The Application of TRT – True Reflection Tomography – at the Unterwald Tunnel

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The geological and geotechnical prediction of the rock mass conditions is of utmost importance in tunnelling. The design, tender, and construction methods are based on the predicted rock mass model. An incorrect or inadequate geological model can generate significant delays and cost overruns. During construction it is necessary to update the geologic model with the increase in geological and geotechnical information as the excavation progresses. This information is then used to predict the forthcoming rock mass conditions. Recently a new seismic imaging technique called True Reflection Tomography (TRT) was developed to image changes in rock mass conditions ahead of the tunnel excavation. This method provides a "picture" of the rock mass conditions up to 150 m ahead of the tunnel excavation.

The TRT method was applied on a systematic basis at the tunnel Unterwald to determine if and where changes in the rock mass conditions will intersect the tunnel. A total of ten surveys were performed over the 1 029 m tunnel length to be excavated. There were several expected changes in the rock mass conditions that were identified during the site investigation, however there was some uncertainty to the exact locations of these changes. To reduce the potential impact of these features, TRT was used to attempt to refine these locations, as well as identify unexpected anomalies during the excavation.

This paper describes the basic survey configuration and its impact to the excavation sequence, the results that were obtained and the correlation to the encountered rock mass conditions, difficulties associated with interpreting the results, and recommendations for improving the amount of information gained during a survey.

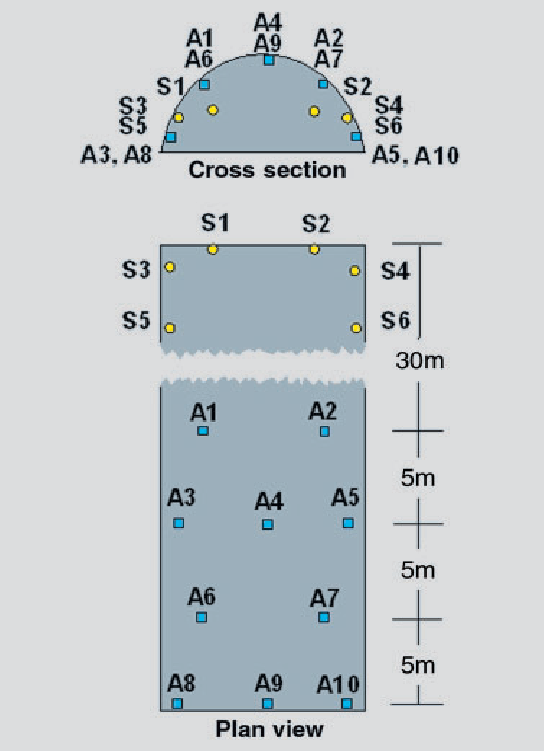

Fig. 1 Typical layout of source (yellow) and accelerometers (blue) configuration for a TRT-survey in the Unterwald tunnel.

Bild 1 *Standardmeßanordnung der Seismikquellen (gelb) und Sensoren (blau) für eine TRT-Meßreihe im Tunnel Unterwald.*

Applying true reflection tomography

TRT was developed by NSA engineering of Golden Colorado (1,2,3,4) to image changes in the rock mass conditions ahead of advancing underground excavations. The software develops a 3D tomogram of velocity contrasts (similar to a CAT scan in medicine) within the rock mass from reflected seismic signals that are recorded with a 3D array of accelerometers. These anomalies are then correlated to different potential geologic features depending of the recorded wave form.

Anwendung der „True Reflection Tomography" beim Unterwald-Tunnel

Eine korrekte Vorhersage der Gebirgsverhältnisse ist im Tunnelbau von außerordentlicher Bedeutung. Es ist notwendig, auch während des Vortriebs das geologisch-geotechnische Gebirgsmodell durch zusätzliche Erkenntnisse anzupassen. NSA-Engineering hat mit der „True Reflection Tomography" (TRT) eine neue seismische Untersuchungsmethode entwickelt, die es ermöglicht, während eines Tunnelvortriebs – ohne diesen wesentlich zu behindern – die Gebirgsverhältnisse bis zu 150 m vor der Tunnelortsbrust zu erkunden. Diese neue Methode wurde beim Vortrieb des Tunnels Unterwald angewandt und wird an zwei ausgewählten Beispielen erläutert.

