Advanced Technology of the Tunnel Seismic Prediction System

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1 INTRODUCTION

A major problem for the driving of a tunnel is the knowledge of the geological environment and its geotechnical parameters. Increasingly more underground construction works are to be carried out under difficult soil and rock conditions. Significant geological boundaries that cut the tunnel axis can cause serious problems and risks such as large break-outs, collapses, flooding and rush-ins during tunnel advancement, especially when they are intersected very suddenly.

A careful risk management has to address such perils by adequate exploration and proper measures. Robust and reliable prediction methods have to be applied, which do not disrupt the tunneling process and yield results quickly and at moderate costs.

Common exploration methods like exploratory drillings or geophysical predictions from the surface can lead to insufficient results due to frequent changes of geological conditions, high overburden, dense infrastructures above the tunnel track etc. Besides exploratory drilling from the tunnel face, non-destructive geophysical methods can detect lithologic heterogeneities within distances up to hundreds of meters ahead of the tunnel face. Seismic imaging is the most effective prediction method because of its large prediction range, high resolution and ease of application on a tunnel construction site.

Since its introduction in 1994, the Tunnel Seismic Prediction System (TSP) has successfully been used in many tunneling projects world-wide [1,2,3,4,5]. In short, the TSP system provides an important impact on logistic optimization that the contractor himself can manage and implement in the tunneling workflow.

2 SEISMIC EXPLORATION DURING TUNNELING

For decades, seismic exploration techniques in use for hydrocarbon prospecting have been continuously developed and proven to be a suitable tool to examine and predict important engineering parameters of the subsoil. By the majority, seismic exploration is based on the reflection method of observing and evaluating elastic body waves. These waves are excited by artificial sources like detonation charges or the impact of a mass (e.g. a hammer). While there are many different seismic energy sources available, in most cases detonation charges provide the best signal to noise ratio and the least restrictive conditions for recording and processing.

Seismic waves travel as compression or shear waves through the ground. They are reflected at interfaces with different mechanical properties like density or elasticity. The ground motion caused by reflected waves is measured with seismic sensors. For the separation of the different types of elastic waves three-component-sensors have to be used. The travel times of reflected signals are proportional to the wave velocities within the ground and to the distance to an interface. Thus, by detection of reflected elastic waves and their corresponding travel times it is possible to deduct information about the mechanical properties of the ground. In this way, important engineering parameters like elastic modules can be predicted.
To perform reliable seismic measurements and thus mitigating risks for tunnel construction in hard rock conditions, the Tunnel Seismic Prediction (TSP) proved its efficiency in hard rock tunnel projects worldwide. Hardware, as well as processing algorithms and user interface have been constantly developed and further refined since the early 1990’s.

2.1 THE USE OF TSP IN TBM TUNNELING

The setup of a single measurement is shown in Figure 1. A series of usually 24 explosive charges is detonated in boreholes along the tunnel wall. The generated seismic waves are received by several 3-component accelerometers installed 2 meters deep in opposing sides of the tunnel wall. The necessary operations to perform a tunnel seismic measurement in a typical TSP setup can be integrated into the construction operations without any interference with the excavation work and tunneling progress. Boreholes for receivers and explosive charges can be prepared continuously together with ordinary support measures, such as utilizing the anchor boring rigs. Installation of seismic receivers as well as loading and shooting of explosive charges may take place during maintenance intervals or short excavation breaks of about one hour. This operation time can be further reduced by splitting the campaign into two parts and carried out on consecutive days. Furthermore, in case of poor knowledge on the geologic conditions ahead of the tunnel face, it is advised to performing campaigns continuously (Figure 2).

Special care has to be taken to provide good coupling of seismic sensors to the rock mass. This is achieved by gluing tailor made receiver casings into the boreholes with fast curing material of high stiffness. Placing two receivers generally provides enough data to obtain reliable results. Thanks to the fast installation procedure and functionality of the recording equipment, placing more sensors implies no complications or delay of total measurement duration.

The TSP method is compatible with all excavation methods. No access to the face or exposed rock is necessary. This also makes TSP applicable for TBM advance with segmental lining. The required explosive charges will not produce any damage to lining elements.

Figure 1: Standard Tunnel Seismic prediction layout in TBM tunneling. The acoustic waves released by small explosive charges (shown are only the wave rays) hit a geological discontinuity (i.e. fault zone) and are being reflected. The 3-component receivers (red bars at both tunnel wall sides) pick up the incoming wave signals.
2.2 TSP IN SEGMENTAL LINING TUNNELS

The use of precast segmental lining doesn’t mean a restriction for seismic surveys although the rock mass isn’t accessible at all. In order to avoid large-scale drilling measures through the precast segments, it is very helpful using the grouting and lifting inserts of the segments as indicated in Figure 3. Segments may have been designed with none, standard or heavy duty steel reinforcement with the latter to be used in sections of tunnels with adverse geological conditions such as squeezing ground and fault zones. Particularly, the latter cases would imply significant effort, if existing inserts aren’t being utilized for the seismic layout.

