International Journal of the JCRM
Japanese Committee for Rock Mechanics

Volume 4, Number 2, December 2008, pp.47-51
[ISSUE PAPER]

Seismic prediction ahead of a tunnel face

- Modeling, field surveys, geotechnical interpretation -

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Received 13 10 2008; accepted 29 01 2009

ABSTRACT

An important precondition for underground construction is a detailed knowledge of the soil and/or rock conditions in the area of the construction. In order to overcome existing limitations in classical exploration methods, research and development for exploration ahead of a tunnel face focuses on: hardware development for excavation integrated measurements, modelling and processing of data measured under these specific circumstances, and integrative interpretation of seismic results with other data from the excavation, from geological mapping, and from exploratory drilling, where available. Finite difference modelling of seismic wavefields around tunnels has shown the general feasibility of seismic measurements for imaging structures ahead of a tunnel face. The modelling results were confirmed by field measurements in various tunnel sites. The integrated interpretation of seismic data with all available geological and geotechnical information is currently in the state of development and aims, in the middle to long term perspective, at an "a priori" detection of structures ahead of the face.

Keywords: Tunneling, Seismic Measurements, Finite-Difference Modeling, Seismic Imaging, TBM Parameters

1. INTRODUCTION

An important precondition for underground construction is a detailed knowledge of the soil and/or rock conditions in the area of the construction. Before a tunnel is excavated, exploratory wells are drilled and geological and geophysical investigations are carried out from the surface in order to image the geological environment along the projected roadway. These, however, provide only detailed data at a limited number of locations (wells), and are of limited resolution (surface investigations). Therefore, in the recent years, geophysical methods have been developed for the prediction ahead of a tunnel during the construction. Commercially available systems make use of seismic methods. They work according to the following principle: Seismic body waves (compressional (P-) or shear (S-) waves) are generated near the tunnel wall or directly at the tunnel face. These waves are reflected or backscattered at geological heterogeneities and the reflections are observed by seismic receivers placed around the tunnel or at the tunnel face. The spatial distribution of heterogeneities is then examined by different migration techniques (e.g., Kneib et al., 2000, Otto et al., 2002). These methods usually rely on a high degree of subsurface illumination using large apertures and multiple coverage of subsurface points. Particularly, methods to derive geomechanical quantities from seismic measurements depend on large apertures which are usually unavailable in typical underground construction sites where the source and receiver spread is restricted to excavated structures and a limited amount of boreholes.

One of the commercially available systems is the Sonic Softground Probing (SSP) by Herrenknecht (Kneib et al., 2000). This system consists of piezoelectric sources and receivers integrated into the cutterhead of a tunnel boring machine (TBM). Due to the difficult mechanical coupling between the cutterhead and the rock mass of the tunnel face, this method is applicable in softground tunneling using Earth-pressure balanced TBM, but not, e.g., in hard rock tunneling using open gripper TBM.

In order to overcome these limitations, research and development for exploration ahead of a tunnel face focuses on: hardware development for excavation integrated measurements, modelling and processing of data measured under these specific circumstances, and integrative interpretation of seismic results with other data from the excavation, from geological mapping, and from exploratory drilling, where available. Funded by the German Ministry of Education and Research (BMBF), a consortium of Research Institutes, Universities and industrial partners works together within the OnSITE (**On**-line **S**eismic **I**maging for **T**unnel **E**xcavation) project addressing the aforementioned research and development topics. In this paper, we will concentrate on the geological and geophysical aspects of the system development and of its application, and therefore, the hardware components will be treated elsewhere.

2. MODELING

2.1 Modeling scheme

3D elastic modeling is applied to understand the complex wavefields which are observed when performing seismic measurements from within a tunnel. A parallelized 3D viscoelastic finite-difference method is applied (Bohlen, 2002). In this algorithm, the velocity stress formulation of the wave equation is discretized using second-order spatial and temporal FD operators on a standard staggered grid. The free surface of the tunnel is not treated explicitly, i.e., no explicit boundary conditions are applied.