This paper discusses the application of True Reflection Tomography (TRT) seismic imaging at the Unterwald tunnel for imaging changes in the rock mass conditions ahead of the tunnel excavation. TRT is a seismic processing technique developed by NSA Engineering of Golden Colorado to create a 3D velocity tomogram of the ground conditions ahead of the tunnel excavation. The survey set up and procedures are discussed in reference to their effect on the excavation schedule. Two examples are used to discuss results and the applicability of this method.

Figure 1 depicts a typical survey setup, accelerometers were placed in four rows beginning approximately 30 m behind the tunnel face. Two different accelerometer configurations were used, two rows consisted of three accelerometers located at the crown and each side wall, while the other two rows consisted of accelerometers at each springline. Four to six source locations are used, typically two at the tunnel face and two on each side wall close to the face separated by several metres. The data acquisition hardware is setup in the back of a vehicle 45 to 60 m from the tunnel face.

The preferred seismic source during drill and blast tunnelling is a sledge hammer which creates both directional shear and compression waves, compared to blasting which results in only compressional waves which radiate in all directions from the source. A problem with using a hammer as a source is that if the material is too soft then the energy is dissipated as plastic deformation of the rock mass and the seismic energy in minimal this is also the case if the shotcrete is not sufficiently cured. In the latter case, the source locations must be slightly farther from the face where the shotcrete is more competent.

The equipment setup and surveying are done prior to the survey without interrupting the excavation cycle. Before the survey, typically during a drilling cycle, the mounting blocks for the accelerometers are installed, the wires are laid out, and the source locations and mounting blocks are surveyed. Immediately before the survey the accelerometers are installed and tested to ensure that they function and that the all connections are good. The excavation works must stop during the survey which consists of four to six source locations, typically ten recordings are made for each source location allowing the data to be stacked to better identify true reflections. The data acquisition lasts for approximately 15 min after which the construction activities can resume while the survey equipment is removed. Processing typically takes 24 hrs. for the first results and typically additional processing is necessary to acquire as much information as possible.

Project background

Tunnel Unterwald is a double track railway tunnel with a length of 1 076 m and a standard cross section of 100 m². The excavation was carried out according to the NATM with round lengths between 1 and 2.2 m. The tunnel was parallel to the hill slope with an overburden up to 90 m. It is located in central Austria and is part of the railroad section Schoberpass, which has the lowest elevation crossing of the Alps (840 m). This railway line from Amstetten to Tarvisio (Italy), connecting Northern and Southern Austria, is a very important transit route and is currently being upgraded to a high-capacity railway.

A field reconnaissance investigation was performed in 1994 and 1995 followed by a detailed site investigation programme. Subsurface investigations were performed from 1994 to 1996. Twenty six cored vertical, inclined, and horizontal boreholes with a total length of 1 600 m were

