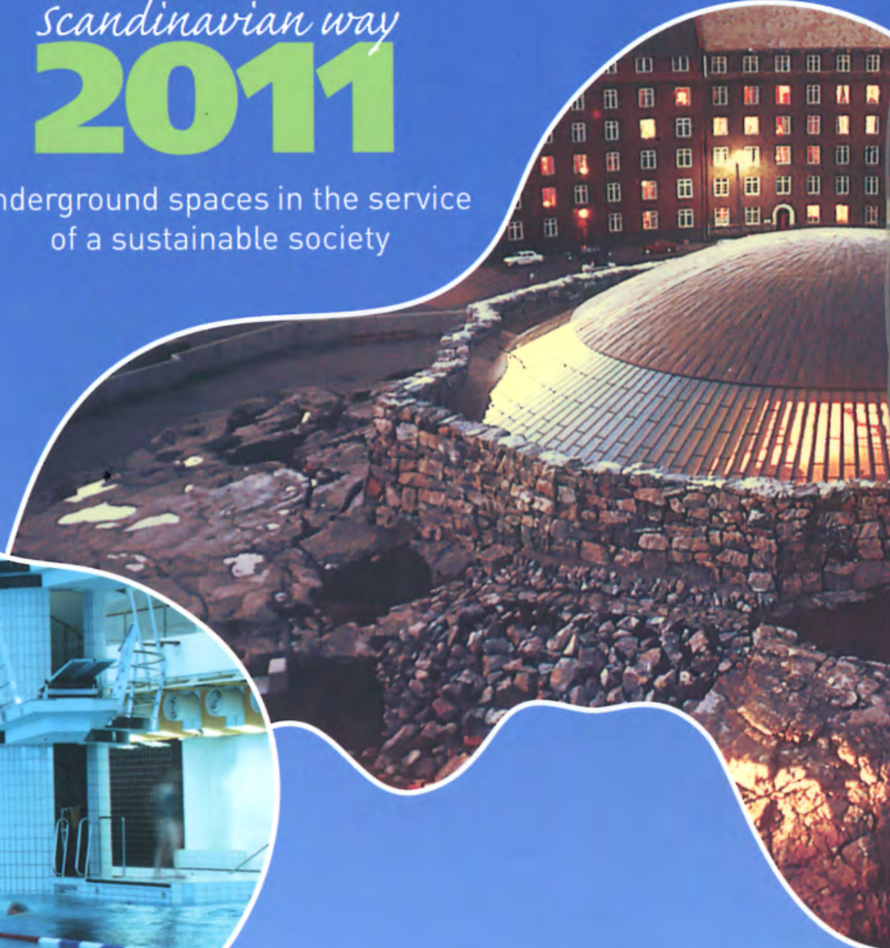

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Underground spaces in the service of a sustainable society

Proceedings

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Summary

Seismic measurements using the VSP principle have been carried out for over 20 years to investigate the rock ahead of a tunnel face which make a significant contribution to reduce the risks during construction for conventional tunnelling, as well as for tunnelling with a Tunnel Boring Machine (TBM). In the case of TBM-Tunnelling, continuous seismic monitoring with the drilling head of the TBM as the seismic source (Tunnel Seismic While Drilling -TSWD) can be used to improve the image of reflecting horizons intersecting the tunnel axis, regardless of their orientation, and near to their intersection with the tunnel axis. In this paper the principles, data, processing and interpretation of the TSWD-method are shown by the means of a gallery drilled in limestone and dolomite of the Northern Calcareous Alps, Austria. This gallery is a prime example, because it intersects a well defined deeply incised valley, filled with sediments. Main goals for the processing of TSWD-data are the derivation of high signal to noise seismograms from the pilot (TBM) and receiver signals and the removal of first arrivals from the data in order to uncover reflected phases, even from reflectors very near to the TBM drilling head. Both goals are achieved satisfactorily. A new mapping method of the results gives a better chance of interpretation, which includes the determination of the dip and strike of major fault zones. Generally, these results show that main geological structures are well resolved by the TSWD-method. Limitations of this method are discussed and geophysical issues for further investigations are addressed.

