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Seismic investigations of the Piora Basin using S-wave conversions at the tunnel face of the Piora adit (Gotthard Base Tunnel)

Stefan Lüth, Rüdiger Giese, Peter Otto, Kay Krüger, Sylvio Mielitz ^a

Thomas Bohlen ^b Thomas Dickmann ^c

^a*GeoForschungsZentrum Potsdam, Department 5, Telegrafenberg, 14473 Potsdam,
Germany*

Tel: ++493312881558, Fax: ++493312881502, Email: slueth@gfz-potsdam.de

^b*Technische Universität Bergakademie Freiberg, Institut für Geophysik,
Gustav-Zeuner-Str. 12, 09599 Freiberg, Germany*

^c*Amberg Technologies AG, Trockenloostr. 21, 8105 Regensdorf-Watt, Switzerland*

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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 True Reflection Tomography [1] or migration [2]. True Reflection Tomography is a seismic imaging method which creates a 3-D velocity tomogram of the ground conditions ahead of the tunnel excavation based on reflected waves. Migration is a seismic imaging method which is commonly used in the hydrocarbon exploration industry [3]. Using a model of the propagation velocity of compressional waves, the measured time series of seismic reflections are converted to spatial images of geological structures.

For tunnelling in unconsolidated rock masses, SSP (Sonic Softground Probing) was developed [2]. This system employs a high frequency P-wave vibrator as a seismic source and accelerometers as seismic receivers. Both are integrated in the cutterhead of a tunnel boring machine (TBM). In solid rock masses, the TSP system (Tunnel Seismic Prediction) is applied [4]. TSP uses up to 30 boreholes with explosive charges as seismic sources and between two and four three-component accelerometers as seismic receivers. Reflections from ahead of the tunnel face are identified in the recordings by their traveltimes and their intersection with the tunnel axis is derived from depth migration images.

At the GeoForschungsZentrum (GFZ) Potsdam, the Integrated Seismic Imaging System (ISIS) has been developed and used mainly for tomographic in-

vestigations of the tunnel surroundings [5,6], and it has also proven to be appropriate for reflection seismic investigations [7]. This system uses a pneumatic hammer or a magnetostrictive vibrator as a seismic source and three-component geophones at the tips of anchor rods as receivers [8].

When seismic waves are generated at the tunnel wall, most of the energy is converted into waves propagating along the tunnel wall. Numerical simulations of a tunnel seismic experiment using the method of finite-difference modelling [9] showed that only little P-wave energy is generated and most of it is directed sideways to the tunnel. P-waves are therefore of limited use for looking ahead when they are not generated at the tunnel face or away from the tunnel wall. Generated S-waves propagate mainly parallel to the tunnel axis, whereas a tunnel surface wave travels along and around the tunnel and shows much higher amplitudes and less amplitude decay with increasing offsets [9]. This wave shows the highest amplitudes near the tunnel wall with amplitudes decreasing with increasing radial distance from the tunnel wall. In Figure 1, the most important wave types are shown which are observed in a typical tunnel seismic survey. The tunnel surface wave (T) is the most prominent phase. It is reflected at the tunnel face (TT). A circulating tunnel surface wave and its reflection can be observed as well (CT). TSST, finally, marks a reflection from a discontinuity ahead of the tunnel. Its wave path consists of a tunnel surface wave from the source to the tunnel face, a shear wave from the tunnel face to the discontinuity, its reflection back to the tunnel face and a tunnel surface wave from the tunnel face back along the receiver line.

The observations made from finite-difference modelling are confirmed by measurements in the Faido and Piora adits (Gotthard Base Tunnel) [8,5]. In the following sections we describe the results of two different tunnel seismic sur-

veys in the Piora adit (Gotthard Base Tunnel, Switzerland). We begin with some general observations from a tomographic survey in the middle of the Piora adit (ca. 2500 m behind the tunnel face). These general observations motivated further measurements at the tunnel face of the Piora adit which are then described and discussed in the subsequent sections.