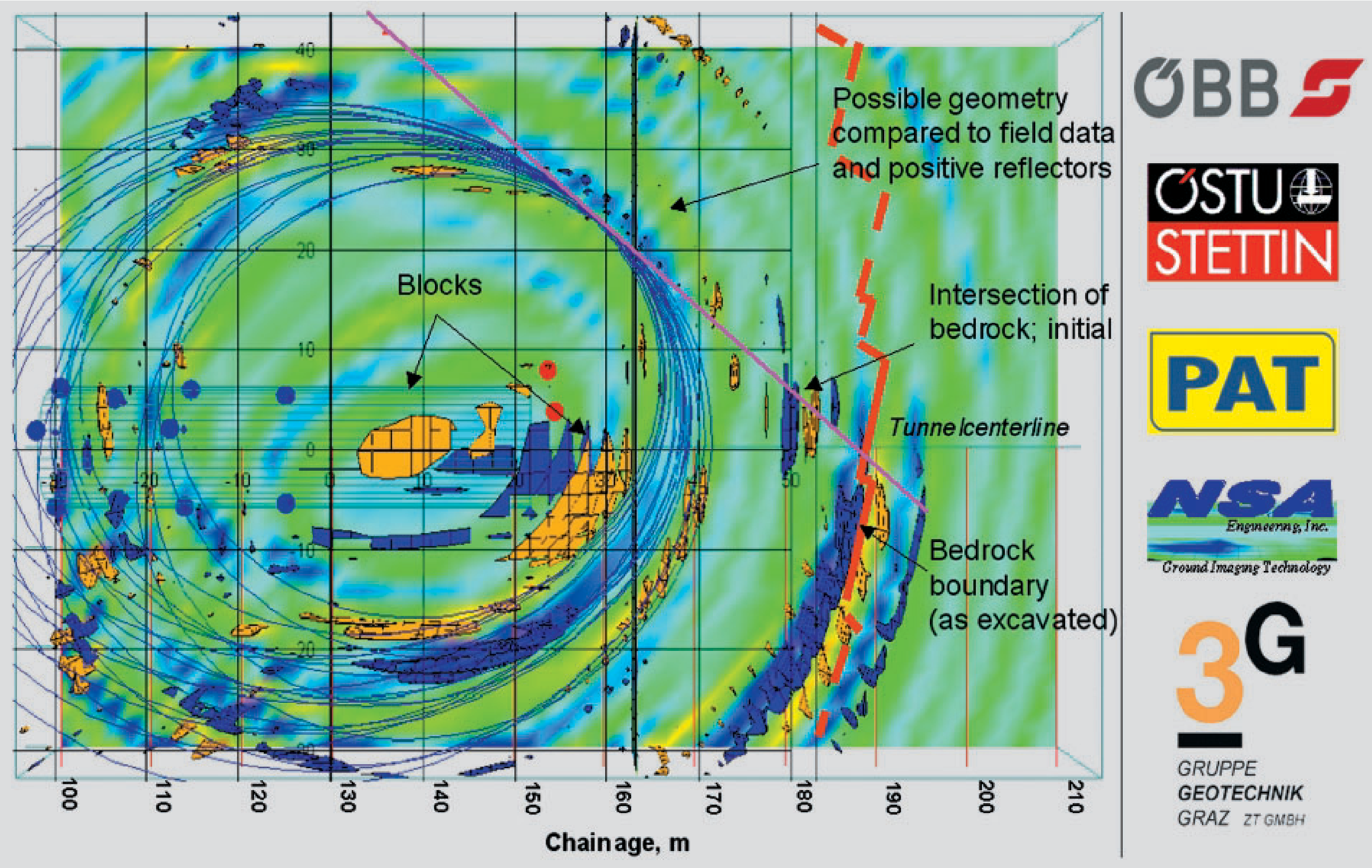

Fig. 2 Plan view of horizontal TRT tomogram at elevation of top heading invert, and contour anomalies for survey no. 2 in the Unterwald tunnel using blasting on June 6th, 2001 with contour line of bedrock contact (as excavated).

Bild 2 *Messung Nr. 2 (Ergebnis der Sprengseismik am 6. Juni 2001): TRT-Tomogramm der seismischen Anomalien (Horizontalschnitt in Kalottensohleniveau) mit dem tatsächlichen Verlauf der Grundgebirgsgrenze (rote Linie).*

drilled. In situ- and laboratory tests were carried out in order to gain reliable rock and soil parameters. To supplement the subsurface exploration geophysical investigations including refraction seismic, electrical resistivity, electromagnetic surveys were performed.

