Geophysical Ahead Investigation Methods
Seismic Methods

ITAtech Activity Group
Investigation

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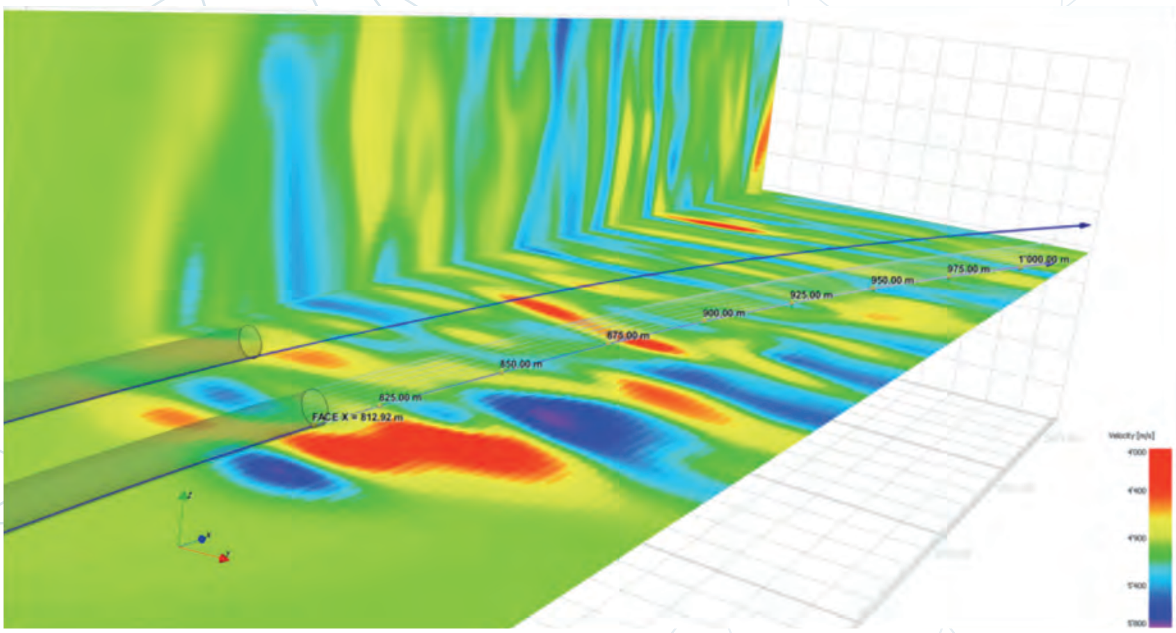

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2 >> Introduction

Using underground space more and more implies improvements to the economic feasibility of underground construction. Common practice nowadays is a geotechnical site investigation that is carried out in order to enable a geotechnical and environmental assessment of the ground conditions. Geological and hydro-geological conditions are key factors during the planning of and budgeting for a project and its subsequent viability.

There is a strategy for site investigation at various stages of a project. This phased strategy consists of investigations for feasibility studies and the preliminary and detailed design and of investigations during the construction phase. Among other purposes, these investigations are carried out to determine the 3-dimensional geotechnical and hydrogeological model during the design studies and validate using face mapping, investigations ahead of the tunnel face (e.g. probe drilling, geophysics), TBM performance data, etc. [1].

Today, machine driven tunnelling has to provide high performance, normally to justify the high initial investment costs. However, geological anomalies and risks can massively reduce tunnelling rates over weeks or months, and sometimes bring a project to a complete stop. Conventional methods, such as probe drilling, generally cover a range of 30 to 40 metres ahead of the tunnel face. They are useful but its execution can reduce the daily advance performance of a TBM because excavation must stop during these periods. In addition, exploratory drilling only provides a selective record of the ground conditions unless multidirectional probing is adopted ahead of the face creating further time delays.

From its origin in oil and mineral resources exploration, investigations ahead of the tunnel face by means of geophysical methods entered into the field of tunnelling in Europe in the early 1990s [2] followed by many applications on Japanese tunnelling sites throughout the 1990s [3] [4]. Since then, commercial systems became available on the market and the number of applications of geophysical methods increased. In addition, a systematic use of such systems began in some regions of the world (Japan and China) where intense tunnelling activities were going on. Hence, geophysical methods increasingly became an essential part of the risk management process over the last 20 years. The tunnelling industry has already identified the potential of these usually non-destructive methods that valuably contributes to the assessment of the ground conditions and to the provision of interpretative reporting.

This guideline gives an overview of existing geophysical methods and technologies ahead of the tunnel face. In its present version, it focuses on seismic methods and describes technical features and case studies of these methods. It further suggests requirements to be included in tender specifications for the described investigation systems for tunnelling projects.

Seismic reflection imaging is the most effective prediction method because of its large prediction range, high resolution and ease of application on a tunnel construction site. In particular, when using the information of the full seismic wave field propagating through the ground, seismic properties such as seismic velocities and their derived elastical parameters like Poisson’s ratio or stiffness present valuable information to characterise the ground. However, geophysics deals with more methods than just seismics. There are electro-magnetical, electrical and gravimetrical methods, which are being used more and more in tunnelling. Certainly all of them can contribute by providing further information on the ground conditions.

This guideline has been written to orientate tunnel designers, contractors and owners towards understanding the benefits and limitations of the currently available technology for seismic investigations during tunnelling that is already used and has a proven record.

3 >> Scope of duties

This guideline deals with the present version of seismic investigations ahead of the tunnel face while tunnelling. It covers options with regard to mechanized and conventional tunnelling considering available technology of seismic methods that had been systematically used on real tunnelling sites known to the members of the ITAtech Activity Group Investigation.

With reference to Figure 1 illustrating the scope of duties, mechanized tunnelling is represented by methods annotated with M1, M2 and M5. The red coloured boxes in the chart indicate that there is no geophysical method adopted for soft or mixed ground tunnelling using Earth Pressure Balance machines (M3). Furthermore, there has been no method identified that is being applied in mechanized tunnelling in soft ground, which is advance cycle integrated (M4).

In conventional tunnelling, there is one dominant method that is applied behind the tunnel face where no access to the tunnel face is necessary (C1). This method also covers the hard rock application in mechanized tunnelling that is not integrated into the TBM advance cycle (M5). Finally, there is a method being described that could be applied at the tunnel face usually related to drill and blast headings (C2).

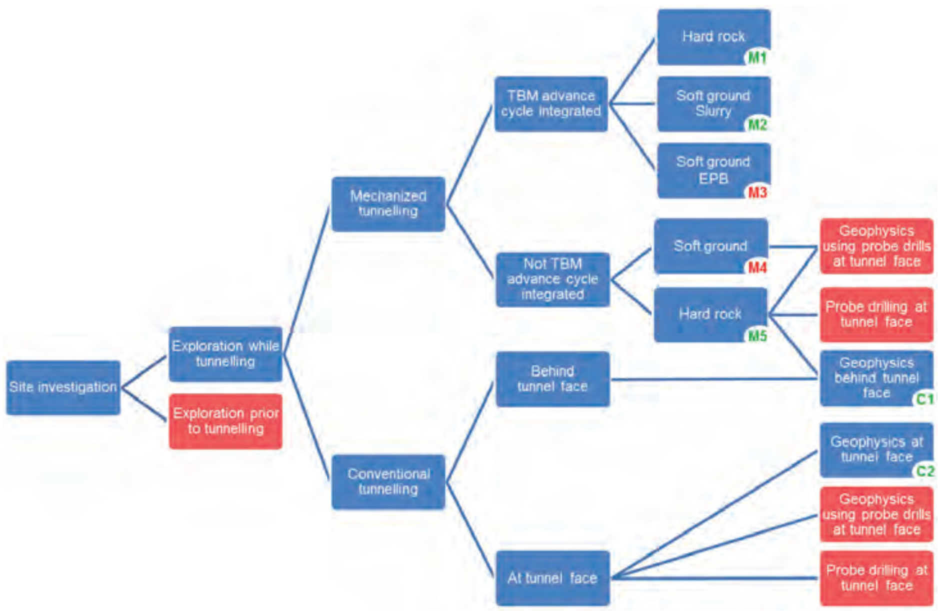

Figure 1 : Scope of duties of guidelines at hand. Note: Red boxes indicate exclusions. Methods with green annotations are described further. Methods with red annotations are not described further due to the absence of proven records.

4 >> SEISMIC METHODS DURING MECHANIZED TUNNELLING

The following chapter deals with seismic methods being applied during mechanized tunnelling. The first section describes the application of a TBM advance cycle integrated technique for tunnelling in hard rock (M1-1). The second section presents a method for mechanized hard rock tunnelling where the cutter head itself serves as a seismic source (M1-2). The third section deals with an exploration system that is applied in soft ground conditions and specialized for use on Slurry TBMs (M2).

4.1. INTEGRATED SEISMIC PREDICTION – ISP (M1-1)

4.1.1. General characteristics and principle

ISP focuses on the earliest possible detection of geological anomalies relevant to the TBM by a high prediction range of up to 120 metres in front of the tunnel face. As a result, the risk of encountering unexpected fault zones is greatly reduced. The number and length of probe holes in advance of the tunnel face is reduced as well as there is no longer need to use it as a standard in TBM tunnelling within rock masses with high geological risks. Hence, the use of probe drilling can be reduced to grouting purposes only in cases where ISP detects severe anomalies in the rock mass.

In addition, the operation of ISP is possible during normal TBM operation; meaning measurement preparation occurs while the TBM advances and measurement itself is done during ring-building and stand-by times avoiding long TBM downtimes.

4.1.2. Measurement principle – Reflection seismics

The excitation of the tunnel wall using an impact source generates both pressure and surface waves, as shown in Figure 2. R-waves (Raleigh waves) run along the tunnel wall towards the face, where conversion to an S-wave (Shear wave, transverse pressure or space wave) occurs, among other effects [5] [6]. If the S-wave encounters an obstruction in the ground, it is partially reflected.

The essential physical quantity of this occurrence is the acoustic impedance (also called the sonic resistance or wave resistance) that is the result of the product of the density of the medium through which the wave passes and its subsequent velocity through the ground. This implies that a noticeable reflection of the S-wave depends on a sufficient impedance contrast, which is usually given in strongly jointed and fractured rock (faults) or by water-filled joints or cavities.

The reflected S-wave travels back to the tunnel face as an S-wave. There, it is again partially converted into a Rayleigh wave (surface wave), which runs back along the tunnel surface where it is detected by geophones attached to the tunnel wall. This type of wave is called an RSSR-wave.

The wave travel times are measured and the data is processed according to the relevant geometry and methodology to produce a migration (i.e. a process of assigning seismic signals to the location of origin from known wave velocities and measured times) and thus an interpretation.

4.1.3. Applicability

ISP can be used in atmospheric hard rock conditions on Open Gripper TBM, Single shield TBM or Double shield TBM.

ISP can be also installed after a TBM advance already started, if the integration of the systems´ main hardware components into the TBM design is proven. For measurements a radial drilling device is required to drill the holes for the measuring anchors.

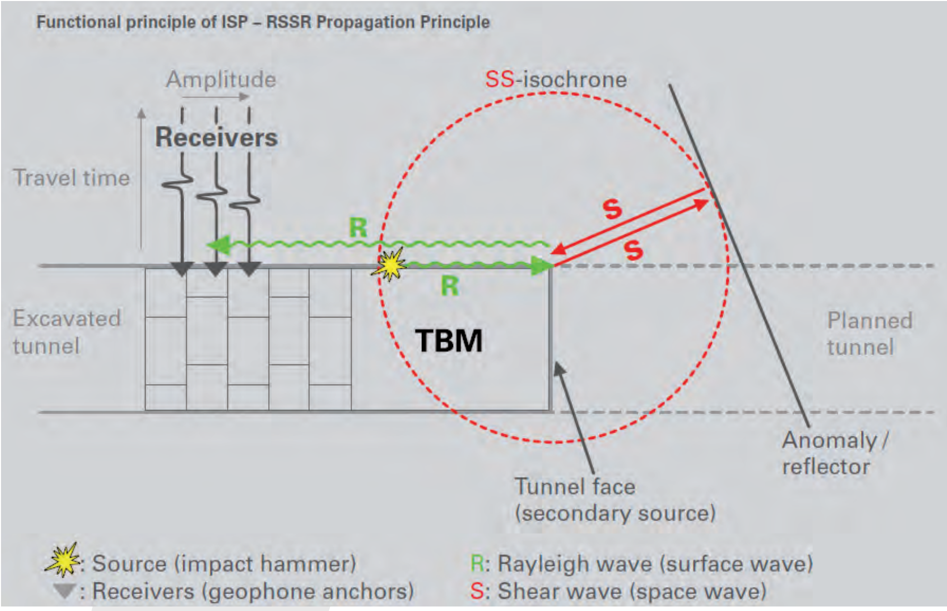

Figure 2 : Principle of the Integrated Seismic Prediction (ISP) system.

4.1.4. Operation

The assembly group of the ISP sources is mounted within the shield in the vicinity of the thrust cylinders and needs unhindered accessibility to the rock wall, meaning a hole of about 30 cm in diameter has to be available for each source within the TBM´s shield, which can be seen in Figure 3. In case of usage on Open Gripper TBMs, the ISP sources are mounted onto the left and right grippers. These two pneumatically driven impact pulse generators are used as sources to induce seismic waves into the rock mass by hitting onto the tunnel rock wall. This happens after every stroke of the TBM.