Fig. 1. Top: Model of a tunnel face approaching a fault zone (top view). A seismic survey was simulated using finite difference modelling on the left side wall of the tunnel. A seismic source and 20 receivers are located at the tunnel wall. Bottom: Modelled shot-gather (component normal to the tunnel wall). The phases indicated are: T - direct tunnel wall wave, TT - tunnel wall wave reflection at the tunnel face, CT - circulating tunnel wall wave, TSST - tunnel-S-S-tunnel reflection from the fault zone ahead.

2 Tunnel seismic measurements in the Piora adit

2.1 *The Piora adit*

The Piora adit was excavated from 1993 to 1996 in order to explore the Piora Basin near the roadway of the Gotthard Base Tunnel. The excavation was carried out using a TBM with a tunnel diameter of 5 m. The purpose of the Piora adit was to investigate the properties of the Piora Basin rocks which separate the Penninic Gneiss Zone in the South from the Gotthard Massif in the North (Figure 2). Whereas the rocks of the Penninic Gneiss Zone and the Gotthard Massif are of good quality, the Piora Basin consists of relatively stable carbonatic sulfatic sedimentary rocks, interspersed with unstable pockets of sugar-like Dolomites [10]. At the tunnel face of the Piora adit, two exploratory wells were drilled, along which geological profiles were derived (Figure 3). The geological units are indicated by their respective RQD-values derived from the cores of the exploratory wells. As the RQD-value indicates the proportion of core fragments longer than 10 cm per meter of cores [11], it can be used as an indication of particularly unstable rock masses. According to these RQD-profiles, between the Piora Basin and the Penninic Gneiss Zone a Kakiritic layer (cohesionless cataclasites) is located which is of extremely low mechanical stability. The thickness of the Kakiritic layer is approximately 18 m and its distance from the tunnel face of the Piora adit is ca. 40 m.

Fig. 2. Sketch of the geological cross-section along the Gotthard Base Tunnel (GBT). The location of the piora adit is indicated by a white rectangle South of the Piora Basin (dark grey area).

Fig. 3. Schematic RQD-profiles along the exploratory wells Bo1.2 and Bo1.3, modified after [10]. The RQD (Rock Quality Designation [11]) values indicate the mechanical stability of the drilled cores. Higher RQD values indicate a higher proportion of undisturbed core which usually indicates higher rock quality. GM: Gotthard Massif. The drilling of Bo1.2 was stopped at 202.5 m, Bo1.3 was drilled 288.75 m and reached the Northern end of the Piora Basin (the Gotthard Massif) at 285.5 m.

2.2 Observations from a tomographic survey

A tomographic seismic survey was carried out along the tunnel wall of the Pi-ora adit with 16 three-component receivers and 147 source points [5]. A pneumatic impact hammer was used as a seismic source, and 15 three-component receivers were fixed in 2m deep boreholes on one side of the tunnel, one receiver was fixed on the opposite side of the tunnel. The source points were on the tunnel wall, on the same side as where the 15 seismic receivers were installed. A sketch of the survey is shown in Figure 4a. Data examples from both sides of the tunnel wall are shown in Figures 4b and c. The peak-to-peak amplitudes of the direct compressional wave and of the tunnel wall wave recorded by the first receiver (at tunnel meter 2888) are plotted in Figure 5. The P-wave shows an offset-dependent amplitude decay which can be described approximately using a function proportional to $1/r$ (r is the source-receiver distance) and including attenuation ($Q = 10$), whereas the tunnel surface wave decays with ca. $Q = 10$ and no contribution of spherical divergence in the far field. The relatively strong attenuation is attributed to fracturing in the excavation disturbance zone around the tunnel and resulting scattering on these fractures. Low Q -values were observed also in borehole-to-tunnel seismic experiments at the Swiss *Grimsel Test Site*, where unweathered granitic rocks with brittle fractures showed Q -values for the P-wave of 20 to 60 even at larger distance from the tunnel [12].

In Figure 4b and c, seismograms from the tomographic measurements are shown indicating the polarity of the tunnel wall wave. The receiver on the same side of the source point line shows the same polarity (black amplitudes, indicating particle velocity to the right hand side when looking in tunnelling

direction) than does the receiver on the opposite side (white amplitudes, indicating particle velocity to the right as well). This implies that the hammer impacts on the tunnel wall generate a tunnel surface wave with a polarity independent on the azimuth along the tunnel. Thus, we can describe the tunnel surface wave as similar to a meandering motion of the tunnel wall and the surrounding rock mass.