Geology

The project area is situated within the Rannach Series, a metamorphic rock unit of Permo-mesozoic age characterized by highly anisotropic rocks with a varying quartz content. The rock mass primarily consists of foliated quartzite and quartz-phyllite with occasional intercalations of sericitic phyllite, chloritic phyllite and carbonaceous phyllite. The foliation strikes parallel to the tunnel and dips on average 25° to 35°, which is parallel to the hill-slope. The micaeous content is crenulated and larger scale folding of the foliation occurs with a similar fold axis as the crenulation, parallel to the foliation strike. Occasionally foliation parallel shear zones were encountered. Two dominant joint sets were encountered striking approximately perpendicular to the tunnel axis and dipping steeply either into or away from the tunnel face. A few minor faults were encountered which were parallel to the dominate joint sets.

The portal areas are located within young sediments consisting of glacial-fluvial gravel and debris with large boulders in the East and landslide debris consisting of boulders and large rock slabs separated by silty-gravelly shears in the West.

TRT imaging results

Imaging the soil-bedrock interface

During the initial site investigation the first 170 to 200 m of the excavation were predicted to be in slope debris consisting of a dense blocky soil and the exact boundary to the competent bedrock was not specifically located. In order to appropriately plan the excavation methods and to have the appropriate support stocks on site knowing this boundary precisely would save considerable costs.

This was the first time that the TRT method was applied in soft extremely heterogeneous ground conditions with weak seismic contrasts and in highly anisotropic material. The first application of the TRT method in alpine tunnels was made at Blisadona Tunnel in 1999 (5). Therefore, an initial survey was performed in order to test the method in this specific type of soil mass to identify and correct any problems. It was determined that the maximum reliable imaging distance was between 60 and 70 m (compared to 100 to 150 m expected in hard crystalline rock) due to the high attenuation associated with the blocky material and the soft matrix.

Fig. 3 Large boulder of quartz-phyllite encountered at station 161 m.

Bild 3 *Großer Quarzphyllitblock aufgefahren bei Station 161 m.*

The second survey was planned so that the imaged distance would include the initially predicted region for the bedrock contact. The survey was performed when the tunnel excavation was at tunnel station 152 m, resulting in an image to approximately station 210 to 220 m.

Initially, a dual velocity model was used with a high velocity bedrock below the tunnel but the data was inconclusive. Figure 2 shows the tomogram developed from the second processing using a uniform velocity model corresponding to the properties of the colluvium. The results identified a large boulder approximately 5 m ahead of the tunnel face. Figure 3 shows a photo taken of the tunnel face at station 161 m which corresponds to the image results.

The results also indicated an positive anomaly (to a higher velocity) at approximately station 190 m to the right of the tunnel axis. This anomaly was initially interpreted to be representative of the bedrock contact but was connected to the series of smaller anomalies forming a contact at an acute angle to the tunnel axis. It turned out that the smaller anomalies were individual features and the large anomaly was the bedrock contact which was orientated approximately

Fig. 4 Bedrock contact at station 191 to 192 m.

Bild 4 *Grenze Lokkergestein/Grundgebirge (Quarzphyllit) bei Tunnelmeter 191 bis 192.*

perpendicular to the tunnel axis as schematically drawn on the tomogram. Figures 4 and 5 show the encountered bedrock contact at station 191 to 192 m. The contact was formed by discontinuities of large planar wall like joints. The bedrock was slightly weathered with widely spaced (approximately 1 m) open joints striking almost perpendicular to the tunnel face and dipping steeply to the East. The joints were filled with sandy-silty material with a thickness up to 20 cm.

Imaging a fault zone and image repeatability

The seventh and eighth surveys serve as an example of the repeatability and the potential accuracy of the TRT method. The results of the seventh survey indicated a fractured zone approximately 25 m ahead of the excavation followed by relatively homogeneous ground conditions. Figure 6 shows the results of a second processing using a different attenuation model to look further ahead of the excavation. It shows an anomaly around stations 825 to 840 m, almost 150 m from the tunnel face. The initial site investigation had provided evidence that there was a probable fault zone in this region. The anomalies imaged during the seventh survey compared quite well with encountered geological conditions.

Fig. 5 Bedrock contact at station 191 to 192 m; detail of Figure 4.