On segmental linings, high safety standards are being applied with regard to serviceability and long term durability. Consequently, any damage of the segmental lining caused by the use of explosive blasts behind the lining should be strongly avoided (Figure 4). We have conducted a study on possible influences, which take into account the following requirements on serviceability of segmental linings:

![Figure 2: Normal or split TSP-layout for sporadic TSP-operation at one single day or two days, respectively (top). An accompanying TSP-operation schedules every day some twelve shot-recordings to be quickly completed, e.g. during the morning maintenance break of a TBM (bottom).](image)

![Figure 3: Example of a segmental lining where possible boreholes become easy to drill for the seismic survey.](image)
− It has to be kept sealed at roof and side wall.
− The concrete and reinforcements need to be kept protected against corrosion.
− The maximum settlement of annular joint between 2 segments has to be kept in range of the manufacturer’s specs.
− The maximum of rotation of longitudinal joint between 2 segments has to be kept in range of the manufacturer’s specs.

In conclusion, stability safety and serviceability of segmental elements and the entire lining are guaranteed using explosives behind. In case of full backfilling of the segments, the blasts could activate settlements with a maximum of 3 mm in worse rock condition like weathered mudstone. The settlements become less with increasing rock strength. The blasts are even practicable, if the buffer of settlements between joints is below 3 mm. Damage-free blasts can be performed if the blow outs are canalized by installed tubes, while the blow out plane behind the segments is concurrently eliminated. The study as well as our many tunnel site experiences document the structural safety verification and ascertain no impairment of serviceability of segmental lining whatsoever.

3 SPECIFIC ASPECTS OF TUNNEL SEISMIC DATA PROCESSING

To obtain reliable and understandable results a processing system with a reasonable level of automation is necessary. A fully automated process would be unacceptable due to the complexity inherent in the necessary processing steps and heterogeneity in different datasets obtained in differing geologic conditions. An integrated software system with flexible ways of data visualization and straightforward user interaction, guiding operators from data acquisition to the final results and interpretations is inevitable. Based on modeling results and field data evaluation, we consider the following processing steps as crucial:

The bulk of seismic energy recorded in tunnel seismology may often comprise direct waves, tunnel surface waves and waves guided through the excavation damaged zone around the tunnel [6]. These wave modes are sensitive to local heterogeneities up to few meters away from the tunnel. But they as well as undesired background noise should be suppressed prior to reflection imaging. We do not recommend muting the air wave because this will also remove late incoming reflections. High-quality data should not display a strong air wave anyway. The extraction of reflected waves can make use of the fact that the reflection travel time reduces as the tunnel advances and the acquisition equipment approaches the reflector. The pressure wave and shear wave reflections can be extracted from the seismic raw data via multi-channel dip filtering and by covariance-based methods to separate different modes of particle motion. Amplitude loss due to geometrical spreading and attenuation must be compensated.

The seismic quality factor Q describes wave attenuation and is related to the structure of rock, in particular to its heterogeneity and to the presence of fluids. [8] summarizes strong evidence that seismic Q is related to static Young’s modulus and rock quality ratings. Generally speaking, low values of seismic Q correspond to the poorer, more jointed rock. From that perspective seismic Q can be seen as indicative for the geotechnical parameter “Q”, even though there is no strict correlation between these two values in a physical sense.
Body waves attenuate exponentially as a function of propagation distance with attenuation coefficients that increase linearly with frequency. This leads to a rock-specific and frequency-independent seismic quality factor $Q$ estimated from signal frequencies up to a few kHz. We have investigated amplitude spectra of direct compressional waves as a function of propagation distance in many hard rock tunnels around the world and found strong attenuation with $Q$-values ranging between 15 and 50. Waves under investigation should not have passed through the excavation damaged zone (EDZ) because attenuation there is much higher and not representative of undisturbed rock. This condition is satisfied by generation and recording of seismic energy inside boreholes and not on the tunnel wall.

Strong attenuation (low $Q$) limits the possible prediction range because signal amplitudes are damped such that they finally disappear in the background noise at specific propagation distances. Strong attenuation also causes wave trains to disperse such that reflected pulses cannot be focused via imaging. Therefore attenuation should be compensated for by inverse $Q$-filtering [10] or spectral whitening [11]. In the computationally most expensive processing step the information of the seismic traces is mapped from time domain into the three-dimensional space domain. This involves velocity model building and migration.