Figure 6 shows data from the Piora adit with clear onsets of the direct body S-wave and of the tunnel surface wave. The S-wave propagates with approximately 3100m/s and the tunnel surface wave propagates with approximately 2900m/s . This velocity relation corresponds to the relation of shear and Rayleigh waves on the free surface of a homogeneous half space [13].

To summarize, hammer impacts on the side wall of a tunnel mainly stimulate tunnel surface waves travelling along the tunnel. They are characterized by the greatest amplitudes near the source points and considerably less amplitude decay along their wave path than are body waves. Considering these properties, together with the observation of tunnel surface waves converting to shear waves at the tunnel face in FD modelling, the measurements at the tunnel face of the Piora adit were designed. These are described in the following chapter.

2.3 Exploration ahead of the tunnel

A seismic survey was carried out at the tunnel face of the Piora adit in March 2005 by the GFZ Potsdam and Amberg Technologies AG. The seismic equipment of the Integrated Seismic Imaging System (ISIS) was used for the mea-

surements. The seismic source is a pneumatic hammer, fixed on a small excavator. Two three-component geophones, fixed at the tips of rock anchor rods were used as receivers. The survey design is sketched in Figure 7. The receivers, located ca. 70 m behind the tunnel face, recorded the seismic signals from 76 source points which were distributed on the left and right tunnel walls and on the tunnel face. The average source point interval was 1.5 m along the tunnel wall and 0.5 m at the tunnel face. At each source point, the hammer was triggered 16 times, and the 16 recordings were vertically stacked in order to reduce incoherent noise with respect to the seismic signal. The record length was $576ms$, with $0.125ms$ sampling interval. The Summit Compact (DMT GmbH, Essen, Germany) was used as recording unit.

The measured data are plotted in Figures 8 and 9. In Figure 8, only bandpass filter (200-400 Hz) and amplitude gain were applied in order to show the relation between signal and noise. In Figure 9, an additional median filtering procedure was applied in order to suppress onsets of unwanted phases, such as the compresional, shear and the direct tunnel wall wave. The following phases can be identified in Figure 8:

- (1) The direct tunnel surface wave (T).
- (2) The reflected tunnel surface wave from the tunnel face (TT).
- (3) Tunnel-S-S-Tunnel reflections from ahead of the tunnel (later onsets parallel to TT, (TSST)).
- (4) Tunnel surface wave reflections from faults at lower tunnel meters (later onsets parallel to T).

In Figure 9, particularly the direct tunnel wall wave is almost completely removed. The seismograms are now dominated by reflected tunnel wall waves

which are characterized by decreasing traveltimes with increasing offsets. The strongest signals are the surface wave reflections from the tunnel face at 30 to 60 ms traveltime. Later onsets, starting at 70 ms traveltime at source point 76, are TSST reflections from ahead of the tunnel.

In order to investigate the correlation between these reflections with the known geology ahead of the Piora adit, we need to project the seismograms from the time-domain into the depth domain. We do that by using a procedure which is similar to Kirchhoff Prestack Depth Migration [3]. Due to the wave type which is considered here (tunnel surface wave along the tunnel wall, S-wave ahead of the tunnel face), we need a velocity model of the tunnel wall wave velocity along the tunnel and of the S-wave velocity ahead of the tunnel face. The tunnel face is the secondary source of the S-waves, the reflections of which we aim to image in space. Usually, the velocity model for migration can be derived by a focussing analysis. In our case, this is not possible, as the tunnel face did not move during the measurements, resulting in an identical S-wave path for all hammer impact points. The tunnel wall wave velocity, however can be determined with high accuracy by evaluating the direct tunnel wall wave onsets (T in Figure 8). According to our observations, the propagation velocity of the tunnel wall wave (V_t) is slightly lower than the S-wave velocity (V_s), which gives the tunnel wall wave a property comparable to a Rayleigh wave travelling on a free surface. We therefore assume a V_t/V_s ratio similar to the V_r/V_s ratio.