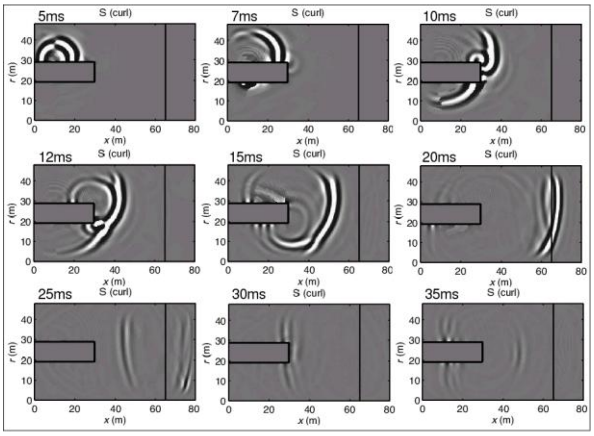

Figure 1. Finite difference modelling snapshots of the wavefields generated by a hammer impact on the sidewall of a tunnel. The time steps from 5 ms to 35 ms are shown from upper left to lower right. A fault zone is located at x = 65 m.

2.2 Properties of seismic waves around a tunnel

In the simulations, a tunnel with a diameter of 10m was considered. The tunnel is surrounded by a homogeneous crystalline rock mass. In front of the tunnel, a fault zone was placed which is characterized by low velocities and strong absorption. Figure 1 shows snapshots of the modelled wavefield between 5 ms and 35 ms after triggering a hammer impact on the sidewall of a tunnel. The snapshots show S-wave particle velocity only which is achieved by computing rot(v) (where v is the particle velocity, Bohlen et al., 2007). Most of the P-wave energy is directed sidewards when the source is located on the tunnel wall and P-waves are therefore not useful for the exploration ahead of the face. However, a Rayleigh wave is generated which travels along the tunnel wall. After approximately 7 ms, this Rayleigh wave reaches the tunnel face. In the subsequent snapshots (Figure 1), a shear wave is dominating the wavefield which travels from the tunnel face towards the fault zone. At 20 ms, it is partially reflected at the fault zone, and the reflection returns to the tunnel face where a part of it is re-converted to a Rayleigh wave at approximately 30 ms. The Rayleigh wave is then recorded by receivers in the sidewall of the tunnel.

3. SEISMIC MEASUREMENTS AND IMAGING

3.1 Exploration ahead of the tunnel

Finite difference modeling has shown that seismic exploration ahead of a tunnel face is possible by using converted surface waves which were generated on the tunnel sidewall. A field survey was carried out in the Piora adit in order to test the transferability of the modeling results to real tunnels (Lüth et al., 2008). The Piora adit had been excavated from 1993 to 1996 in order to explore the transition from the Penninic Gneiss Zone in the South to the Gotthard Massif in the North along the roadway of the Gotthard Base Tunnel which is currently under construction. These two stable rock units are separated by the Piora unit and a Kakiritic layer (cohesionless cataclasites).

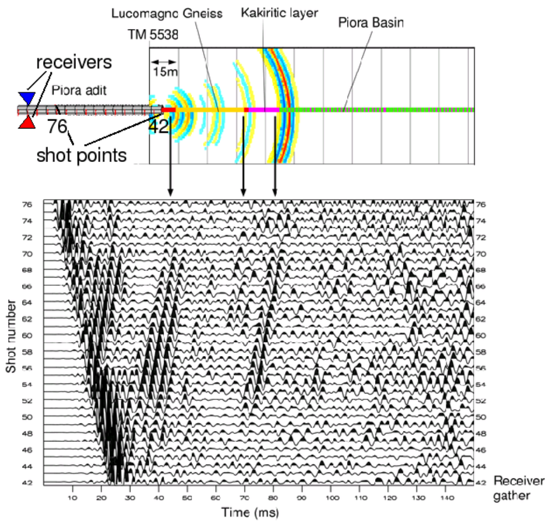

Figure 2. Bottom: Seismic receiver gather, showing the records of one receiver (red triangle) and shot points 42 - 76. Top: Piora adit with source (shotpoint location numbers 42 and 76 indicated) and receiver distribution (data shown in the gather were recorded by the receiver indicated by a red triangle), geological profile along exploratory drilling and migrated section. For reference, tunnel meter 5538 is marked at the migrated section. Linear events in the receiver gather (indicated by black arrows) sum up to strong reflection events in the migrated section. For further explanation please refer to main text.