If the seismic waves are reflected at a geological anomaly, they are received by measuring anchors that are drilled and glued at about every 10 m left and right into the tunnel rock wall. In case of a shielded TBM with concrete lining segments, these segments have to be perforated through the grouting holes in order to install reusable measuring anchors into the tunnel rock wall.

Then, the acquired data is logged and sent via Wi-Fi from the data loggers to the processing unit in order to analyse the data and image and interpret the results. Data processing steps can be seen in Figure 4.

This measurement cycle (Figure 5) requires a complete standstill of the TBM, i.e. during ring building or re-gripping times, in order to avoid background noises such as those caused by a rotating cutting wheel. The main preconditions for ISP operation in TBMS are shown in Table 1.

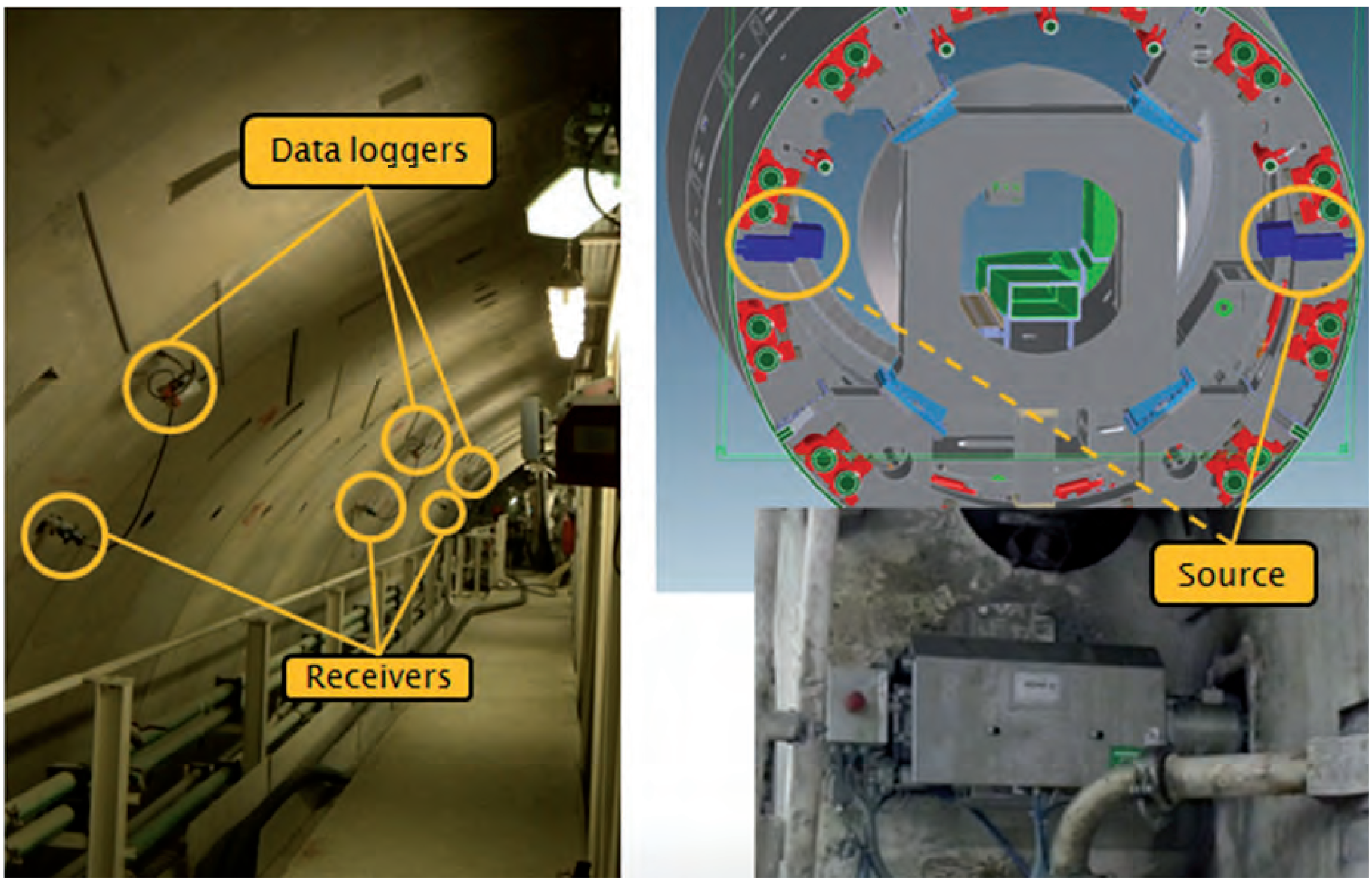

Figure 3 : Allocation of the main ISP data acquisition hardware on a Double shield TBM.

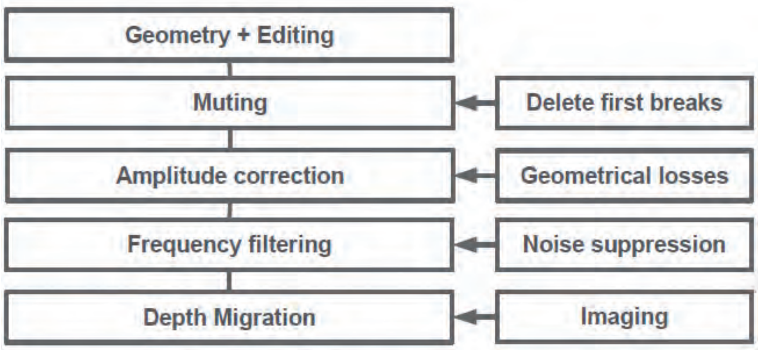

Figure 4 : Data processing.

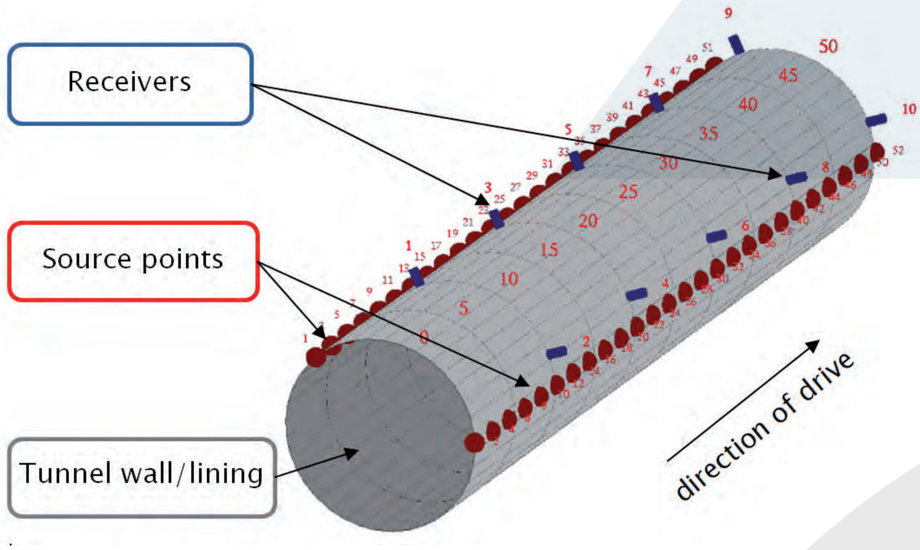

Figure 5 : Perspective view of the tunnel with the planned distribution of acquisition points via geophone measuring anchors (blue) and source points (red).

ITEM	SPECIFICATION
TBM type (only atmospheric conditions)	Shield/Double shield TBM; Open Gripper
Geology	Hard rock
Power supply	230 V
Compressed air supply	4-8 bar
Usage of Wi-Fi frequencies	2.4 GHz
Availability of TBM status and geometrical data	Reading access to TBM´s PLC
Radial drilling devices for installation of measuring anchors	1.0 to 1.6 m deep radial holes every ~10 m left and right

Table 1 : Preconditions for ISP operation.

4.1.5. Strengths and Weaknesses

STRENGTHS	WEAKNESSES
System installation possible after TBM start	Radial drilling equipment necessary
Minimal intrusive investigation method ⇒ Probe drilling in direction of drive only for verification of detected anomalies	If used on shielded TBM, perforation of concrete lining segments for installation of receivers
TBM advance cycle integrated ⇒ Avoiding downtimes for measurements	Hole (~Ø 30cm) in TBM shield structure for rock wall access of the sources neces-sary
Usable on all hard rock TBM types	Not able to predict the type of rock
1-3 days of ensured tunnelling due to high detection range	Moderate position accuracy
Continuous stroke wise measurement allow for overlapping results ⇒ Verification of detected anomalies	Only big anomalies detectable
Data acquisition possible by jobsite personnel	Data processing and interpretation not automated ⇒ to be done by qualified personnel
	~50m of data pre-flow necessary for first calibra-tion of system

Table 2 : ISP strengths and weaknesses.

ITEM	SPECIFICATION
Detection range in direction of drive	maximum 120 m (best at 20-80 m)
Detectable objects	Cavities (no distinction between water-/air filled) Weakness-/fault zones in rock mass
Resolution	> 5 m
Position accuracy	> 5 m

Table 3 : ISP capabilities.

4.1.6. Reference projects

Selected case studies are presented in this section demonstrating how ISP data can provide useful information during the tunnelling process.

4.1.6.1. Railway project Tel Aviv – Jerusalem, A1 Tunnel No. 3 Hahamisha, Israel Background

Tunnel No.3 is part of the fast train connection from Tel Aviv to Jerusalem in Israel. After completion, it will reduce travel time from the current 90 minutes to 30 minutes. Two parallel tunnels have been driven by two Herrenknecht Double Shield TBMs with a diameter of 9,990mm each.

Objectives

The tunnel alignment crosses several geological fault zones. Because of increased risk of karst in the dolomite sections, the furthermost of these two TBMs has been equipped with the Herrenknecht Integrated Seismic Prediction (ISP) system. The objective has been the detection of karst caves in front of and below the TBM that are big enough to hinder the overall tunnelling works or even damage the TBM itself.

Approach

Consecutive and regular stroke wise measurements - i.e. every 1.6 m - with the ISP during the TBM advance delivered the necessary seismic data to be processed and to suppress and filter out the seismic noise in order to focus only on the stationary main reflector of the approached karst cave.

Results

Detection of a karst cave right below the tunnel trace of the Double Shield TBM. Verification of the anomaly by ongoing consecutive processing of investigation data indicates a stationary reflector of seismic waves (Figure 6). After stopping the TBM, the karst cave was examined and found to have dimensions of 4 m in depth and 2 m in width (Figure 7).

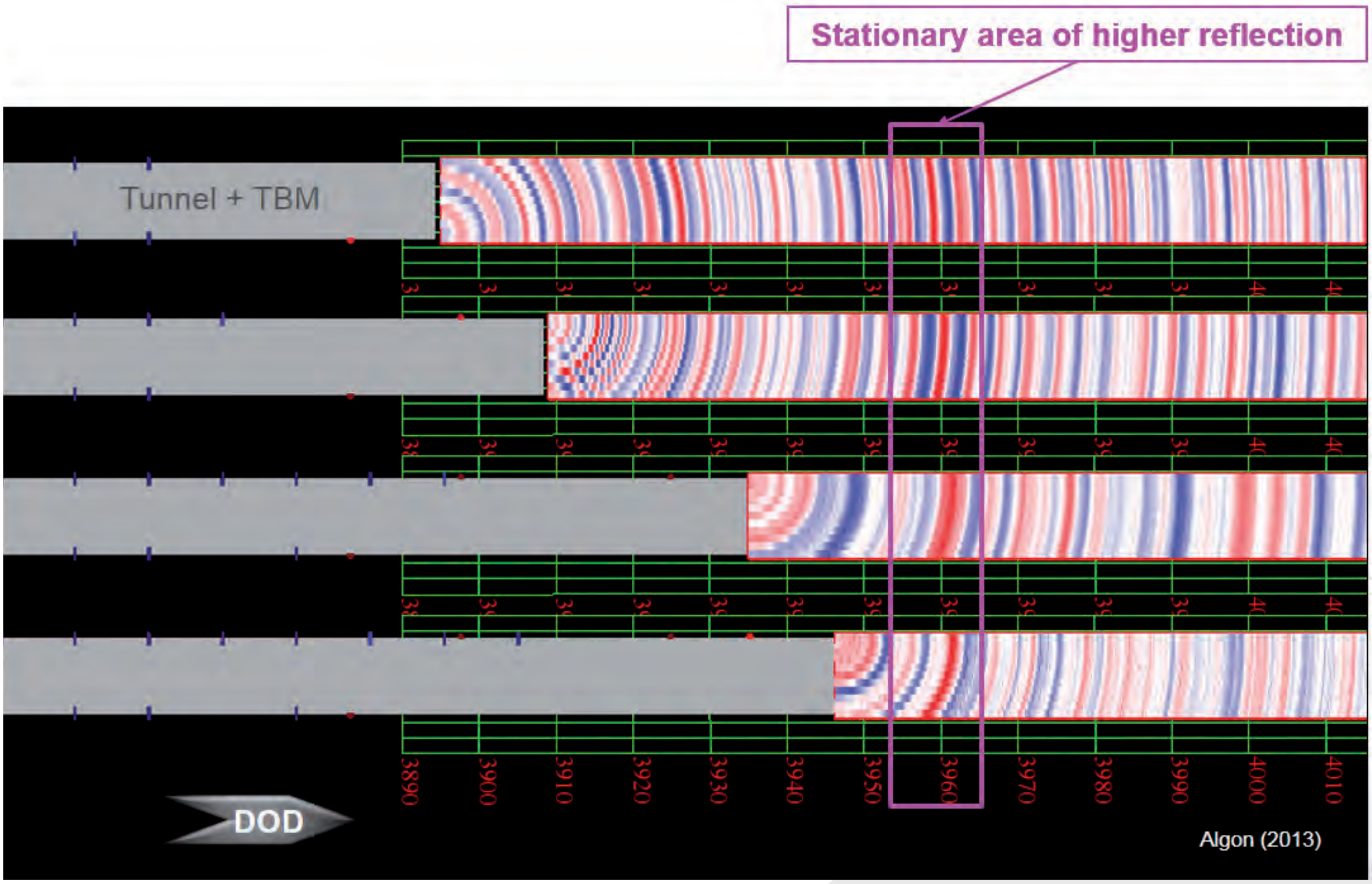

Figure 6 : Consecutive results of ISP data processing show a stationary area of higher reflection [Herrenknecht AG].