Bild 5 *Grenze Lokkergestein/Grundgebirge (Quarzphyllit) bei Tunnelmeter 191 bis 192; Detail von Bild 4.*

The eighth survey was performed with the face at station 771 m, the initial velocity model did not indicate any anomalies ahead of the face. Therefore, a second velocity and attenuation model was used and several anomalies were identified from stations 785 to 835 m as shown in Figure 7. The first anomalies were described as a possible fracture zone while the anomalies from station 820 to 840 m were interpreted to be a fault zone. The encountered conditions consisted of two sets of sub-vertical discontinuities spaced between 0.5 to 1 m crossing the tunnel at an angle of 60° to 70°.

At station 820 m the tunnel entered a 8 m wide sharply defined shear-zone, steeply dipping 70° to the East and striking perpendicular tunnel face. This fault consisted of lens like anastomosing shear-bodies formed by two sets of slickensided planes. The location of this fault corresponded to the feature imaged during the seventh survey. The difference in the amount of information between the two surveys shows how different attenuation models can be used to recognize either smaller features closer to the excavation or larger features at much greater distances. The anomalies identified in this survey and their interpretations correlated very well with the encountered geological conditions as shown in the previous figures.

Discussion

As shown with the two examples above the TRT method can provide accurate predictions of changes in the rock mass conditions. It is in our opinion that more work needs to be incorporated into the reliability and use of the TRT data to appropriately predict what conditions will be encountered during the excavation and if the changing ground conditions actually effect the excavation behaviour. This also would include more information on the extrapolation of features not directly in the path of the tunnel to an appropriate position.

This was the first time that the TRT method was used in the ground conditions encountered during the first 200 m of the excavation and some initial difficulties had to be overcome. The soft and blocky nature of the soil mass resulted in a very rapid attenuation of the seismic signal considerably reducing the reliable image lengths. A second problem was delivering enough energy into the ground to compensate for the increased attenuation. Because the soil was “softer” then