The Piora adit was excavated by a tunnel boring machine with a diameter of 5 m. The adit is 5.5 km long and its face is located at ca. 30 m distance from the unstable Piora unit. The seismic survey took place along the final 75 m of the Piora adit. Two 3-component receivers were fixed on the tips of rock bolts. A pneumatic hammer was used as a seismic source. The hammer was positioned on 76 source points where it was triggered five times, respectively, in order to enhance the signal-noise ratio (SNR) by vertical stacking. A part of the resulting receiver gathers is shown in Fig. 2. The tunnel wall perpendicular component is shown in the receiver gather which mainly contains shear and surface wave energy. Processing of the data shown includes a recursive median filter to remove direct waves, a 200-400 Hz bandpass filter, and amplitude gain with the squared traveltime. Remnants of the direct Rayleigh wave can still be identified in the receiver gather as a linear event with increasing traveltime from shotpoint number 76 (closest to the receiver) to shotpoint number 42 (at the tunnel face). Reflections from ahead of the tunnel face appear as linear events with decreasing traveltime from shotpoint number 76 to 42, such as, e.g., at approximately between 70 ms and 80 ms. The spatial location of the corresponding reflectors is determined by Kirchhoff migration (Fig. 2 (top)). Due to the limited aperture (sources and receivers are located along a line and the structures to be investigated are located in the extension of this liear profile), the image of the reflectors is blurred and there remains a spatial ambiguity. This spatial ambiguity can be reduced by repeating the measurements while the tunnel face is advancing and by placing sources and receivers at different azimuthal positions in the tunnel.

In Fig. 2 (top), the results of the Kirchhoff migration and a lithological profile from an exploratory well (Schneider, 1997) are plotted. The main reflecting events in the migrated section are (from left to right in Fig. 2 (top)): The transition from a concrete seal of the Piora adit to the Lucomagno Gneiss, the transition from the Lucomagno Gneiss to a Kakiritic layer, and the boundary between the Kakiritic layer and the Piora Basin rocks.

3.2 Exploration around the tunnel

When seismic measurements are performed in order to explore the surroundings of an excavation, converted surface waves will not be appropriate as these propagate perpendicularly to the desired direction of focus. In this case, imaging of body wave reflections or diffractions is to be applied. Contrary to surface seismic measurements, the aperture is strongly limited by the excavated structures. Therefore, in order to avoid imaging artefacts and to reduce spatial ambiguity, the imaging operator must be restricted to the region around the point of specular reflection. Takahashi (1995) proposes a restriction based on the polarization angle from multicomponent data. This concept is extended by Lüth et al. (2005) by applying the concept of Fresnel volumes. For single component data, Buske et al. (2006) formulated an approach based on slowness analysis and applied it to standard seismic exploration datasets.

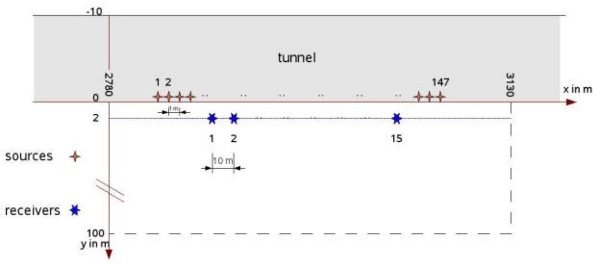

Figure 3. Schematic source and receiver distribution along the tunnel (Piora adit). The source points are on the tunnel wall, the receivers are installed in the tips of anchor rods which are located at 2m depth from the tunnel wall.