Figure 7 : Dimensions of the approached and examined karst cave.

4.1.6.2. Railway project Tel Aviv – Jerusalem, A1 Tunnel No. 3 Hahamisha, Israel

Background
Tunnel No.3 is part of the fast train connection from Tel Aviv to Jerusalem in Israel. After completion, it will reduce travel time from the current 90 minutes to 30 minutes. Two parallel tunnels have been driven by two Herrenknecht Double Shield TBMs with a diameter of 9,990mm each.

Objectives
Primary objective had been the detection of geological fault zones or karst caves in the dolomite sections of the tunnel alignment, just as mentioned as in the previous case study. The special situation of advancing towards a construction cavern within the detection range of the ISP could be used as described in the approach below.

Approach
The tunnels driven by the TBMs ended in a construction cavern at a known location. This cavern worked as a kind of known reflector like a big karst cave to the ISP system. Due to this, the function of the ISP itself could be verified while approaching this construction cavern (Figure 8).

Results
The cavern shows optimal conditions as a known reflector, i.e. vertical walls for best possible reflection of seismic waves as well as high enough acoustic impedances between the hard rock geology and the air filled cavern. Due to this, a very early first detection of the cavern ~80m before its beginning as well as the quite good accordance of the end of the construction cavern were shown in the processed ISP data and the actual end of the cavern at TM 10.741m could be stated.

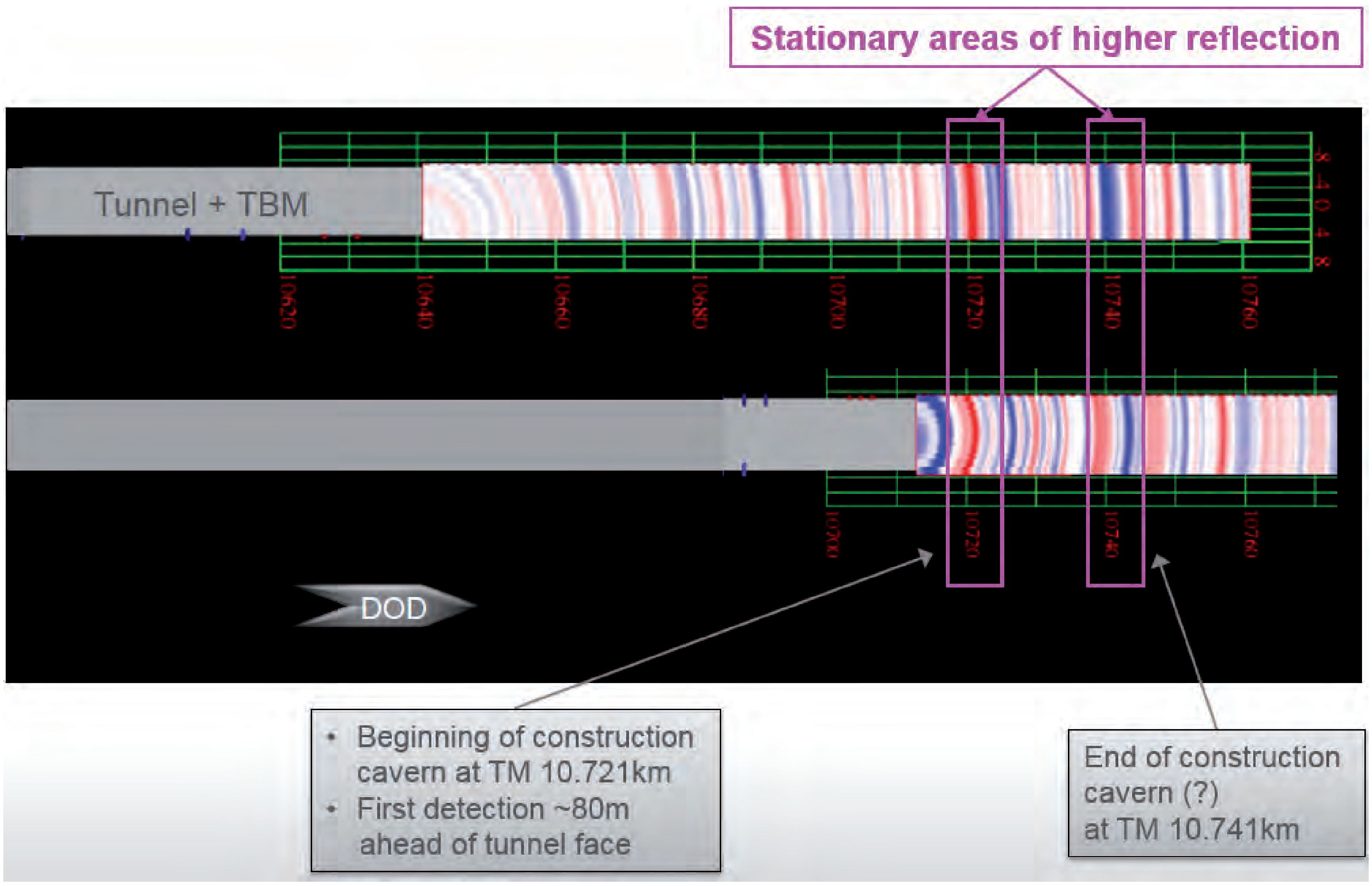

Figure 8 : Detection result of the TBM approach to a construction cavern [Herrenknecht AG]

4.2. TUNNEL SEISMIC WHILE DRILLING – TSWD (M1-2)

4.2.1. General characteristics and principle

The TSWD-method has been developed for seismic exploration ahead of the tunnel face during machine driven tunnelling where the cutting process of the Tunnel Boring Machine (TBM) itself is used as the source of seismic waves. In order to predict deeply incised valleys, karst cavities, fault zones and other unexpected degradations of rock quality, 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. However, since tunnelling with a TBM became the main technique in recent years, the vibrations of the drilling head, resulting from the cutting process, can be used as a seismic source signal, ensuring a continuous seismic monitoring without hindering the drilling and driving operations. This method is based on SWD - Seismic While Drilling [7] and has been called TSWD - Tunnel Seismic While Drilling [8] [9].

Applying appropriate signal processing, the recorded vibrations of the drilling head resulting from the cutting process can be converted to conventional seismic traces, from which relevant geological structures within a geophysical forecast window of up to 150 m ahead of the current tunnel face can be predicted. Because of the continuous seismic monitoring and the large amount of seismic data, the TSWD-method is very effective for imaging reflecting horizons, regardless of their orientation, and near to their intersection with the tunnel axis. Since the implemented instrumentation, data transfer and logistics guarantee processing on a daily basis, relevant fault zones can also be observed over long distances.

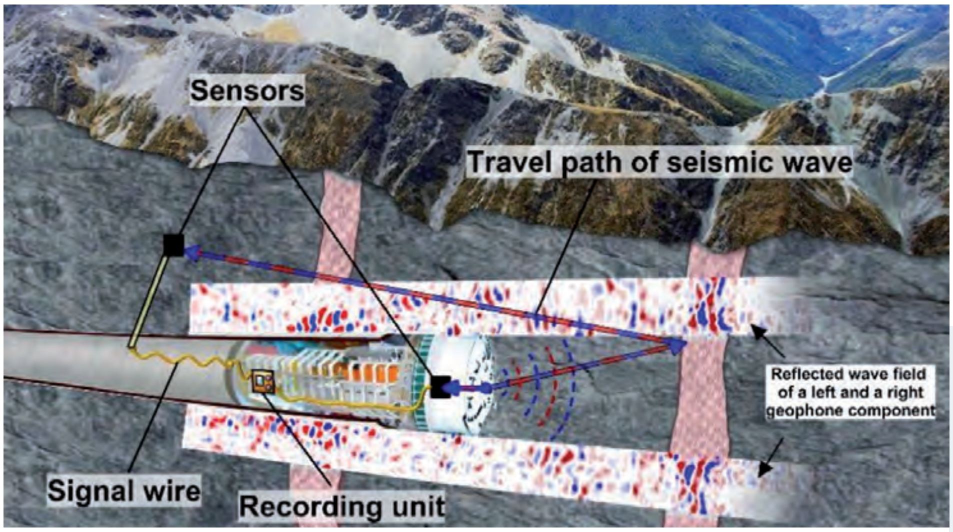

Figure 9: Scheme of Tunnel Seismic While Drilling: Sensors at the TBM head continuously collect the pilot signal; Geophones behind the TBM record the complete wave field. With the resulting reflected wave field, a prediction for changes in rock properties (e.g. fault zones) is possible ahead of the TBM. [Pöyry Infra GmbH]

4.2.2. Measurement principle – Reflection seismics

The TSWD-method is based on continuous seismic monitoring of the vibration signal of the cutting head of the TBM by the means of geophones planted in boreholes along the tunnel wall (Figure 9). The seismic monitoring produces continuous seismic data, which are stored in recording units. The high production rate of modern TBMs imposes a major challenge on the real time monitoring. Therefore, to handle this amount of data in real time requires automatic processing, which will result in a daily update of predictions.
There are two different wave fields recorded at the geophones; the direct wave field straight-forward coming from the source (TBM) and the reflected wave field propagating from the source to a reflector and back to the geophones. 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.

4.2.3. Applicability

The TSWD-method can be used under hard rock conditions independent of the type of rock. Various projects show that there are no limitations in the type and the size of the TBM. The installation of the TSWD-system can be done before or during the TBM operation phase. The TSWD-layout and -instrumentation is adaptable to the construction site.

4.2.4. Operation

The geometrical installation concept of the seismic instruments consists of a seismic monitoring recording unit with 3-component accelerator(s) at the head of the TBM and 3-component geophones behind the TBM (Figure 10). All instruments are connected with cables, to synchronize the units in time (e.g. with a GPS-signal from outside the tunnel or an atomic clock) and for the data transmission to the data centre [10]. The whole configuration moves as the tunnel progresses.

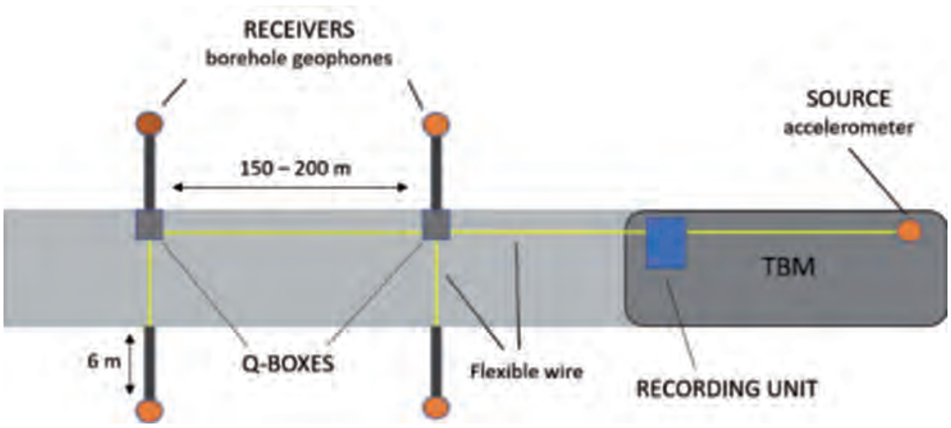

Figure 10 : Top View of the geometrical layout..