Keywords: TBM, Prediction, continuous, Monitoring, Hard rock

1. Introduction

During tunnel constructions the highest risks are coming from deeply incised valleys, karst cavities, fault zones and other unexpected degradations of rock quality, which can cause extended interruptions and high expenditures [1]. In order to predict such seismic reflectors ahead of the tunnel face, conventional seismic measurements with various shot and receiver layouts using the Vertical Seismic Profiling (VSP) principle have been carried out in the last two decades [2]. Since tunnelling with a Tunnel Boring Machine (TBM) became the main technique in recent years, the vibrations of the drilling head of the TBM offer to be employed as a seismic source signal. This method is based on SWD - Seismic While Drilling [3] and has been called TSWD - Tunnel Seismic While Drilling [4] [5]. Because of the continuous seismic monitoring and the great amount of seismic data, the TSWD-method is more effective to image reflecting horizons, regardless of their orientation, and near to their intersection with the tunnel axis.

In this paper we describe the main features and the main findings of the TSWD-method with the experience of a gallery drilled in limestone and dolomite of the Northern Calcareous Alps, Austria [6].

2. TSWD-Method

The method is based on continuous seismic monitoring of the vibration signal of the cutting head of the TBM by the means of several geophones planted in boreholes along the tunnel wall (Fig.1). The seismic monitoring produces continuous seismic data which are stored in capable registration

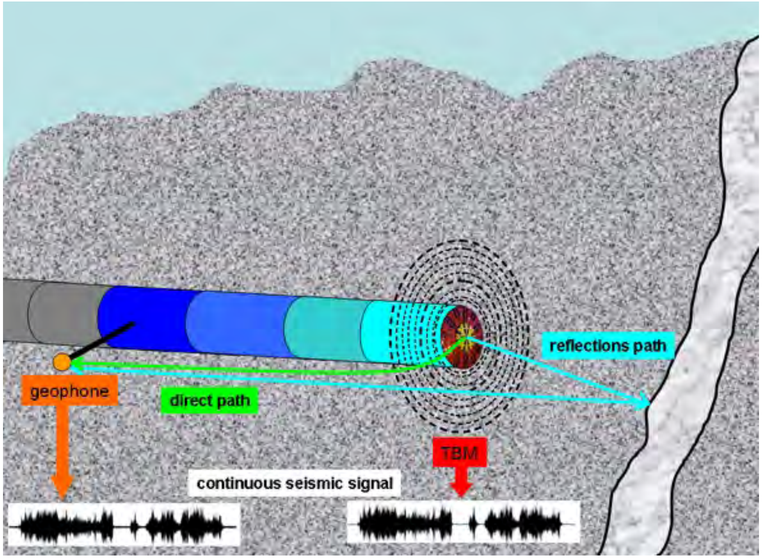

Figure 1: Schematic image of the TSWD-method; different blue columns presents the daily progress of TBM; direct and reflected path are inserted, continuous seismic data from the geophone and TBM-head is shown

units. To handle this amount of data in real time mainly automatic processing must be implemented. The high production rate of modern TBM´s also imposes a major challenge on the real time monitoring, which should result in a daily update of prediction.

There are two different wave fields recorded at the geophones, the direct wave field straightforward coming from the source (TBM) and the reflected wave field propagating from the source to a reflector and back to the geophones. From these wave fields primarily the P-waves are processed in the TSWD-method, because they are normally observed as first arrivals, but also S- and R-waves are recorded [7] [8] [9].

A main task for the seismic processing is to separate the reflecting wave field, with which reflecting boundaries ahead of the tunnel face are spatially predicted, from the direct wave field.