We use a constant tunnel wall wave velocity $V_t = V_r = 2900\text{m/s}$ and estimate the shear wave velocity to be $V_s = 3100\text{m/s}$, using the relationship between Rayleigh-wave velocity and S-wave velocity for a normal Poisson's ratio ($\sigma = 0.25$): $V_r/V_s = 0.92$ [13]. The resulting migrated sections are shown

in Figure 10 for only one receiver and in Figure 11 for all receivers and source points. A comparison of the receiver gather to the migrated section in Figure 10 shows that the summation of amplitudes along the traveltime curves of TSST reflections results in quasi circular reflection images due to the fixed secondary S-wave source at the tunnel face. However, the reflection image shows a good correlation with the known geological boundaries. By a migration of the data from both sides of the tunnel (Figure 11), the reflection image is better focused ahead of the Piora adit. The migrated images (Figures 10 and 11) show clear reflectors correlating with the boundary Lucomagno Gneiss - Kakirite and Kakirite - Piora Basin. Further reflections can be attributed to the transition from a concrete seal near the tunnel face to the Lucomagno Gneiss. The following events can be identified in the migrated section of all data (Figure 11): 1 - transition from concrete seal to Lucomagno Gneiss (the previous tunnel face of the Piora adit); 2 - internal reflections from the Lucomagno Gneiss; 3 - transition from the Lucomagno Gneiss to Kakirite layer; 4 - the southern boundary of the Piora Basin.

3 Discussion

Finite difference modelling and field observations have shown that, when seismic waves are generated at or very close to a tunnel wall, most of their energy propagates in a wave travelling along the tunnel, which we may call tunnel wall (or surface) wave. At the tunnel face, part of the tunnel surface waves converts to body waves which are emitted by the tunnel face. Modelling and field measurements have shown that reflections of these body waves partly return to the tunnel face and their reconversions can be used for imaging structures

ahead of the tunnel.

A qualitative estimation of the contrast of mechanical properties at the locations of the reflectors can be made using the polarity of the migrated section of a single receiver gather (Figure 10). The layer boundary between the Lucomagno Gneiss and the Kakiritic layer is characterised by a strong reduction of the RQD value from the Gneiss towards the Kakiritic Layer (see also Figure 3). The polarity of the reflection correlating with this layer boundary is negative (blue) in the migrated section indicating a negative impedance contrast. The impedance is defined as the product of P- or S-wave velocity and density. A negative impedance contrast is thus connected with a reduction of the body wave velocity and/or density and can generally be regarded as an indication of decreasing rock mass quality at the respective layer boundary. The polarity of the reflection image of the transition from the Kakiritic layer to the Piora basin rock mass is positive (red), indicating an increasing impedance from the Kakiritic layer to the Piora basin rock mass.

The imaging of structures ahead of a tunnel excavation is an important prerequisite for prediction ahead of the tunnel. The image alone, however, is not sufficient, as it does not allow the tunneling personnel to derive relevant technical parameters (e.g., rock quality, joint frequency, water content, etc.). Imaging structures ahead of an excavation site can be useful when the general geological structure is already known, but the exact location of, e.g., a fault zone is still unknown. It can also be used as an indication of the presence of heterogeneities which are then to be further investigated by explorational drilling.

For a quantification of tunneling relevant parameters based on the seismic

measurements future research should be directed towards

- understanding the amplitudes generated by the conversion of tunnel wall waves to shear waves at the tunnel face, and
- the correlation of seismic reflection images and geotechnical parameters which are relevant for the excavation.

4 Conclusions

The study presented here shows an application of the concept of seismic exploration ahead of a tunnel using converted tunnel wall waves. Tunnel wall waves are generated at the lateral tunnel wall behind the tunnel face. A part of these reaches the tunnel face where it partially converts to S-waves travelling in tunnelling direction. Reflections of these S-waves return to the tunnel face where they re-convert to tunnel wall waves (TSST reflections). Using an imaging technique derived from the classical Kirchhoff Prestack Depth Migration, it is possible to image reflectors ahead of the tunnel.