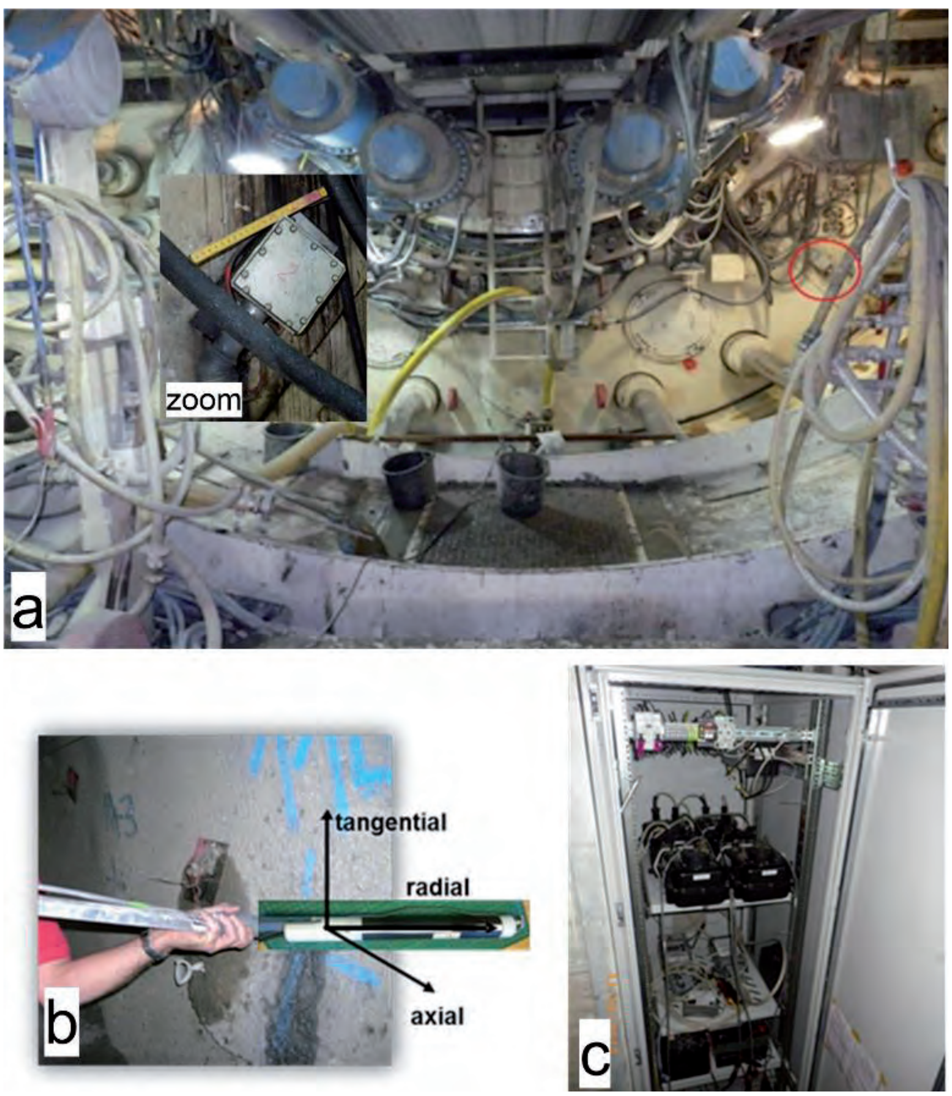

Figure 11 : Instrumentation of TSWD, a) Pilot sensor on the cutting head of the TBM; b) geophone planted in borehole at the tunnel wall; c) Cabinet of recording units.

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 (Figure 11). Using a 3-component 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) on both side walls with a longitudinal spacing of 150 - 200 m. The three components of the geophones are oriented axial, tangential and radial to the tunnel axis. The sampling rate for the pilot and receiver signals should not be less than 1,000 Hz because the main frequencies of the vibrations of the TBM are up to 250 Hz. Raw data are sent to the recording units and further on to the data centre, which requires a transmission rate up to 4x192kBit/s for the whole system.

The high production rate of data and the request of real time monitoring, processing and prediction requires automatic processing of the continuous data. To derive interpretable seismograms a correlation between the pilot- and the receiver signal is applied which is done for time windows from 30 sec - 5 min of the pilot and receiver data at the same absolute time. 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 from 30 sec to 5 min corresponds to source distances in the range of a few millimetres to centimetres. During one day of observation a large amount of seismic traces are produced. For data reduction and regular offset interval use, all seismic traces recorded within 1 metre of tunnel axis are stacked to one single trace. Stacking of seismic traces improves the signal to noise ratio and therefore the data quality.

The most crucial processing step is the removal of the direct wave field to extract the reflected signals. This is done by frequency – wave number filtering and the subtraction of an average wavelet, which is generated by mixing from 25 up to 51 traces.

In order to make the reflections more interpretable, a mapping of these data is performed. This transformation ensures that signals from interfaces crossing the tunnel axis perpendicularly are mapped at constant tunnel stations, presuming the velocity has been estimated correctly (Figure 12).

The results of the TSWD-method are seismic reflections with various amplitudes, which incorporate the information of velocity and density contrasts ahead of the tunnel face. If these amplitudes are quite low, the rock tends to be homogeneous and no disturbances are expected. Reflections with higher amplitudes may reflect fault zones of different types depending on the rock in which the tunnel is drilled. The reflections are usually classified following a traffic light system (green, yellow, red) where green is no fault zone, yellow a weak fault zone and red a strong fault zone. A calibration with the encountered geology is necessary to sharpen the interpretation.

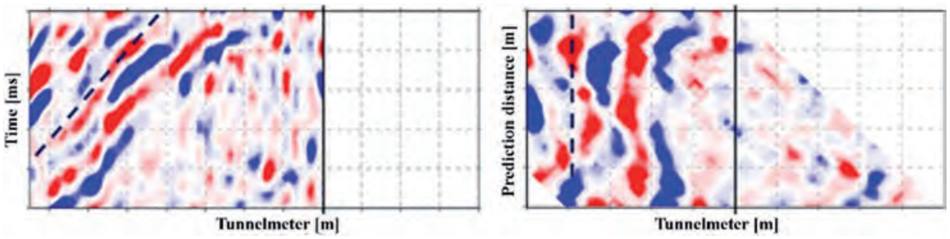

Figure 12 : Mapping of TSWD-results, left – time domain, right – space domain, blue line indicates the same reflector. [Pöyry Infra GmbH].

4.2.5. STRENGTHS AND WEAKNESSES

STRENGTHS	WEAKNESSES
Daily prognosis	Not able to predict the type of rock
Continuous monitoring	No information about seismic velocities ahead
No hindering of construction works	Long seismic wavelengths – Limitation to determine the thickness of the fault zones
High fault detection rate	Inclined fault structures (<25°) are hard to detect
System installation possible after TBM start	Data processing and interpretation is only done by qualified personnel
Begin of fault zones is detected with the accuracy of < 10 m	

Table 1 : Preconditions for ISP operation.

4.2.6. REFERENCE PROJECTS

Selected case studies are presented in this section, demonstrating how TSWD data can provide useful information during the tunnelling process.

4.2.6.1. Koralm Railway Tunnel – KAT2 / Austria

Background
The Koralm tunnel is the key part of the Koralmbahn, which itself is part of the new southern route in Austria. Upon completion of its construction it will not only massively reduce the travel time from e.g. Graz to Klagenfurt (45 min instead of 2h54min) but also play an important role in the Baltic-Adriatic Corridor, connecting Gdansk on the Baltic Sea with Bologna and the Adriatic. Two parallel tunnels are excavated by two Aker Wirth TBMs with a diameter of 10 m. The measured section for TSWD was 17 kilometres and was completed in January 2017.

Objectives
The main aim was the detection of relevant fault zones and water-bearing layers during tunnelling and to reduce the number of exploratory drillings at the tunnel face.

Approach
Since TSWD is sensitive to changes in the rock parameters, the approach was to perform exploratory borings when the results of TSWD indicated a relevant change in impedance within 100 m ahead of the tunnel face.

Results
Wider fault zones over a thickness of several meters can be successfully resolved, smaller fault zones are mostly detected, depending on seismic impedance contrast and the position relating to the tunnel axis.

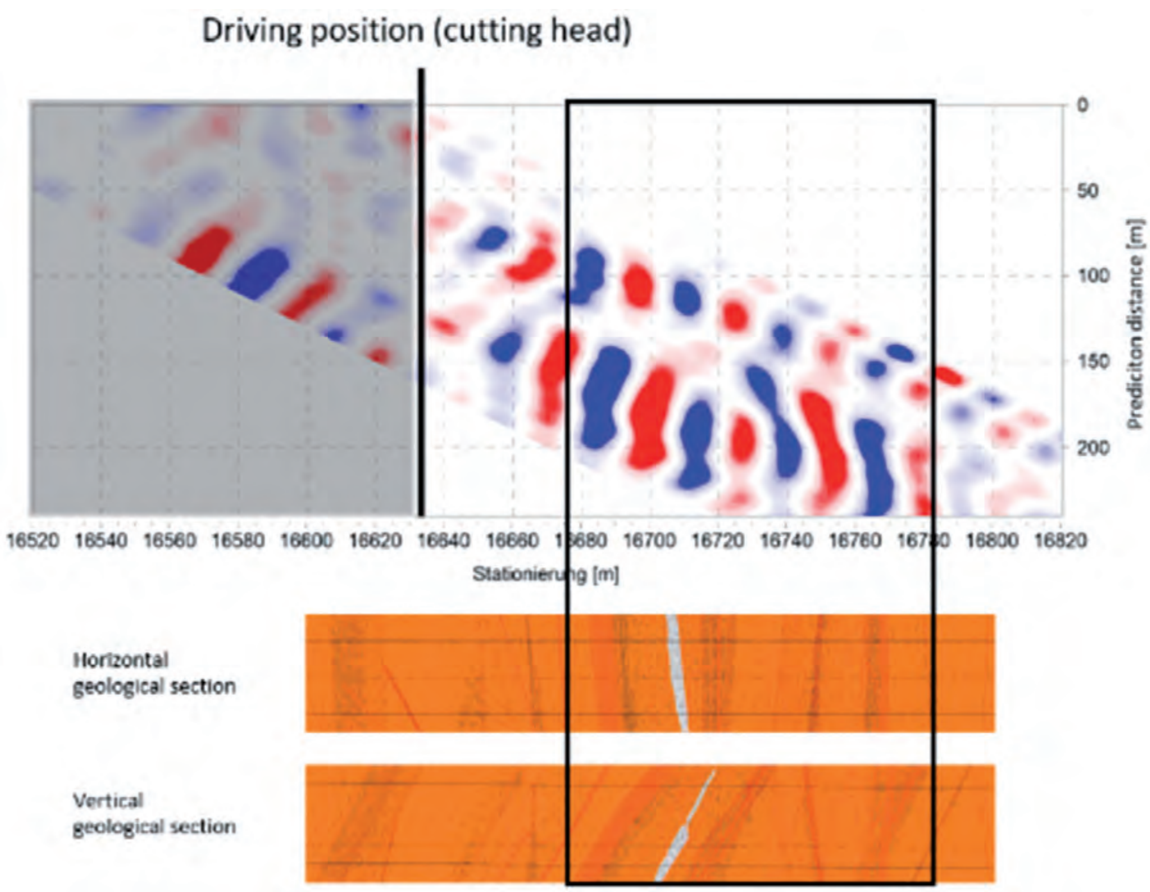

Figure 13 : Example of detected fault zones. The data was recorded with the axial component of a geophone planted in a borehole at the right tunnel side wall. The area of reflections with higher amplitudes implies strong contrast in the rock mass that correlates well with the geological sections below. (Source: arge:geo:kat2).

4.2.6.2. Reisseck II - Water pressure tunnel / Austria

Background
This water pressure tunnel was constructed in Carinthia in Austria and is part of a water power station system of Malta and Reisseck I. This tunnel was excavated by a Robbins TBM with a diameter of 4,5 m.

Objectives
The aim was the detection of relevant fault zones and water-bearing layers during tunnelling.

Approach
Since TSWD is sensitive to changes in the rock parameters TSWD indicated a relevant change in impedance within 100 m ahead of the tunnel face.

Results
Over 80 % of the fault zones were detected but none of these was relevant to the construction of the tunnel.

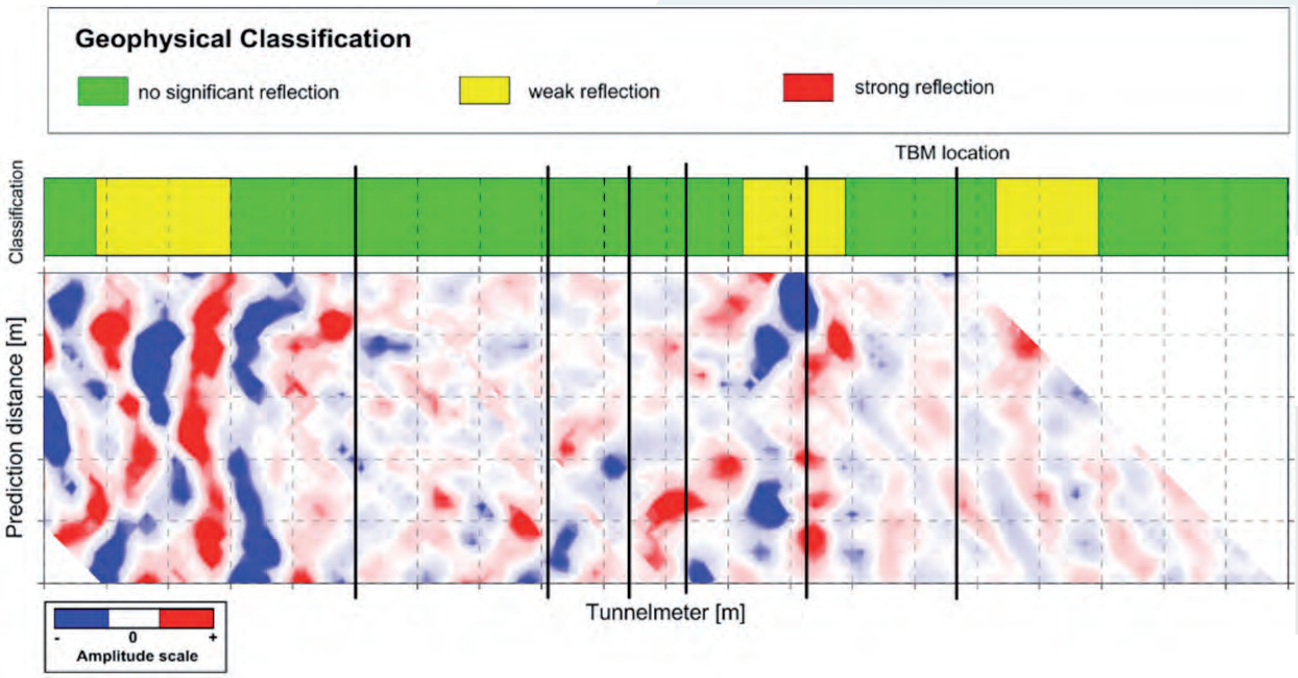

Figure 14 : Example of a detected fault zone. [Pöyry Infra GmbH].