2.1 Geometrical Layout

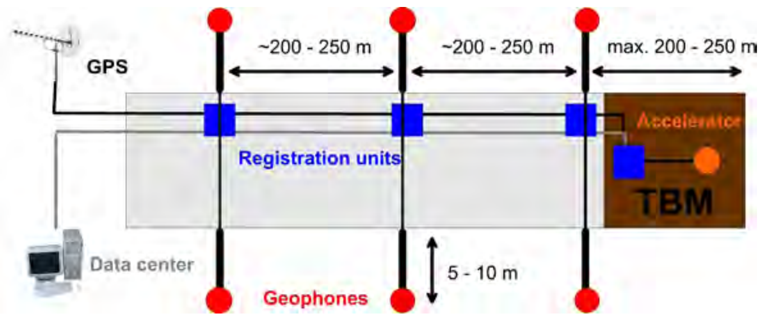

Figure 2: Top view of the geometrical layout

The geometrical installation concept of the seismic instruments consists of a seismic monitoring registration unit (e.g. REFTEK 130) with a 3C accelerator at the head of the TBM and 3 registration units with 3C geophones behind the TBM (see Fig. 2). All instruments are connected with two cables, on the one hand to synchronize the units in time (e.g. with a GPS-signal from outside the tunnel) and on the other hand for the data transmission to the data centre.

The most essential part of the TSWD data acquisition system is the sensor for recording the vibrations (pilot signal) of the TBM´s cutting head during drilling. Using a 3C accelerometer planted at the non-rotating shaft of the main bearing records a good pilot signal, which is primarily directed in the axial direction.

To get a good receiver signal the geophones are installed in deep boreholes (5 - 10 m) at the right and left tunnel side wall in cross sections with a distance of 200 - 250 m to each other. The whole configuration moves as the tunnel progresses. The three components of the geophones are axial, tangential and radial to the tunnel axis. Because of the direction of motion the P-waves are mainly recorded at the axial component. The sampling rate for the pilot and receiver signals should not be smaller than 1000 Hz, because the main frequencies of the vibrations of the TBM are up to 250 Hz [10]. Raw data are sent permanently to the data centre, which requires a transmission rate up to 4x192kBit/s for the whole system.

2.2 Automatic processing of raw data

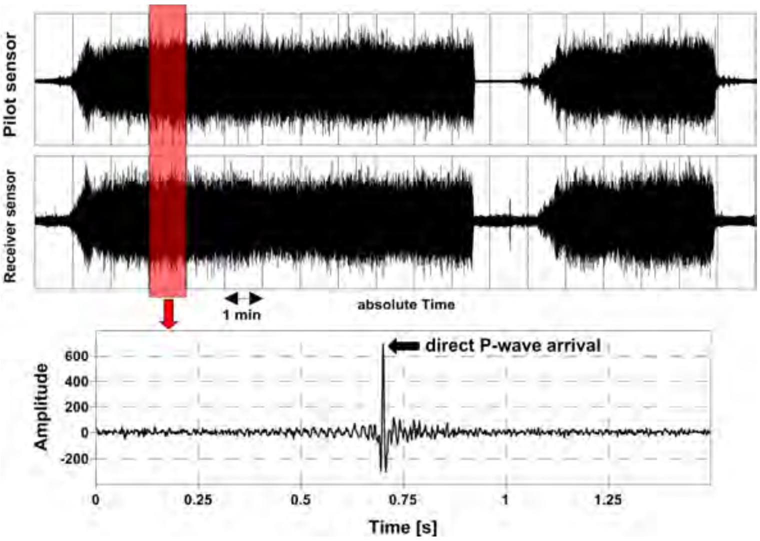

Figure 3: Raw data (18 min) recorded by the TBM sensor (above) and the receiver sensor (middle); seismogram derived from 1 min of continuous recording (below)

The high production rate of data and the request of real time monitoring, processing and prediction demand an automatic processing for the continuous data. Because the standard method, the correlation between the pilot- and the receiver signal [3], to derive interpretable seismograms from this data gives not sufficient results an alternative method is applied. This method is based on the assumption that the pilot signal is a source wavelet convolved with a random sequence of spikes [6]. Therefore the automatic processing consists of cutting out time windows from 30 sec - 5 min of the pilot and receiver data at the same absolute time, the calculation of the minimum delay transform of the pilot signal and the application of this filter to the receiver record.