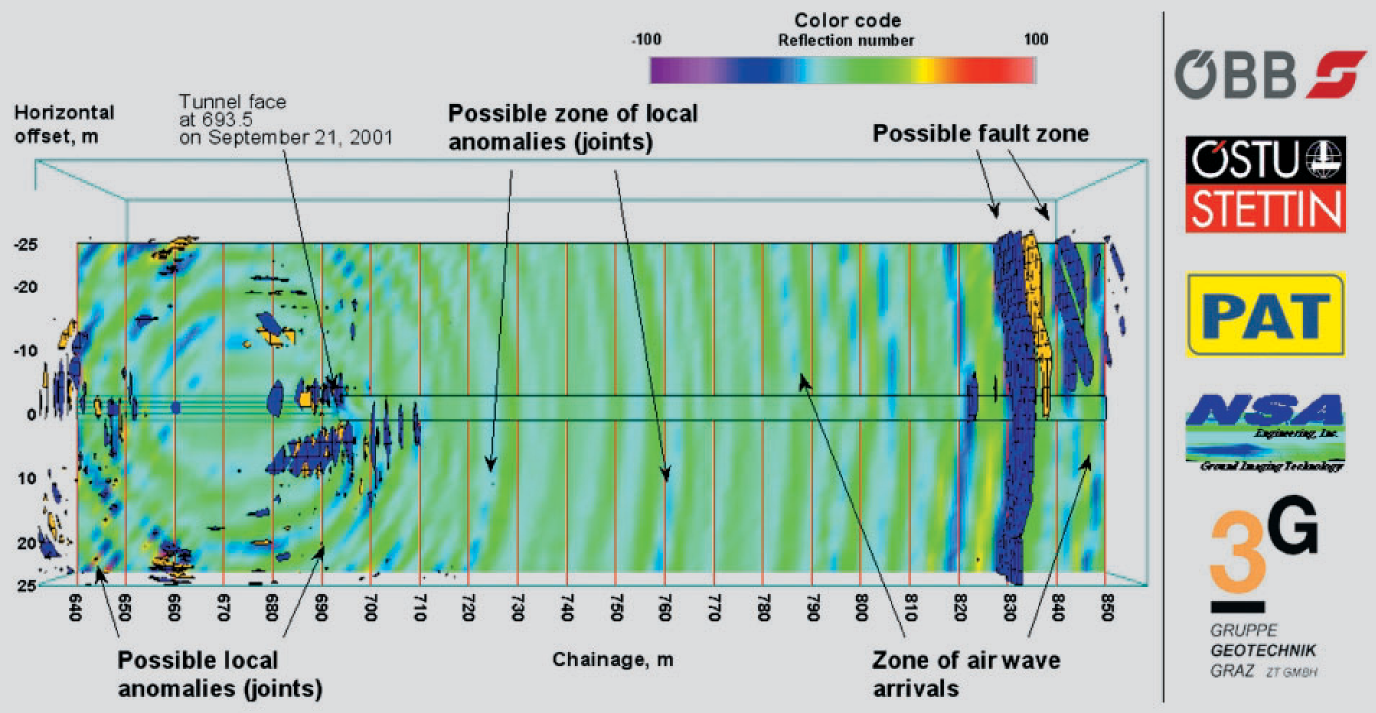

Fig. 6 Plan view of horizontal reflective tomogram at the tunnel crown elevation for TRT hammer survey no.7 (2^{nd} processing).

Bild 6 *TRT-Hammerschlagseismikmessung Nr. 7: Tomogramm des zweiten Processing der seismischen Anomalien (Horizontalschnitt im Tunnelfirsteniveau).*

the lining or the large blocks the energy delivered by the source was not efficiently transferred into the soil also resulting in decreased image lengths.

This was also the first time that the TRT method was used in an highly anisotropic material. Since the strike of the foliation was parallel with the survey direction the anisotropic nature of the material was generally avoided but may have contributed to the localized imaging of features that were quite extensive compared to the survey dimensions. The rock mass was rather homogeneous except for the portal locations. With the low overburden and relatively good rock mass conditions deformations over a majority of the tunnel were minimal and did not change significantly in the predicted zones of weaker material. Instead the fault zones contributed to increased overbreak and occasionally to increased