4.3. SONIC SOFTGROUND PROBING – SSP (M2)

4.3.1. General characteristics and principle

SSP is a seismic investigation system used on Slurry-TBMs with bentonite slurry. The slurry is necessary as a coupling medium in order to induce seismic energy from the transmitter into the ground as well as to detect seismic waves with the receivers in case the waves are reflected by a boulder or similar feature.
In loose soils, the exploration system SSP helps to identify boulders, old sheet piles or shafts before the TBM reaches them. The SSP system is a Herrenknecht system that could be principally used on TBMs of other brands as well.

The required transmitter and three to four receivers are integrated into the cutting wheel. A signal is emitted during tunnelling operations; it spreads out and is reflected at geological or artificial surfaces. The reflected signals are recorded by several receivers. In this way, obstacles with a diameter larger than 0.5 m and lying up to 40 meters ahead can be detected and displayed.

The pre-exploration system SSP is carried out simultaneously to the advancing process and in most instances automated without impairing tunnelling operations. For the interpretation of the seismic results, additional information about the possible origin of the measured impedance contrast must be considered. Sources of information are geotechnical explorations, machine data, artificially generated density contrasts such as injection blocks or muck, which can be examined on the separation plant.

Essential features are:
- Drive-accompanied and non-destructive measurements
- Automated geophysical data processing
- Generally understandable results in 3D

4.3.2. Measurement principle – Reflection seismics

SSP is a system based on reflection seismics for drive accompanied exploration of the loose soil ahead of the tunnel face. A source emits a signal of varying frequencies (sweep), which is reflected at the surface of features such as boulders or changing geological formations (Figure 15).

The SSP source generates seismic waves with frequencies from 0.5 - 4 kHz, which results in a good resolution as already discussed in the chapter above. The reflected waves are recorded by accelerometers mounted within the receivers, which are embedded into the cutting wheel. Correlating the known sweep with the noise-contaminated record, the desired signal can be isolated. By means of a continuous velocity analysis, the measured travel times of the seismic events are being converted to geometrical locations of the reflecting area. As a result, one receives a three-dimensional coloured picture in which areas of higher and lower reflection energy are separated.

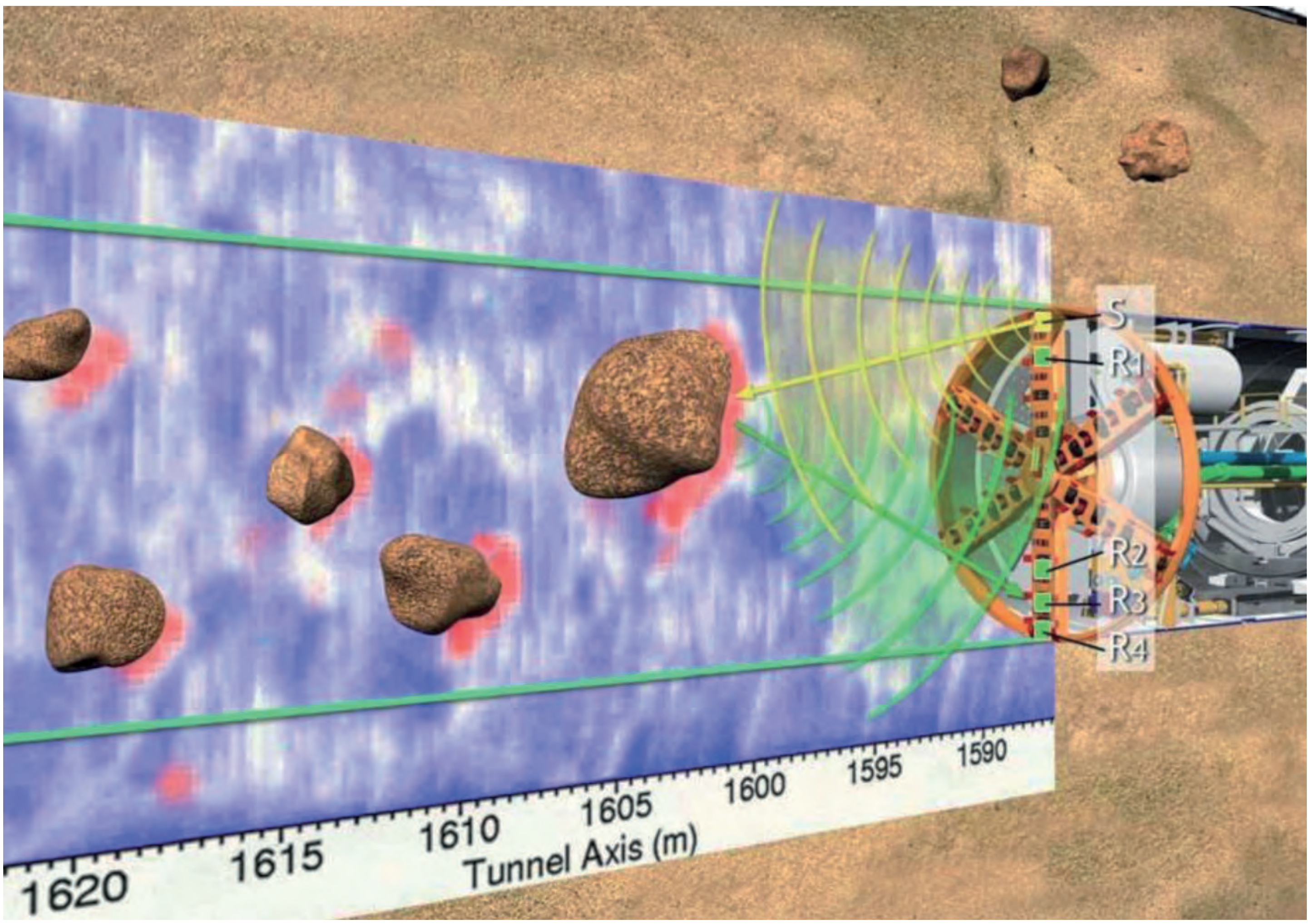

Figure 15 : Sonic Softground Probing – Exemplary illustration of the measuring principle [Her-renknecht AG].

4.3.3. Applicability

SSP is used on Slurry-TBM in pressurized, water-saturated, sandy-gravelly soft ground geology in addition with bentonite slurry. SSP consists of components directly mounted to the cutting wheel of the Slurry-TBM, as well as a switch cabinet placed in the control cabin on the gantry. The switch cabinet includes all necessary server and activation components. Depending on the diameter, three to four receivers are installed on the cutting wheel (Figure 16).

Both system component groups are connected by a slip ring transmission, which can be seen in the overall installation scheme (Figure 17).

4.3.4. Operation

As the SSP measurement process runs parallel to the process of TBM boring, it is necessary to precisely determine the emitted signal. Therefore, the movement of the transmitter´s source plate during the cutting wheel´s rotation is recorded via a rotary encoder. All signals are digitalized within the cutting wheel´s system components and transferred to the switch cabinet via slip ring transmission. The system controls the source, data transfer as well as data processing (Figure 18) and visualization. The whole measurement is controlled by a high-performance computer.

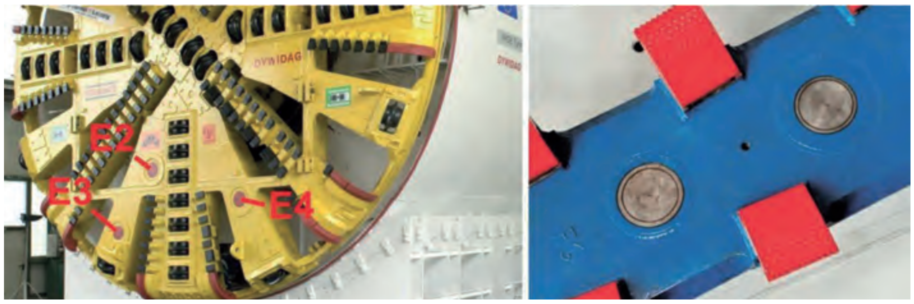

Figure 16 : SSP sensors, embedded into the cutting wheel, are continuously transmitting and recording data during advance [Herrenknecht AG].

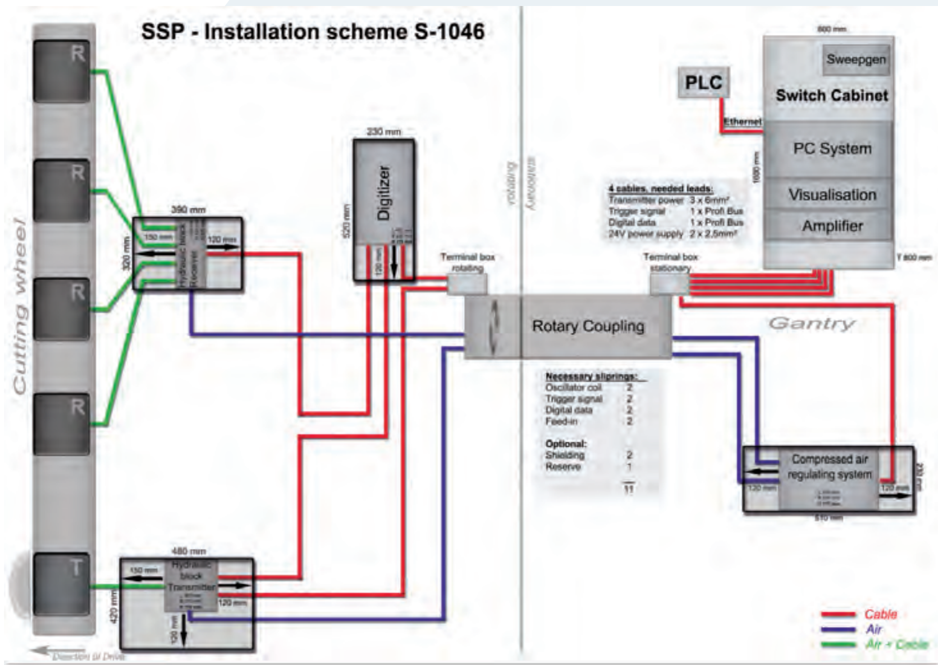

Figure 17 : Exemplary scheme of the SSP hardware (T = transmitter, R = receiver) [Herrenknecht AG].

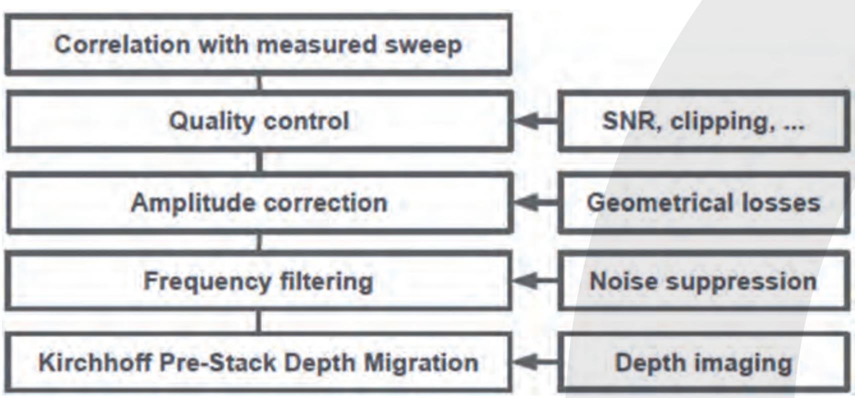

Figure 18 : Data Processing steps [Herrenknecht AG].

Main tasks of the system are:
- Assign measurements to the geometrical data from the PLC of the TBM
- Intensive computational geophysical data processing
- Visualization of the results
- Reporting

SSP´s main prerequisites for operation and functionality can be seen in Table 5 below.

ITEM	SPECIFICATION
TBM type	Shield with bentonite slurry
Early integration in TBM design process	SSP IPC and Server in control cabin Suitable rotary coupling Cutting wheel positions for 1 transmitter 3-4 receivers
Availability of TBM status and geometrical data	Reading access to TBM PLC
Connectivity via Dial-in-connection for remote maintenance and control	High speed internet 10 Mbit Upload

Table 5 : Preconditions for SSP operation.

4.3.5. Strengths and Weaknesses

The purpose of exploration is the early acquisition of additional seismic information about changes in the subsurface. These changes can be a potential source of danger for the construction or the TBM with the risk of expensive repairing actions or downtimes.