Figure 3 shows continuous seismic data from the pilot and the receiver sensor and the seismogram derived from 1 min recording of the simultaneous pilot and receiver signal of the axial component (direction of the tunnel axis). It is clearly to see that the envelopes of the pilot- and receiver signals correlate well and that the seismogram shows high amplitudes for the first arrival. The major energy of the receiver signal is found in a frequency range below 200 Hz [6].

Each trace can be interpreted as a shot source at the tunnel face being recorded by a receiver. The production of seismic traces for time steps of 30 sec – 5 min corresponds to source distances in the range of a few millimetres to centimetres.

2.3 Interactive Processing

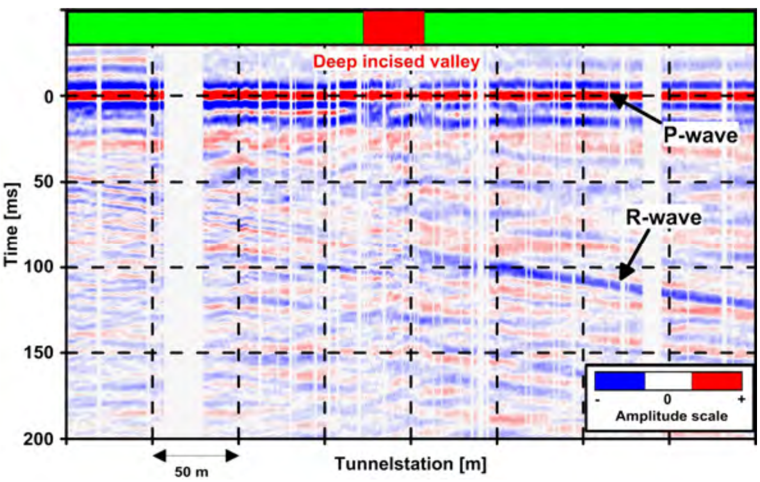

Figure 4: P-wave aligned seismic traces in the range of 400 m for the axial component with a source interval of 1m: P- and R-wave arrivals are marked by arrows

During one day of observation a great amount of seismic traces are produced. To reduce this data amount and to have the seismic traces in well-defined intervals, the traces are stacked to a bin size less than 1m. Stacking of seismic traces improves the signal to noise ratio and therefore the data quality. Prior to this step, the seismic traces are aligned horizontal and the traces with a low signal to noise ratio or no seismic signal are eliminated.

Figure 4 shows an example of such seismic traces for the axial component in the range of 400 m including a deep incised valley. The direct P-wave, which has positive amplitudes and the R-wave are clearly visible.

The most crucial processing step is the removal of the first arrivals as well as the R-wave in order to extract the reflected signals. Normally this is done by frequency – wave number filtering, but the subtraction of an average wavelet, which is generated by mixing from 25 up to 51 traces, is more successful. The preceding application of an amplitude normalisation with the amplitude of the first arrival for each trace is essential for this procedure.

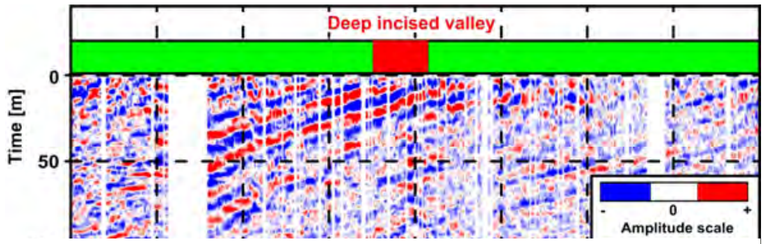

Figure 5: Reflecting wave field for the axial component for the same area as in Figure 4

Figure 5 shows the same range of data as in Figure 4 after the suppression of the direct P-wave (first arrivals) and the R-wave. The reflected signals coming from the deep incised valley become clearly visible also near to the arrival times of the direct P-wave.

3. Advanced Mapping and Interpretation

3.1 Mapping of fault zones

The data shown in Fig. 5 represent the basis for a prediction of geological boundaries and fault zones ahead of the current tunnel face.