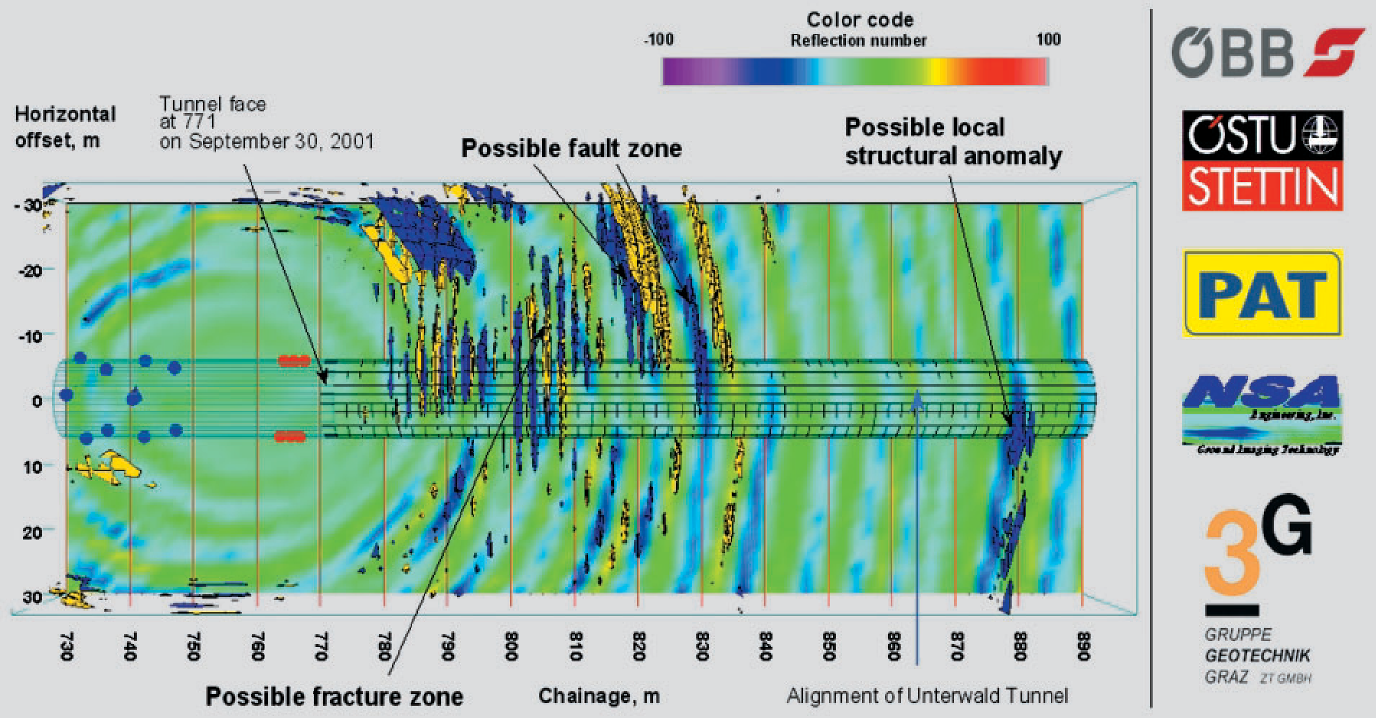

Fig. 7 Plan view of horizontal reflective tomogram at the tunnel top heading elevation for TRT hammer survey no.8 (2^{nd} processing).

Bild 7 *TRT-Hammerschlagseismikmessung Nr. 8: Tomogramm des zweiten Processing der seismischen Anomalien (Horizontalschnitt im Kalottensohleniveau).*

water flow. The gradual increase in fracture density that proceeded the fault zones generally contributed to the smoothing of the reflection data making features less pronounced.

The TRT method provides a tool that can be used to image changes in the rock mass conditions typically directly ahead of the excavation. One of the difficulties that was encountered during this project, and is not a unique problem, was that many times the optimum reflection point of a given geological feature is not directly ahead of the excavation. For example, if a fault zone is crossing the tunnel axis at a acute angle of 30° then the reflection is going to appear to the side of the tunnel, and depending on the dip either above or below the tunnel level. Dipping reflectors perpendicular to the tunnel axis also produce reflectors that are not in the immediate vicinity of the tunnel but at some point above or below the tunnel axis. Determining the orientation, continuity and size of a given reflector is not as accurate as the location this makes the extrapolation of the anomaly to the tunnel axis somewhat difficult and should be the focus of further research.

Conclusions

The True Reflection Tomography seismic imaging method was used at the Unterwald tunnel on a systematic basis to identify potential weakness zones intersecting the tunnel axis. Generally, the data was processed several times to clarify the results and uncertainties in the data interpretations. As with any seismic method, one must use all of the available information to interpret the results. Sometimes this philosophy can be misleading if too much is read into the data from pre-existing models as demonstrated with the example showing the bedrock contact. When integrating this method into the tunnel construction the reliability of the data should be quantified so the engineer can feel confident with the interpretation of the results. This requires communication and cooperation between the data processors, the geologists, and the engineer to discuss not only the current data results, but also the past evaluations so improved forward predictions can be made for the given the site specific conditions.

Overall, the TRT method provided good results as most of the major features were imaged. However, the uncertainty in many cases was quite high and it is always easy to look after the fact to recognize what was imaged. The difficulty is the forward interpretation and the associated reliability of the interpretation. This is what is important to the engineer and the construction crew. The confirmation of the location of features that are generally, but not specifically known, is possible with this method as well as locating unexpected geological conditions, but it must be stressed that proper communication must exist between all the parties involved to delineate the strengths and weakness of the system in a given geologic environment. This is still a relatively young technology that will improve with time as more experience is gained in different ground conditions.

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