Possible examples of observable changes are large granite blocks (boulders) or a steel or a concrete pile in loose soil or a change in geological formation.

SSP thus represents a local high-resolution supplement to large-scale geological exploration. To date, 18 SSP-equipped TBM-projects have been completed within the last 20 years.

Its strengths and weaknesses as well as its capabilities are shown in Table 6 and Table 7.

STRENGTHS	WEAKNESSES
Operation parallel to TBM advance	Long hard rock passages request protection against permanent rock contact and abrasion of transmitter and receivers
No downtimes for TBM advance	No detection functionality in hard rock passages
Very high degree of TBM-integration	Transmitter and receivers installed in the cutting wheel: no or restricted access for maintenance
Automated measurement and data acquisition	
Automated reporting possible	
Remote control and maintenance via dial-in-connection possible	
Functional under high water pressures	

Table 6 : SSP strengths and weaknesses.

ITEM	SPECIFICATIONS
Detection range in direction of drive	40 m
Contrast in acoustic impedance	> 20 %
Detectable objects	Boulders HDI-/Sealing blocks Diaphragm walls, Bored piles Vertical geological layer boundaries
Operation pressure (Earth and water pressure)	< 10 bar
Resolution	> 0.5 m
Position accuracy	> 0.5 m

Table 7 : SSP capabilities.

4.3.6. Reference project

A selected case study is presented in this section, demonstrating how SSP data can provide useful information during the tunnelling process.

4.3.6.1. S-326 City-Tunnel Leipzig / Germany

Background

The City-Tunnel Leipzig is part of the restructuring of Leipzig´s railway network and includes a double-tube tunnel connection beneath the centre of Leipzig. The tunnel length is 2x 1,438 m and a Herrenknecht Mixshield TBM with 9 m in diameter was used.

Objectives

The primary objective was the detection of boulders and occasionally occurring Quartzite layers within the soft ground geology mainly consisting of gravel, sand, silt and clay.

Approach

In addition to the measurements and processing results done with SSP, TBM data was used for the correlation of the TBM´s reaction while advancing in comparison with the SSP visualization. Thus, data like torque cutting wheel (D; see TBM graphs in Figure 19), tilting moments of the cutting wheel (Mx, My) as well as cutting wheel displacement force (Fa) and cutting wheel rotation speed (n) are evaluated and shown within the results below.

Results

SSP enable the early detection of an iron pipe and hard Quartzite layers. Thus damage of cutting tools and the cutting wheel itself was avoided simply by a timely reduction of the TBM advance speed.

Figure 19 shows in red circles the visualized relevant reflectors in a birds-eye-view as well as in a longitudinal cross section. On the right hand side the remains of the Quartzite and the steel pipe can be seen, which have been retrieved from the separation plant in a timely manner.

The TBM data graphs in Figure 19 show a good correlation and coincidence of the minimum and maximum peaks of the cutting wheels´ tilting moments Mx and My with the occurrence of the detected anomalies.

As a detection benefit, a validation of the SSP function could be undertaken with some known obstacles (i.e. bored pile wall and diaphragm wall of a building pit), again correlated with TBM data, which can be seen in Figure 20.

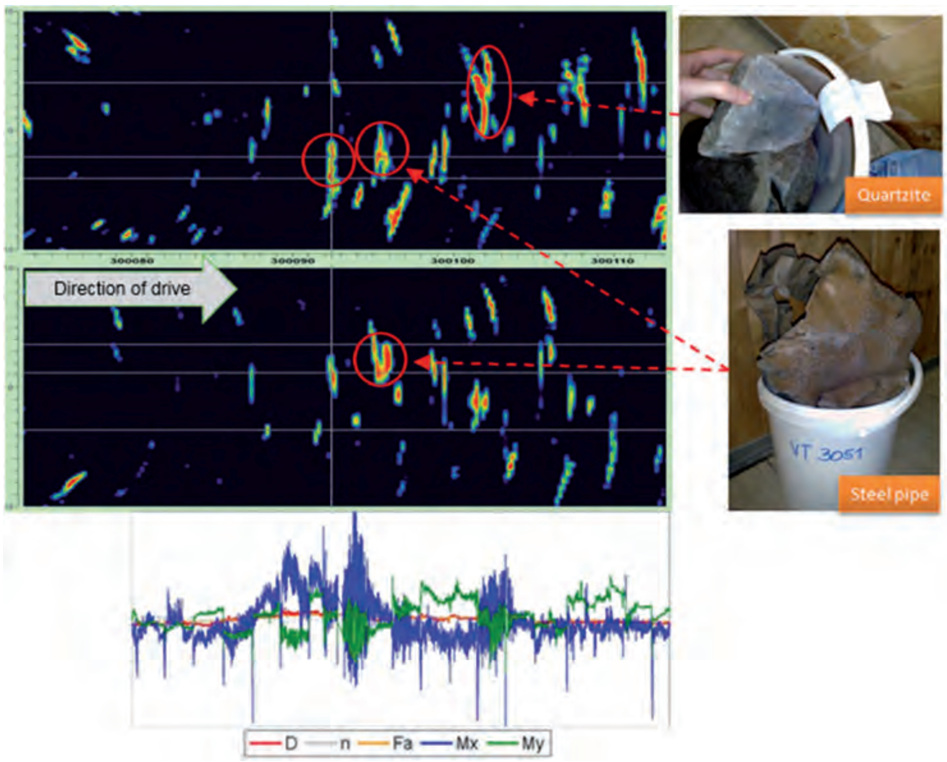

Figure 19 : Correlation of the detected seismic anomalies to the development of TBM data sensors [Herrenknecht AG].

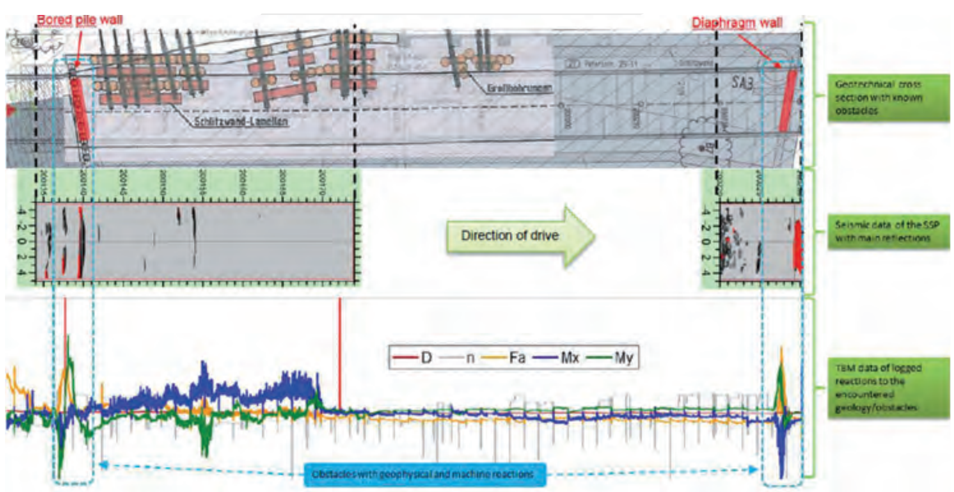

Figure 20 : Correlation of known seismic anomalies to the development of TBM data sensors [Herrenknecht AG].

4.4. TUNNEL SEISMIC PREDICTION – TSP (M5)

Tunnel Seismic Prediction (TSP) is an advance-type independent geophysical investigation method in any type of rock. In mechanized and conventional tunnelling it works independently from the advance cycle of the TBM and operates from behind the tunnel face.
For a detailed description see chapter 5.1.

The following chapter deals with a seismic method being applied during conventional tunnelling but which can be used during mechanized tunnelling. The first section describes the application that works behind the tunnel face (C1). The second section points out that the same principle of measurement of C1 is applicable to investigations at the face (C2).

5.1. TUNNEL SEISMIC PREDICTION –TSP (C1)

With the use of innovative technologies, a more rapid construction of extremely complex underground structures is possible. In each instance the safety and progress of the project is based on the assumed knowledge of the rock's properties ahead of the face. It is possible to obtain information by drilling probe holes but these are costly and considerably delay many tunnel works.
A meaningful alternative is Tunnel Seismic Prediction TSP - a rapid, non-destructive and highly sophisticated measuring method and system especially designed for underground construction works. The TSP method was firstly introduced to the underground construction market in 1994. Since then, it has been successfully used in several hundred underground projects worldwide. Today, the third generation of the TSP technology is available using true 3-D data processing tools and presenting parameters of rock characterization ahead of the face in three dimensions [11] [12].

5.1.1. Measurement principle

The standard measurement layout of the TSP® method is approx. 55 m long and aligned along the tunnel wall behind the tunnel face. Four receiver probes consisting of highly sensitive tri-axial sensors are mounted in protection tubes whose tips are firmly cemented into boreholes of about 2 m length and 50 mm diameter in both side-walls. About 15 meters apart from the front receiver

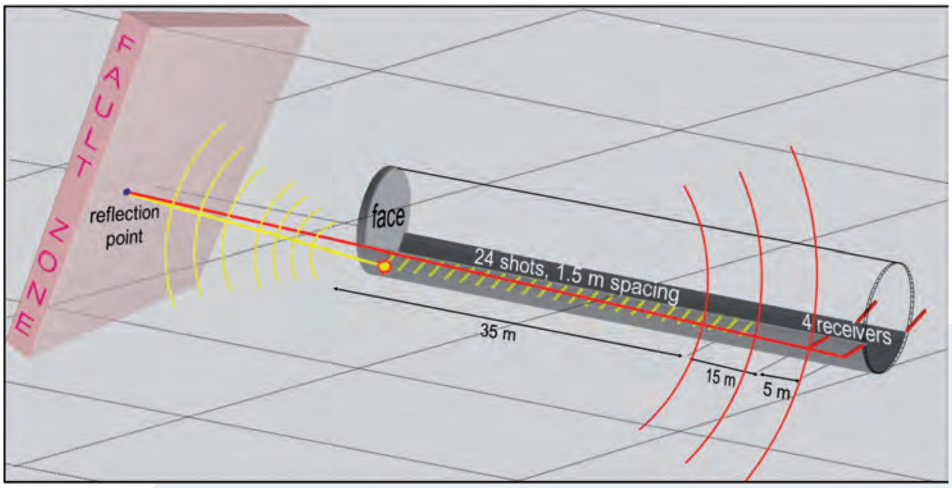

Figure 21 : The measurement principle of TSP is based on reflection seismics. Yellow wave fronts represent forward moving and red wave front reflected waves arriving at the receivers..

positions towards the face, 24 shot points are located along one tunnel wall side with a spacing of 1.5 m. As a seismic source, explosive charges of approx. 20-100 g are used in each shot hole fired consecutively. The 3-component receivers pick up the seismic signals which have been reflected back from any kind of discontinuity in the rock mass ahead (Figure 21).

5.1.2. APPLICABILITY

With the use of the latest technology of the TSP®303 system, TSP is applicable in any underground project fulfilling the following conditions :

- Acoustic impedance contrast (i.e. contrast of the product of wave velocity and rock density) of a minimum of 20% in conjunction with fault zones or changes in rock formation in order to receive sufficiently high amplitudes of reflection signals.
- Rock boundary orientations that intersect the tunnel axis at moderate to high angles. Thus, strike and dip angle >25° with reference to the tunnel axis are required to be predictable ahead of the face. In cases where angles of ground boundaries are lower, reflections from these boundaries are receivable from the space around the tunnel.
- Rock strength with a minimum UCS value of 10 MPa.
- An accessible stretch of minimum 35 meters along the right or left tunnel wall right behind the tunnel face or up to 20 m behind the tunnel face is available.

5.1.3. OPERATION

The shooting and recording of 24 shots will last approx. 45-90 minutes (Figure 22). During recording, other noisy work in the tunnel should be avoided within 100 m of the TSP working area.

The prediction range of TSP® varies with the quality of the surrounding rock mass. If the rock conditions are good (hard rock, sparse fractures), a prediction range of minimum 150 m can be expected. This range may drop down to 80-100 m in case of poor rock quality (soft or highly fractured rock) due to higher signal attenuation. Hence, it is recommended planning measurement intervals every 120 m in normal rock and 80-100 m in sections of fractured ground conditions.

On-site data processing and evaluation can be carried out immediately after recording of all shots for a quick quality control. Further sophisticated data processing and result presentation can be carried out on site within 2 to 4 hours.

5.1.4. DATA PROCESSING AND EVALUATION

Once seismic data acquisition in the tunnel is done, the subsequent seismic data processing per receiver immediately starts to run through a number of primary steps controlled by a given flow chart. The aim of seismic data processing is an extraction and enhancement of the reflected wave field. For this purpose the data have to run through specially designed processing steps where intermediate results are stored enabling a review during processing at any time.
The wave separation process of Amberg TSP Plus software separates the recordings into wave types (P, SV and SH waves) according to their polarisation type via rotating the coordinate system as a function of recording time. At the end of the flow chart, all pre-processed data is passed on to the 3D processing where a velocity distribution of a user-defined 3D-model is presented. Finally, extracted reflectors are interpreted and rock property calculations of relevant reflectors are presented in an evaluation set (Figure 25).