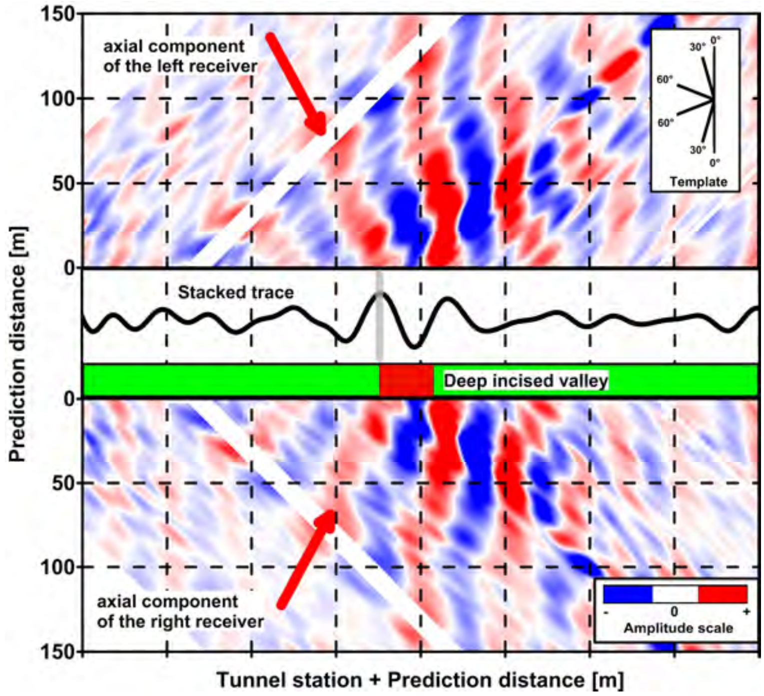

Figure 6: Mapping of reflected wave field of the axial component for the left and right receiver for the same area as in Figure 4 und 5; red arrows mark the reflected signal of the beginning of the deep incised valley; template for different dip angles and stacked trace are inserted

In order to make the reflections more interpretable a mapping of this data from the original space (tunnel station, time) to (tunnel station + prediction distance, prediction distance = velocity*time/2) is performed. 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.6).

Before this mapping a correlation of the reflected wave field with an average wavelet of the direct P-wave is applied, which is shifting the reflected signal of a boundary to the maximum amplitude. This supports exact location of the discontinuities.

A stacked trace of this data shows the exact beginning of the deep incised valley. From this data we estimate the location accuracy for the beginning of significant discontinuities crossing the tunnel axis to be about +/- 5 m.

Because the source (TBM drilling head) works like a drill-bit (see also chapter 4), the reflected signal of the boundary from the compact rock to the deep incised valley, which represents a decrease of the acoustic impedance, has the same polarity as the direct P-wave at the receiver location.

3.2 Dip and Strike of fault zones

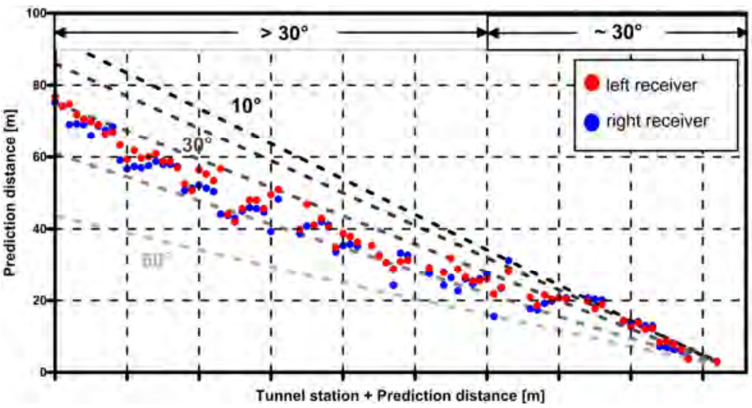

Figure 7: Determination of the dip angle for the reflected signal from the beginning of the deep incised valley