The technique was applied at the tunnel face of the Piora adit (Gotthard Base Tunnel construction site), which is located ca. 50m south of the southern boundary of the Piora Basin. Processing and imaging of the seismic data acquired at the Piora adit tunnel face revealed strong onsets which can be attributed to TSST reflections from the transition between the Lucomagno Gneiss and the Piora Basin. The reflection image correlates well with the geology, known from two exploratory wells drilled from the tunnel face of the Piora adit.

As the seismic measurements were carried out with a fixed tunnel face, being

the secondary source of S-waves propagating in tunnelling direction, a spatial ambiguity of the reflectors' location remains which can only be resolved by an increased aperture. This can be achieved by measuring with a moving tunnel face and with sources and receivers located at at least three different azimuthal positions on the tunnel wall. Thus, the method presented here is particularly useful when continuously applied in an active tunnel excavation.

From an operational point of view, no additional work is necessary directly at the tunnel face, as sources and receivers are located several meters behind it. Integrating these measurements into tunnelling is therefore possible without interfering the excavation process.

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Fig. 4. a): Source and receiver geometry of seismic tomography measurements in the middle of the Piora adit (top view). The 147 source points are indicated by a thick black line, the receivers are indicated by grey triangles. Receiver 16 is located on the opposite side of the source points. b): Receiver gather of receiver 8 (Z component normal to the tunnel wall) with tunnel wall waves labeled. c): Receiver gather of receiver 16 (Z component normal to the tunnel wall). The inset shows the polarity of the receivers and of the tunnel wall wave. The receivers are installed with negative (black) Z-amplitudes directed away from the tunnel wall. The tunnel surface wave at receiver 16 (located opposite to the source point) has a polarity towards the tunnel wall.

Fig. 5. Scaled peak-to-peak amplitudes of the P-wave and the tunnel wall wave observed in seismic measurements in the Piora adit (Gotthard Base Tunnel) [5]. The scaled tunnel wall wave amplitudes are indicated by a black solid line, the scaled P-wave amplitudes are indicated by a grey solid line. Dotted and dashed lines indicate theoretical amplitude functions for an amplitude decay due to attenuation ($Q = 10$, $\lambda = 16m$) (1) and due to spherical divergence and attenuation (with $1/r$, $Q = 10$, $\lambda = 16m$) (2), respectively. Q indicates the attenuation coefficient, λ is the wavelength of the considered wave type.

Fig. 6. Seismic data from the Piora adit showing P-, S-, and tunnel wall wave onsets. The data are the normal component (with respect to the tunnel wall). A reduction velocity $V_{red} = 2900\text{m/s}$ was applied, thus showing tunnel wall wave onsets horizontally. Solid black lines indicate the direct P-, S-, and tunnel wall waves, respectively.

Fig. 7. Top view of the seismic survey at the tunnel face of the Piora adit. The receivers are indicated by grey triangles. Black diamonds indicate the source points. Receiver 1 is on the right tunnel wall (in tunnelling direction), receiver 2 is on the left tunnel wall. The source points 37 through 41 are at the tunnel face.

Fig. 8. Receiver gathers of the seismic data. The normal component relative to the tunnel wall is shown. Processing of the data: Bandpass filter (200-400 Hz), amplitude gain with t^2 , trace normalization. The following phases are indicated: T - direct tunnel wall wave; TT - tunnel wall wave reflection at the tunnel face; TSST - Tunnel-S-S-Tunnel reflection from the Piora basin.

Fig. 9. Receiver gathers of the seismic data after removal of direct P-, S-, and tunnel wall waves. Processing of the data: Recursive median filter to remove direct waves, bandpass filter (200-400 Hz), amplitude gain with t^2 , trace normalization.

Fig. 10. Receiver gather (bottom) and selected TSST migration of receiver 1 (right tunnel wall) and source points 42-76 (top). The geological profile is indicated along the exploratory well Bo1.2. Red: 8 m concrete seal at the tunnel face, yellow: Lucomagno Gneiss, pink: Kakiritic layer, green and pink: Piora Basin. Black arrows show the correlation of the migrated image with the RSSR onsets in the receiver gather.

Fig. 11. Migrated section of all data and geological (RQD) profile. Four distinct events can be identified in the migrated section (for a description see text).