5.1.5. ACCURACY/PRECISION

In seismics, accuracy is highly reliant on and related to seismic resolution, which is the ability to distinguish separate geological features. The measurand is the minimum distance between two geological features that is necessary to define them separately rather than as one. The seismic measurand of the vertical resolution is the wavelength of the reflection signal presuming that a sufficient acoustic impedance contrast exists at the boundary. Hence, signal frequency and wave velocity determine the resolution.

Figure 22 : TSP measurement in a conventional tunnelling environment. Here, two receivers and 24 shot points along the right tunnel wall side are shown.

Figure 23 : TSP measurement in a mechanized tunnelling environment of a double shield TBM. Here, receivers and shot holes are set out thru the pre-cast segment lining.

The examples in Table 8 illustrate realistic assumptions based on non-dispersive rock types with no frequency dependent velocity and negligible seismic background noise. The values given for the vertical and lateral resolution don't define the minimum size of a reflective feature to be detectable in the ground. They rather define the minimum spacing of reflective features in order to be distinguishable as a single feature.

ROCK TYPE	DISTANCE TO REFLECTOR	P-WAVE VELOCITY	SIGNAL FREQUENCY	RESULTING WAVELENGTH	RESULTING RESOLUTION	
					vertical	lateral
Granite or Limestone	10 m 100 m	6,000 m/s	1,000 Hz 500 Hz	6 m 12 m	1.5 m 3.0 m	1.9 m 8.7 m
Weathered Limestone	10 m 100 m	5,000 m/s	900 Hz 400 Hz	5.5 m 12.5 m	1.4 m 3.1 m	1.9 m 8.8 m
Shale	10 m 100 m	3,500 m/s	800 Hz 300 Hz	4.4 m 11.7 m	1.1 m 2.9 m	1.7 m 8.5 m

Table 8 : Examples of typical seismic resolution.

5.1.6. STRENGTHS AND WEAKNESSES

STRENGTHS	WEAKNESSES
Due to its mobility the system can be used at any time in any rock type without direct access to the tunnel face.	At least hand drilling equipment required for necessary boreholes.
3D investigation with a range up to 150 m ahead of the face that leads to safe tun-nelling for the next one to two weeks. - Spatial resolution: 1 – 5 m - Positional accuracy: 1 – 5 % of target distance	If used in precast segment lining, perforation of concrete lining segments (thru grout holes) is required in order to have boreholes available.
- Detection of hazardous fault zones & cavities - Exploration of water bearing formations - Discovery of changes in rock mechanical properties due to full wave field analysis.	Downtime of 20-90 minutes during shooting.
Provides rock mechanical properties.	Requires little explosive charges and detonators
Delivers reliable results within 3-4 hours.	
Site personnel are able to acquire, process and evaluate TSP data independently.	

Table 9 : Strengths and Weaknesses of TSP.

5.1.7. REFERENCE PROJECTS

Selected case studies are presented in this section, demonstrating how TSP data can provide useful information during the tunnelling process.

5.1.7.1. Road tunnel project in Himachal Pradesh / India [13]

Background
This project is composed of five tunnels with full length of about 5 km and one escape tunnel with length of 1.8 km. The tunnel, in which the TSP campaign took place, was 1,836 m in length. Parallel to this tunnel, an escape tunnel was also under construction connected by several linking galleries.

Objectives
The construction of these tunnels by conventional excavation methods is complex due to mostly weaker rock mass formations and low overburden. The tunnel under investigation is located in a rock mass that is characterized by a succession of layers of lower and higher hardness of siltstones, clay stones and sandstones of varying thickness. The variation in the degree of weathering and hardness hinders a smooth and continuous execution and already led to high water ingress. The average overburden at the face location is about 230 m.

Approach
All necessary drill work for the TSP layout in the tunnel had been previously carried out by the contractor, who had prepared 22 shot holes and 4 receiver holes in the side walls (Figure 24). During TSP system installation, little explosive charges from 60 to 300 g had been prepared and connected to electric detonators. After 30 minutes of system installation, the stepwise shooting of the 22 charges took about 90 minutes, longer than usual to ensure that inexperienced staff could understand the process . After the shooting and recording of all shots, the system's disassembly and packing-up took another 20 minutes while excavation work had already started.

Results
P-wave velocities in sandstone vary from 2,700 m/s to 5,600 m/s. The prevailing geology lies in the lower velocity range indicating rather poor rock. A reference Edyn of 20 GPa and thereof derived Estat of 7.9 GPa was estimated. Based on estimated Vp, Vs and geotechnical pa-rameters ahead of the face, two fracture and water bearing zones were identified (Figure 25).

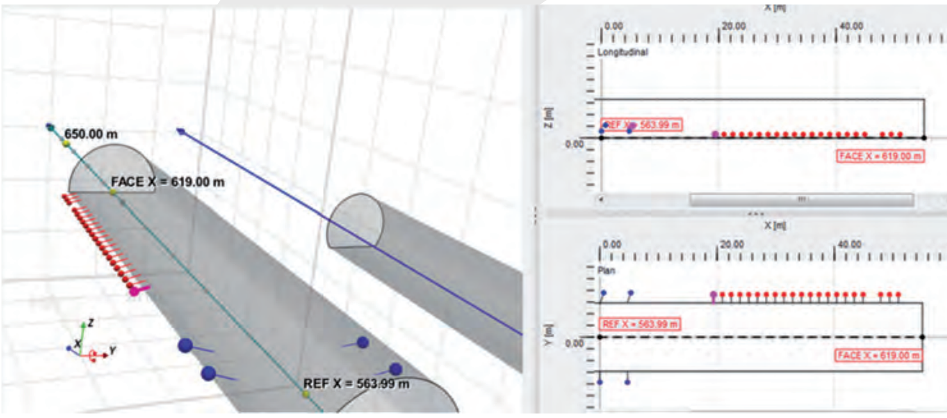

Figure 24 : Actual TSP layout at campaign site in. Blue dots: receivers, red dots: shots. At the time of measurement, the face of the main tunnel (left tube) was about 20 ahead of the face of the escape tunnel (right tube), whose axis lies 20 m east of the main tunnel axis.

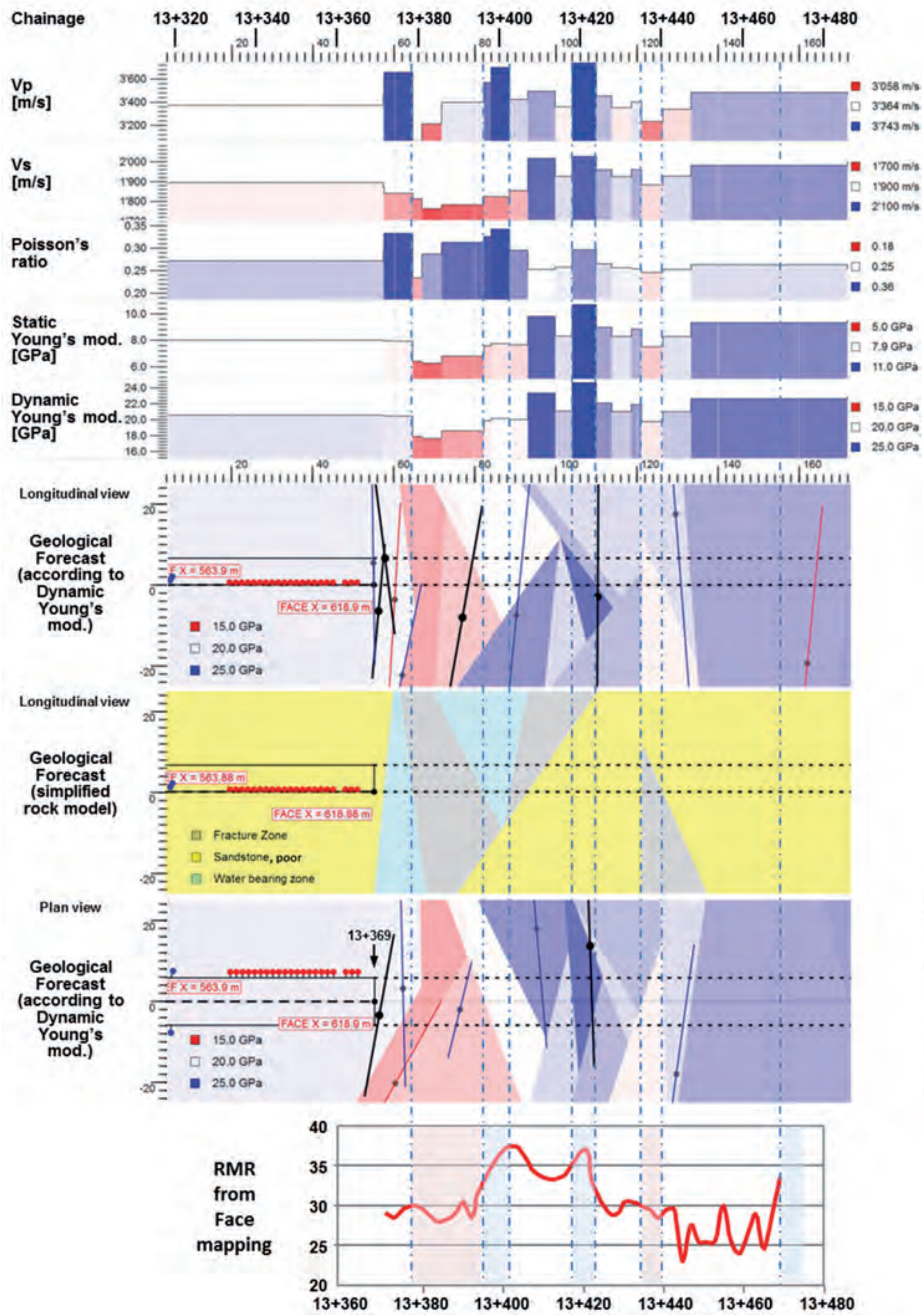

Figure 25 : TSP charts (top) of Vp, Vs, Poisson's ratio, static Young's Modulus (Estat), dynamic Young's Modulus (Edyn) along the prediction range. Longitudinal and plan views (middle) and Rock classification (RMR) from face mappings (bottom) are shown. The blue dashed lines indi-cate further boundaries in the general poor rock mass, which correlate with the forecast.

According to the RMR values obtained from face mapping during excavation, rock mass within the prediction range is being classified as poor rock mass (rating 21 to 40) as it was evident also from the low P- and S-wave velocities. The entire prediction range revealed poor rock conditions with a lower prediction range of < 100 m. Despite these overall poor ground condi-tions and related high wave energy attenuation, even less significant differences in the rock mass had been forecasted. Comparing the charts of moduli and velocities with the values of rock classification (RMR) in Figure 25, it is visible that both curve shapes look similar. In particular, the above mentioned fracture zones were being well predicted (compare with red zones in bottom chart of Figure 25).

In Figure 26, the 3-D distribution of P-wave velocity is shown beside the already excavated tunnel tube from the reference location to the tunnel face as defined in the tunnel model. The same is available for S-waves. Here, exposed areas represent velocity anomalies below 3,200 m/s that correspond to hazardous zones in the generally poor rock.

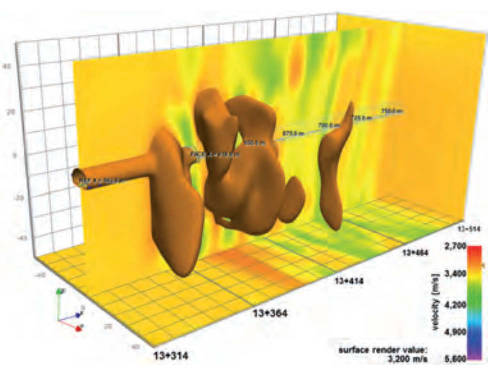

Figure 26 : 3D-velocity distribution of the P-wave around and ahead of the tunnel face at chainage 13+369. The velocity range corresponds to P-wave travelling though sandstone (2,700-5,600 m/s). The exposed areas represent velocity anomalies below 3,200 m/s that correspond to hazardous zones in the general poor rock.

5.1.7.2. Exploratory tunnel of the Brenner Base Tunnel Project / Austria

Background

The 15 km long exploratory tunnel driven by an open hard rock gripper TBM (∅ 8 m) is part of the 64 km long Brenner Base Tunnel from Innsbruck in Austria to Franzensfeste / Forte di Fortezza in Italy that will be the longest railway tunnel in the world when complete. The tunnel route crosses nappes of Quartzphyllite in the northern part with flat lying, isoclinal fold structure whereas Upper and Middle Bündner Schists prevail in the southern part [14].

Objectives

Even though a geological model along the tunnel route was generated beforehand from the results of geological field mapping and deep drilling campaigns from the surface, uncertainties persist due to the high overburden of up to 1,300 m. In particular, several fault systems intersect the tunnel route, but their position and orientation is uncertain. In addition, flat lying structures need to be looked at rather by lateral than ahead investigations.

Approach

The TSP measurements were carried out periodically at intervals of approx. 120 m. Four receivers were installed in boreholes drilled with a drill carriage mounted on the TBM on both sides about 65 m behind the face. Two shot lines with 18 shot holes on both sides for small explosive charges of 60 g were drilled in the accessible invert with a carriage on an excavator from about 8 to 35 m behind the face. Using the Multiple Shot Recording (MSR) method, several shots were fired consecutively with about a one second delay between shots. This significantly reduces the shooting time to only 10 minutes for all shots. Data processing and first result presentation was done within 2-4 hours right after the data acquisition in the tunnel.