The reflection band correlating with the deep incised valley is not exactly orthogonal to the tunnel axis in Figure 6, indicating an oblique intersection of the boundary to the deep incised valley with the tunnel axis. The dip of a reflection is influenced by the seismic velocity and the dip of the reflection boundary. If the seismic velocity is known or is estimated in a good manner a template for the dip angles can be constructed. Such a template (small insert in Figure 6) shows the expected slopes of the reflection band for different angles of intersection. In order to determine the dip angle more exactly the reflection signal, picked from Figure 6, can be compared to these calculated dip angles (Fig 7). In this case the dip angle nearby the intersection with tunnel axis is about 30° and further away from the tunnel axis more than 30°. Unfortunately, the dip direction (left or right) cannot be determined from the kinematic data alone, because the time difference of the reflected signal between the left and right receivers is diminutive.

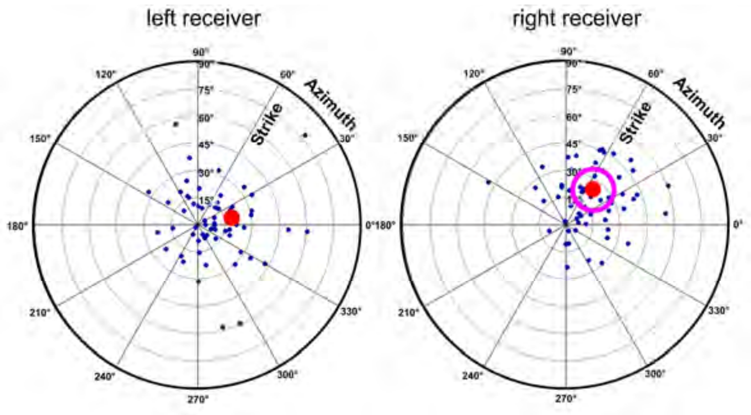

Figure 8: Determination of the strike angle and the azimuth (dip direction) for the reflected signal from the beginning of the deep incised valley; strike 0° is vertical to the tunnel axis

Hence, to determine the dip direction and the strike of a reflection the radial and the tangential components of the receivers must be used. After the determination of the amplitudes for a reflection a polar scattering plot of the particle motion is calculated. Figure 8 shows these results for the left and the right receiver for the reflection from the beginning of the deep incised valley. It clearly indicates that the reflection is coming from the right and upper side. Because of the influence of the tunnel the most appropriate results for the strike are coming from the receivers at the right side, which results in 30° to the vertical direction.

In this case the prediction of the beginning of the deep incised valley with the determined position, dip and strike for this reflection fitted perfectly with the geological tunnel profile and the information of the digital terrain model, drillings and an older gallery.

4. Discussion

In general, the prime example of the deep incised valley shows that the TSWD-method is working excellent for the prediction of fault zones. This case study indicates that the distance between the source (TBM-head) and the reflector is more important than the distance between the reflectors and the geophone cross sections. Therefore the concept of several geophone cross sections, which could be far away from the TBM-head, should have no problem with energy [10], if the seismic ground noise is not too high. A second advantage of this geometrical layout is that the R-wave does not disturb the signal of the P-wave reflection, which is a major problem at near distances to the source.

If logistic problems occur with the absolute timing of the seismic registration units, the exact information on the P-wave velocity of the rock is lost. This does not pose a fundamental obstacle to image all reflecting horizons very close to the tunnel axis, if an adequate estimation of P-wave velocity can be achieved.

The main goal of processing, to produce interpretable seismic traces, can be managed in an excellent way. Hereby, the quality of the seismic traces mainly depends on the knowledge of the source function (direction of energy of the vibrations) generated by the drilling of the TBM. In our example the TBM drilling head works like a drill-bit which represents a single force source. This generates compressional P-waves in forward direction and dilatational P-waves in backward direction of the tunnel. This must not be valid for other TBM drilling heads. Thus, at other tunnel construction sites, the observation of the pilot signal at the shaft of the main bearing could be insufficient. For that reason other locations on the TBM-head, to record the pilot signal, must be arranged until the pilot signal correlates well with the geophone signal.