A reflection seismic dataset was acquired in the Piora adit (near the Gotthard Base Tunnel construction site). The survey consisted of 15 receiver points and 147 source points (Fig. 3). The receivers are located at two meters depth in the tunnel wall, integrated into the tips of rock anchors. A pneumatic hammer was triggered every 1 m. The first breaks of the seismic measurements were used to compute P-wave and S-wave velocity models by tomographic inversion. The (2D) velocity models were rotated around the tunnel axis in order to define 3D velocity distribution around the tunnel for the seismic imaging. Each receiver gather was migrated separately and the final 3D image was obtained by stacking the migrated data taking into account either the true phase or the absolute value. This imaging method does not take into account the angle of incidence such that reflectors appear as concentric shells around the tunnel in the 3D volume as the measuring aperture is extremely restricted. If the emergence angle of incoming reflections can be determined, Fresnel Volume Migration (Lüth et al., 2005; Buske et al., 2006) can be used in order to concentrate the resulting image to the vicinity of the actual reflection points and thus reduce spatial ambiguity. The emergence angle of reflections is computed using the slowness and polarization analysis of the data. The results of applying this concept are shown in Figure 4. Strong reflections (red) in Fig. 4 correlate with a fault zone which is identified by geological mapping. The vertical cross section (Fig. 4 a)) runs parallel to the acquisition spread and shows a well resolved structural image. Perpendicular to the tunnel axis, the spatial coverage is smaller, therefore the image appears smeared (Fig. 4 d)). However, the strongest amplitudes (in red) are restricted to a relatively small area so that it is possible to identify the spatial position of the reflection points in 3D within a small range of azimuths.

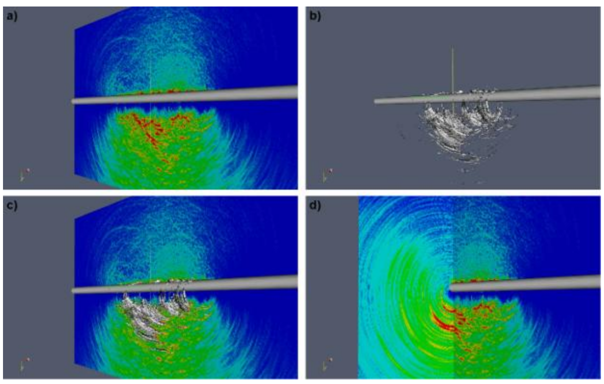

Figure 4. Images of 3D migration of seismic reflection measurements along the Piora adit. A) Image plain along tunnel axis. B) 3D envelopes of main reflections. The envelopes describe the volumes of maximum reflection amplitudes (values above 80% threshold). C) 3D envelopes and image. D) Composition of images along tunnel axis and perpendicular to the tunnel axis.

4. INTERPRETATION

Compared to geophysical observations from Earth's surface, measurements from within a tunnel are spatially restricted resulting in spatial ambiguitiy and limited options for the quantification of imaged anomalies (using, e.g., AVO/AVA - amplitude versus offset/angle). Seismic measurements, combined with geological mapping of the rock mass drilled through, were performed on the construction site of the Glendoe Hydroelectric Scheme (Scotland). The migrated section, depicted in Fig. 5 a), shows the spatial distribution of seismic reflectivity along a tunnel trajectory, as derived from the migration of shear waves generated by conversion at the tunnel face (Fig. 1). The main reflectors all show a circular shape which is a "migration artifact" due to insufficient aperture perpendicular to the tunnel axis. The highest amplitudes of these reflectors are distributed near the tunnel trajectory. The reflectors fade out and become broader with increasing distance from the tunnel axis which indicates that the image results from superposition of different signal recordings and that the actual position of the reflection, respectively backscattering, points is near the tunnel axis. In Fig. 5, the migrated seismic data is compared to geological mapping as performed during the excavation and to control parameters of the tunnel boring machine (TBM), thrust force and penetration rate. The tunnel was excavated in relatively homogeneous rock mass consisting of quartz shist and quartz mica schist with varying quartz content. Minor faults and fractures as well as quartz lentils were detected along the tunnel trajectory. No major faults or geological layer boundaries were found.