The velocity models are input to prestack migration which focuses reflection energy along portions of the ellipsoidal isochrones (i.e., surfaces of constant travel time) using incidence angle information. Since the TSP method records three-component seismograms, the incidence angle can be derived by polarization analysis of the ground motion. The resulting migration image is a three-dimensional map of acoustic impedance representing changes in seismic velocity and density. Thus, combining the velocity model and the reflection image allows interpreting density variations. With this information further rock mechanical parameters of interest such as elastic modules, Poisson ratio etc. can be calculated using empirical relationships [8].

4 SYNTHETIC CASE STUDY

The proposed processing sequence and all required functions for data acquisition are fully integrated into a single comfortable software package (Figure 6).

A typical result of a seismic survey will be showcased by a realistic synthetic case study. Seismic input data was produced by numerical simulation using a subsoil model as shown in Figure 5. It contains features of high relevance for tunneling, like cataclastic fault zones, seismically showing as low velocity layers and a water bearing cavity. The tunnel has a diameter of 9 meters and is 60 meters long, and is filled with air. For a realistic condition, the tunnel is surrounded by an excavation damaged zone (EDZ). In the model an excavation disturbance of radial 1.5 m depth is assumed combined with gradients in P- and S-wave velocity and in density. At the tunnel face the EDZ reaches 2.5 meters ahead into undisturbed rock and gradients are 60 percent lower.

Based on this model the elastodynamic equations of motion have been solved using staggered grid finite-difference algorithms simulating 24 shots and a single receiver.

In this study the algorithm presented by [6] was being applied because it is stable and accurate even at locations of extreme elastic contrasts, as they frequently occur in tunnel seismic.

The simulated seismograms were fed into the processing software. After completion of all necessary trace processing, full three-dimensional velocity analysis and migration have been performed. The resulting images clearly show the main features of the underlying velocity model. The water lens just
ahead of the tunnel and the two cataclastic zones are correctly identified. This is most clearly demonstrated by the software functionality of extracting high amplitudes in the 3-D migration image and plotting these structures at their true spatial location (Figure 6, bottom right). However, the slopes of the cataclastic zones are not being imaged to full scale, because only constricted portions of these zones could reflect waves toward the receiver due to the physical law of reflection (Snell’s law). The image will be enhanced by the use of more than one receiver. For real exploration the use of two to four receivers at both tunnel wall sides is envisaged as a standard.

5 TUNNEL CASE HISTORY

Figure 7 shows migration cuboids of seismic field data obtained with two receivers in a tunnel project situated in a slate gneiss formation. The geology consists of thin deposits or transitions to coarse grain gneiss (augengneiss, light resp. black mica gneiss), fine grain gneiss and mica schist embedded in a schistose anisotropic rock mass. Secondary, there were marble facies as well as single thin deposits of amphibolites. The rock mass exhibits an intensive and narrow folding in ranges of metres to decametres. From the three separate wave field components, which are P-wave, SH-wave and SV-wave, the most dominant reflectors were being extracted and projected along the tunnel axis (Figure 7, bottom right).
Figure 7: Three-dimensional displays of migrated P-wave, SH-wave and SV-wave data and their extracted dominant reflector planes around the tunnel course axis.

Furthermore, figure 8 shows the graphical comparison where the TSP results are being presented in a longitudinal view. Indicated are the dominant reflectors with zones of colour shading according to the computed Young's Modulus in-between. It demonstrates clearly arranged characteristics of the geology. It is found that the TSP prognosis is in good agreement with the geological findings. Both point out that there aren't any relevant faults, which could have been strongly affected the tunnelling.

Figure 8: Extracted dominant reflector planes from figure 7 in longitudinal view (top) and the dynamic Young's Modulus derived from the computed velocity model of the seismic data (middle). Geologic cross-section mapped after excavation (bottom). Notice the good agreement with the TSP prognosis.
6 CONCLUSION

Tunnel Seismics can yield quantitative seismic predictions of dynamic ground properties ahead of the tunnel if high-quality specialized hardware and software is used. Multi-component seismic registrations are essential to estimate rock physical parameters and to back propagate reflection energy toward the true reflector position. The accurate determination of an attenuation model is an important asset to characterize rock mechanical properties and to prevent a loss of resolution with seismic wave travel time that yields in a sufficient prediction distance. Careful seismic data processing is very important. Thereby, velocity analysis is a complex process under the tunnel seismic acquisition geometry. If the principles of migration are followed under the application of a heterogeneous velocity model, structural images of impedance contrasts and hence geologic changes are being revealed.

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8 REFERENCES