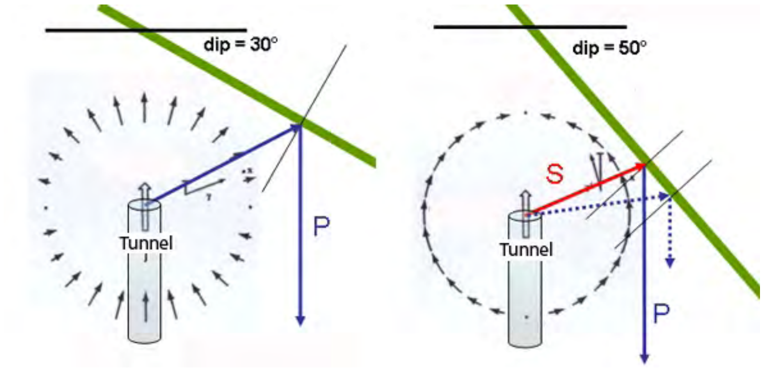

Figure 9: Schematic images (top view) of different seismic waves producing the same reflection; PP-reflection of boundary with a dip of 30° (right side); SP-reflection of boundary with a dip of 50° (left side)

Another uncertainty comes from the propagation of different waves generated by the source. It is possible that an observed reflection is coming from a PP-reflection and/or from a SP-converted reflection at the same distance but with a different dip (Fig 9). This kinematic ambiguity can lead to a wrong interpretation of the dip, but hence to a correct intersection with the tunnel axis.

Dip angles more than 60° are difficult to detect, because for flat reflections the separation of reflected wave field from first arrivals becomes less efficient.

Currently, the major restriction of the interpretation accuracy is the frequency range (<250 Hz) of the recorded pilot signal. This limits the spatial resolution, which is usually ¼ of the spatial wavelength, and therefore the information of the thickness of the predicted fault zones. Results of first numerical modelling efforts show that the beginning of fault zones can be detected for small thicknesses, but the thickness itself has to be unassigned. To understand the reflection pattern of fault zones with small thicknesses, further numerical investigations are planned.

5. Conclusions

The TSWD-method gives excellent continuous seismic data from which deeply incised valleys, karst cavities, fault zones and other unexpected degradations of rock quality can be predicted. The geometrical layout depends on the tunnel construction site, but in optimal cases geophones in cross sections with a distance of 200 – 250 m to each other should be situated in 5 – 10 m deep boreholes. Good interpretable seismic traces are obtained from the vibrations (pilot signal) of the drilling of the TBM-head. Hereby, the most crucial task is the seismic monitoring of the pilot signal with an accelerator. Normally, for this purpose the pilot signal is taken from the non-rotating part of the main bearing of the TBM drilling head, but in cases where there is no correlation with the receiver signal, the position of the accelerator have to be adapted.

The processing of the continuous data with the minimum delay transform produces seismic traces with a nominal shot distance in the range millimetres and centimetres, which is an advantage to the conventional seismic methods. Additionally, the stacking of the traces improves the data quality. After the separation of the reflection wave field from the direct wave field, the reflections are mapped with a new method, which makes the interpretation more flexible. This is shown for a prime example of a deep incised valley, where the reflection from hard rock to the sediment filling can be followed from about 150 m to less than 10 m prediction distance ahead of the TBM drilling head. This new achievement implies a significant reduction in prediction uncertainty to ± 5m. With the help of a template for the dip angle this mapping offers a quick way to decide if a discontinuity recognized in the reflected wave field intersects the tunnel axis nearly orthogonally or obliquely. The dip of the reflection signal and the particle motion recorded by the 3C borehole geophones can be used to unequivocally estimate the dip and the strike of such a discontinuity.

To overcome some discussed limitations and to improve the resolution of fault zones, further investigations have to be done.

Modern TBM´s can drill about 50 m per day under favourable geologic conditions and therefore a half/daily to daily update of prediction has to be done. This imposes a major challenge on real time monitoring, data transmission and logistic, processing and prediction, which have to be adapted for every tunnel construction site.

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