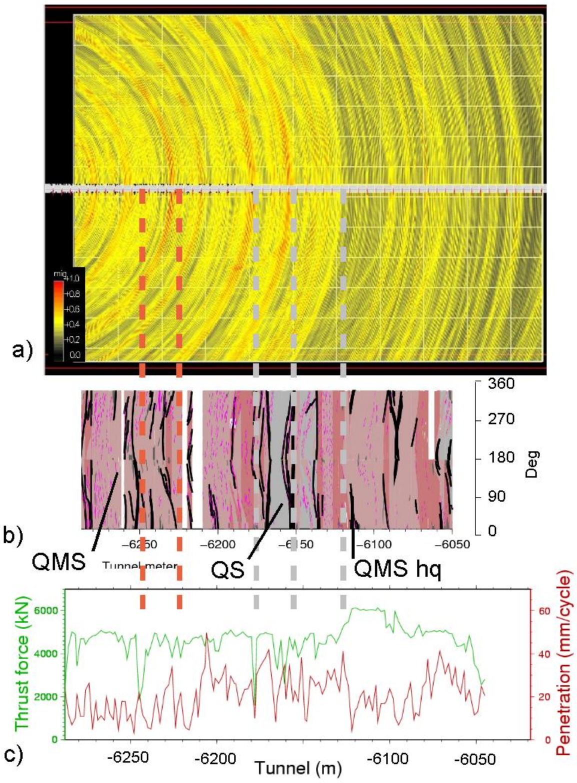

Figure 5. a) Migrated seismic section of measurements during tunnel construction. Data acquisition took place along 200 m of tunnel excavation (-6400 m - -6200 m). Only reflections from ahead of the respective position of the tunnel face were imaged. Squared amplitudes were imaged, corresponding to the energy of the signal. Red colors indicate strong reflectivity, faint yellow indicates low reflectivity (normalized amplitudes, max. amplitude eq. 1). b) Geological mapping of the tunnel wall. Geological units were assign to the following rock types: QS (grey) - quartz schist, QMS (pink) - quartz mica schist, QMS hq (dark pink) - quartz mica schist with high quartz content. Additionally, faults and fractures (black lines) and quartz lentils (magenta patches) were mapped (mapping by Herrenknecht AG). White areas indicate mapping gaps. c) Thrust force and penetration rate of the tunnel boring machine (TBM) recorded during the excavation.

Five events within the seismic section and the TBM parameter curves (Fig. 5) are highlighted by read and grey dashed lines, red indicating rather bad correlation, grey indicating very good correlation. The first two of the grey events (at tunnel meters -6177 and -6156) correspond to strong reflections in the seismic section, whereas the third grey event (at tunnel meter -6127) corresponds to a transition towards seismically transparent rock mass. Comparing the reflections at tunnel meter -6177 and -6156 with the geological mapping shows good correlation between the location of the reflectors and the start of rock mass units with considerably increased fracture density. This indicates that the strong reflections along the tunnel trajectory can be attributed to fractured rock. Although the single fractures are too small for being directly imaged by seismic reflection measurements, an increased fracture density reduces the effective shear strength of the respective rock mass and thus produces an impedance contrast for seismic waves. The third event, at tunnel meter -6127, has completely different characteristics. In the seismic section, looking from left to right, this event marks the onset of a seismically transparent rock mass unit between tunnel meters -6127 and -6100. This seismically transparent unit coincides with very low fracture density in the geological tunnel wall map which can be observed between tunnel meters ca. -6130 and -6095.