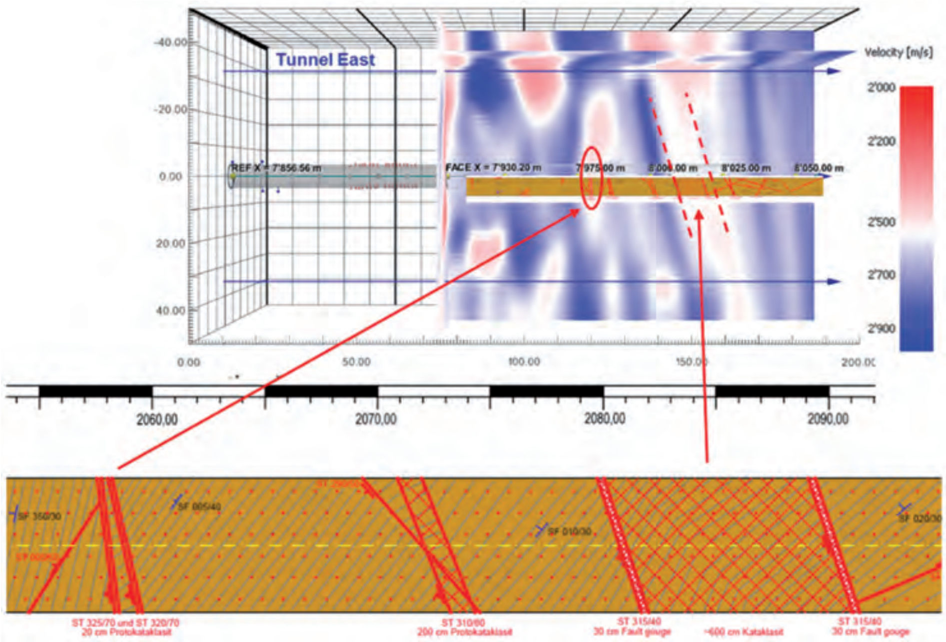

Figure 27 : Comparison of TSP result (top) with observed geology after excavation. Cataclasite zones are identified by low velocity zones illustrated by red coloured anomalies in top chart. Colours refer to velocity of shear waves. Note different stationing in top and bottom chart. Top: chainage, bottom: tunnel meter. Plane view.

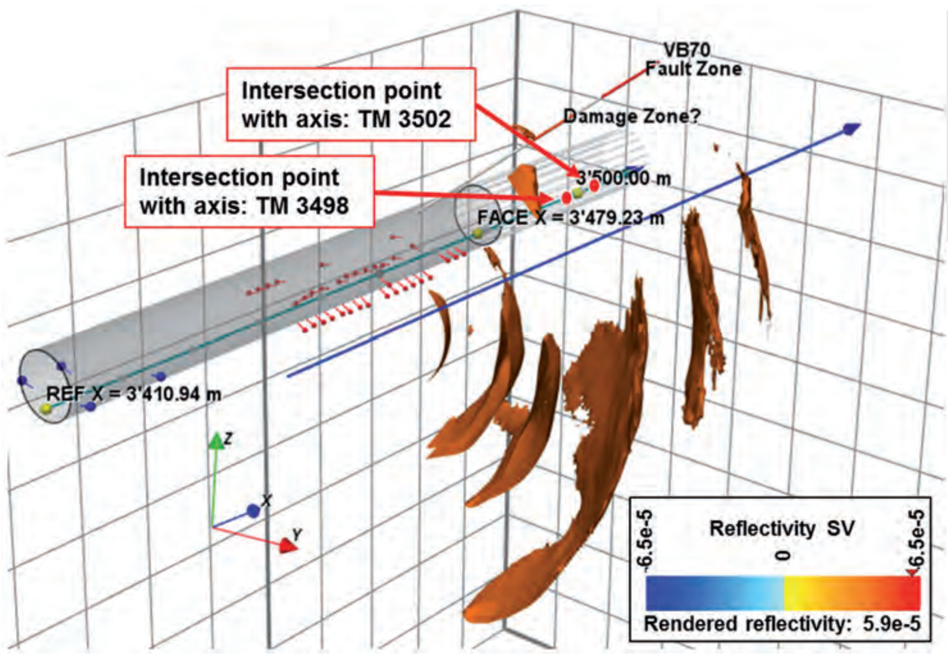

Figure 28 : Result of TSP side processing focus showing reflectivity of smoothly dipping reflec-tors. The designated intersection points represent the cutting of the extrapolated planes of the main reflectors with the tunnel axis. After Schwarz and Schierl (2017).

Results
Figure 27 illustrates TSP data example where a velocity distribution of the shear wave (s-wave) has been computed. Low velocity anomalies which represent fractured rock or rock of reduced shear strength are indicated by red colour. The prediction range is about 130 meters ahead of the face. Some weeks later, the predicted area was excavated and the comparison of the observed geology represented in the bottom chart of Figure 27 shows good correlation with the prognosis of the TSP result. Particularly, the potentially problematic cataclasite zones of the rock mass had been well predicted [15].

Setting the focus of data processing also to the tunnel side, the image of real s-wave data in Figure 28 reveals widespread areas of reflectivity in the section right below of the tunnel. As reflectivity is high, it indicates a big contrast in the rock mass most probably related to a fault zone that could intersect the tunnel axis at chainage 3,502 m [11]. Looking at the orientation of the features, sharp angles reveal a smooth strike towards the tunnel axis. This smoothly striking fault zone would have been unlikely to have been predicted by only using the look ahead processing approach.

5.2. TUNNEL SEISMIC PREDICTION WHILE EXCAVATING – TSPwE® (C2)

Tunnel seismic prediction – TSP – can be applied sporadically, on a regular basis or continuously. The name for that is TSPwE® – Tunnel Seismic Prediction while Excavating. The following description focuses on differences to TSP.

One of the main features of TSPwE® is that seismic data acquisition is linked to the excavation progress, where the face moves ahead while shot data is being collected from a set of shot points along one or both tunnel walls or at the face itself. Hence, TSPwE® can be applied behind the tunnel face and at the tunnel face.

5.2.1. Measurement principle

TSPwE® consists of three receiver pairs being deployed during seismic data acquisition along each of the tunnel wall sides. The concept rests upon a minimum number of shots being recorded by all six receivers, which are then being taken for data processing and its computing of updated 3D models. Herewith, each shot data is being assigned to the current face position at time of shot since the tunnel building itself does affect the wave propagation released by each shot. Once enough data has been collected – usually a minimum number of 20 shots per receiver is sufficient – data pre-processing per receiver can be initiated. A campaign is fully data pre-processed and ready to enter the 3-D processing step if all six receivers contribute with their minimum number of shot recordings to a new 3D result. Hence, a new 3D result is being presented at every progression of advance that corresponds to approximately one receiver spacing along the tunnel wall. This is ideally 10 to 15 meters (Figure 29).

5.2.2. Applicability

With the use of the latest technology of the TSP®303 system, TSPwE® is applicable in any underground construction project fulfilling the following conditions :

- Acoustic impedance contrast (i.e. contrast of the product of wave velocity and rock density) of a minimum 20% in conjunction with fault zones or changes in rock formation in order to receive sufficient high amplitudes of reflection signals.
- Rock boundary orientations that intersect the tunnel axis at moderate to high angles. Thus, a certain strike and dip angle (> 25°) with reference to the tunnel axis has to be expected to be predictable.
- Rock strength with a UCS value of 10 MPa.
- An accessible stretch of minimum 35 meters along the right and/or left tunnel wall right behind the tunnel face or up to 20 m behind the tunnel face is available. Alternatively, shooting is being carried out at the tunnel face along with the heading (Figure 29).

5.2.3. Operation

Blasting and recording of shots will last a few minutes along with the heading and mean no substantial delay of the construction work. The prediction range of TSPwE® is the same order of magnitude as for the TSP application (see 5.1.3.). On-site data processing and evaluation can be carried out immediately after recording of a sufficient number of shots. TSPwE® as a method that is continuously applied delivers an updated 3-D visualization of the geological ground condition ahead of the face each 10-15 m of advance.

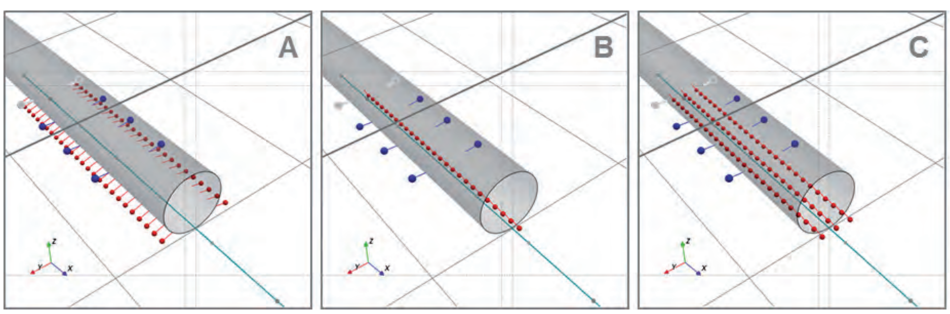

Figure 29 : Concept of TSPwE®: continuous tunnel seismic prediction with rolling deployment of 6 receivers each 10-15 m (blue dots). (A) Shooting in small boreholes along the side wall happens along with heading. (red dots). Shooting can alternatively happen in small boreholes at the tunnel face; single shot (B) or few shots (C) at the face. After 20 shots along advance direction, the rear receivers are being deployed as front receivers.

6 >> Applications of Seismic Investigations at a glance

	ISP	TSWD	TSPwE	TSP	SSP
Applicable in :					
Ground type	Rock	Rock	Rock	Rock	Soft ground
Mechanized tunnelling	✓	✓	✓	✓	✓
Advance cycle integrated	✓	✓	✓	✗	✓
Conventional tunnelling	✗	✗	✓	✓	✗
Use of :					
Seismic signal source	active	passive	active	active	active
Seismic wave type	s-waves	p-waves	p- & s-waves	p- & s-waves	p-waves
Prediction range :	Max. 120 m best at 20-80m	Max.100 m	120-150 m	120-150 m	Max. 40 m
Detection/Evaluation of :					
Fault zone	✓	✓	✓	✓	n/a
Formation change	✓	✓	✓	✓	✓ (air-filled)
Cavity	✓	✗	✓	✓	✓
Water bearing	✗	✗	✓	✓	n/a
Boulders, HDI-/Sealing blocks, Diaphragm walls, Bored piles	n/a	n/a	n/a	n/a	✓
Seismic velocities	✓	✗	✓	✓	✓
Ground properties	✗	✗	✓	✓	✗
…w/ resolution of	> 5 m	10 m	1-5 m	1-5 m	> 0.5 m
…w/ position accuracy of	> 5 m	< 10 m	1-5 m	1-5 m	> 0.5 m
…in true 3D images	✗	✗	✓	✓	✓
Operation :					
Small dia. boreholes in side wall required	yes	yes	yes	yes	no
Heading down time	almost no	no	small	20-90 min.	no
Data acquisition by	site personnel	qualified personnel	site personnel	site personnel	remote controlled
Processing/evaluation by	qualified personnel	qualified personnel	site personnel	site personnel	qualified personnel

As described in the Introduction, there are different geophysical methods, i.e. seismic, geoelectric, electro-magnetic etc. This guideline only describes the seismic systems, but all other methods mentioned above should also meet the following specifications.

GEOPHYSICAL INVESTIGATION AHEAD DURING TUNNELLING					
SN	**Item**	**Unit**	**Qty.**	**Unit Rate Cost**	**Total Cost**
1	**Allocation of Instrumentation**	lump	na	aa	na * aa
1.1	Allocation of a system for geophysical investigation ahead during heading, which is capable to reach prediction ranges of minimum 40 m (soft ground) and 100 m (hard rock) ahead of the tunnel face and consists of i.) minimum two sensitive seismic sensors w/ frequency response in the kilohertz range (uniaxial type in softground and preferably triaxial type in hardrock), ii.) a recording unit that provides digital signal reading with a sampling frequency of minimum 16 kHz, iii.) all additional accessory items for setting and detaching the sensors minimum 1 m deep into the ground or integrated in the cutter head, iv.) a processing and evaluation system software that is capable to process seismic data (one- or three-component data, resp.) according to state-of-the-art 3D-processing techniques and that is able to visualise the data results in 3D, v.) all consumables necessary for the geophysical investigation				
1.2	Optional: a seismic source that generates seismic waves of sufficient energy and frequencies of 0.5-4 kHz or explosive material w/ detonation speed of minimum 5,000 m/s and electric detonators that is necessary to generate seismic waves when deployed in small bore holes along the tunnel side wall within one campaign.	lump	nb	bb	nb * bb)
2	**Geophysical investigation**				
2.1	Optional: drilling of sensor and shot holes along tunnel side walls per each campaign.	metres	m	xx	m * xx)
2.2	Mobilisation of operator, preparation and implementation of measurement every 100 m of heading or at shorter intervals or permanently.	lump	tir/cint	yy	tir/cint * yy
2.3	Data processing, evaluation and reporting per each campaign or result image. Due to the high advancing speeds in mechanical tunnelling, it is necessary to carry out the data processing already in the tunnel. Results should be available within a few hours.	lump	tir/cint	zz	tir/cint * zz

ir = total investigation route cint = campaign interval

8 >> References

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