Additionally, the TBM control parameters such as, e.g. its thrust force (i.e. the force which is applied to press the cutterhead against the tunnel face) and penetration rate (i.e. the advance of the tunnel face during one cycle of the cutterhead) are indicators of the geotechnical properties of the rock mass being excavated. Comparable observations were also made using the drilling data acquired in conventional tunnel excavation using the NATM (New Austrian Tunneling Method, Kim et al,. 2008). It can be noted that reflection events in the seismic section spatially correlate with negative peaks in the thrust force of the TBM. These negative peaks are due a reduction of pressure applied onto the cutterhead which is a usual reaction on the excavation of rather unstable rock mass. On the other hand, the third seismic event at tunnel meter -6127, correlating with very low fracture density, also coincides with a section of particularly high TBM thrust force (6000 kN versus 5000 kN along the rest of the considered tunnel section). This, together with a very low penetration rate between tunnel meters -6120 and -6090, is an indication for very stable rock mass units in terms of cavability, crushability and abrasiveness, which are important factors affecting the life cycle of cutterhead wheels and the need for stabilizing measures right after the excavation.

The red dashed lines in Fig. 5 indicate events in the migrated seismic section or in the TBM parameter curves which do not show direct correlation between the independent observations. A strong negative peak in the TBM thrust force at tunnel meter –6245 correlates with mapped fractures but does not coincide with strong reflectivity. A strong reflector near tunnel meter –6230 does not seem to correlate with a significant change in the Geology or the TBM control parameters. These examples show that the relations between seismic images, Geology and the behavior of a tunnel boring machine are complex and that seismic observations alone may be misinterpreted if not combined with additional observations. Particularly in highly complex geological environments, seismic measurements image structures which are located near the tunnel trajectory but which do not affect the excavation. Imaging artifacts can not be completely avoided. On the other hand, variations in the TBM control parameters may have technical or man made variations which are not triggered by geological events. Seismic imaging while tunneling contributes to providing locations of heterogeneities which might affect the excavation process. If, based on additional geological and geotechnical investigations before the construction, particular hazards for the excavation are expected, a continuous geophysical exploration while tunneling provides the locations of anomalies which then have to be further investigated, e.g., using exploratory wells, in order to safely characterize the imaged structures.

5. CONCLUSION

Seismic modeling using finite differences and field measurements in different tunnels aiming at reflectors along and ahead of the existing tunnels have shown that structural images of reflectors representing fault zones and/or geological layer boundaries can be gained by seismic measurements. Compared to measurements from the surface, the spatial aperture is restricted and therefore spatial ambiguity has to be reduced by special means such as three component recording of seismic waves and evaluation of the polarization or by exciting seismic signals with well defined radiation characteristics, restricted to a narrow angle. Seismic measurements were performed in several active tunnel excavation projects, using seismic sources and receivers positioned at the tunnel wall between 10 and 30 m behind the face. In this case, surface waves are generated on the tunnel wall which partially convert to shear waves propagating from the tunnel face in the direction of the tunnel trajectory. Images of reflected and/or backscattered waves correlate well with fault zones or varying rock mass conditions, detected by geological mapping and evaluating control parameters of the tunnel boring machine. However, this correlation has been found after the tunnel was drilled through the respective rock mass units. For the detection of possibly problematic structures before the excavation process has reached them, it is necessary to interpret the results of the seismic measurements "a priori". This is impossible without calibrating the measurements, i.e., assigning reflections to a specific type of structures or to specific rock mass properties. The campaigns carried out to date, provide punctual information which are good indications on the general feasibility of the seismic method, but they still do not even provide a representative data base for the complete tunnel project, and certainly are not transferrable to other tunnel projects. Therefore, for a future development of real time a priori interpretation of seismic measurements in tunnel excavation, the seismic data must be integrated with all available geological, geotechnical and geophysical information which is available for the respective tunnel projects and the rock types which are excavated.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support of the project provided by the German Ministry of Education and Research (BMBF), research and development programme GEOTECHNOLOGIEN, grant 03G0637A. This is publication no. GEOTECH – 1202. The seismic measurements on tunnel construction sites were carried out with the logistical support of Herrenknecht AG, Hochtief Construction AG, and Züblin AG.

The authors would like to express their gratitude for the constructive remarks of the two reviewers which helped to improve the paper.

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