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SEISMIC PREDICTION WHILE TUNNELLING IN HARD ROCK

SEISMISCHE VORAUSERKUNDUNG BEIM VORTRIEB VON TUNNELN IM FESTGESTEIN

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1 INTRODUCTION

One of the most important requirements for the realisation of a tunnel is the knowledge of the geology and its geotechnical parameters. Owing to different circumstances, more and more underground projects must be realised in very difficult rock and soil conditions. Significant geological boundaries that cut the tunnel axis can cause serious problems and risks as there occur large break-outs, collapses, flooding and rush-ins during tunnel advance, especially when they are intersected very suddenly.

On the basis of the restrictions of rock mass overburden, accessibility, resolution etc. new geophysical methods have been developed since the late nineteen eighties and are still in the process of development since the early nineteen nineties, in order to predict in the tunnel the near surrounding. At the same time it is decisive, how fast the geophysical data are measured, processed and interpreted in order to deliver the information about the heading conditions already during the tunnel work. Besides exploratory drilling from the tunnel face, non-destructive geophysical methods can detect lithological heterogeneities within distances up to hundreds of meters. Seismic imaging is the most effective method because of its large prediction range and high resolution.

Since many years, the Tunnel Seismic Prediction System (TSP) has successfully been used in tunnelling projects world-wide (Sattel et al., 1992, 1994; Dickmann and Sander, 1996, Dickmann and Awasthi, 1999). The latest TSP generation – the TSP 203 *PLUS* system – has been introduced to the tunnelling market and ongoing developments aim at further improvements for better interpretation of geotechnical relevance. However, essential for the acceptance of this system is the easy handling of best technology and the sophisticated software package that both provide an important impact on logistic optimisation that the contractor himself can manage and implement in the tunnelling work flow.

2 THE TSP METHOD

Small explosive charges are fired individually in 1.5 deep boreholes aligned in the tunnel wall. Each shot sends out seismic wave energy which propagates through the rock mass. (Fig. 1). Changes in rock strength (acoustic impedance) as they occur for example at fracture zones or at changes of rock formations, will reflect a certain portion of the signals whereas the remaining portion will be transmitted. After a certain travel time the reflected signals will arrive at the highly sensitive receivers that are deployed in the tunnel wall. Analysing the wave propagation velocity field of the given rock formations allows the travel time of the reflection signals being converted into distance (depth). As a result, the location of the reflection (rock discontinuity) in space can be determined presenting the intersection angles with the tunnel axis as well as the distance to the tunnel face.

Figure 1 illustrates only the interested wavefronts (red-coloured: released energy from the shot, blue-coloured: reflected energy from the discontinuity) as parts of the full spherically spreading waves.

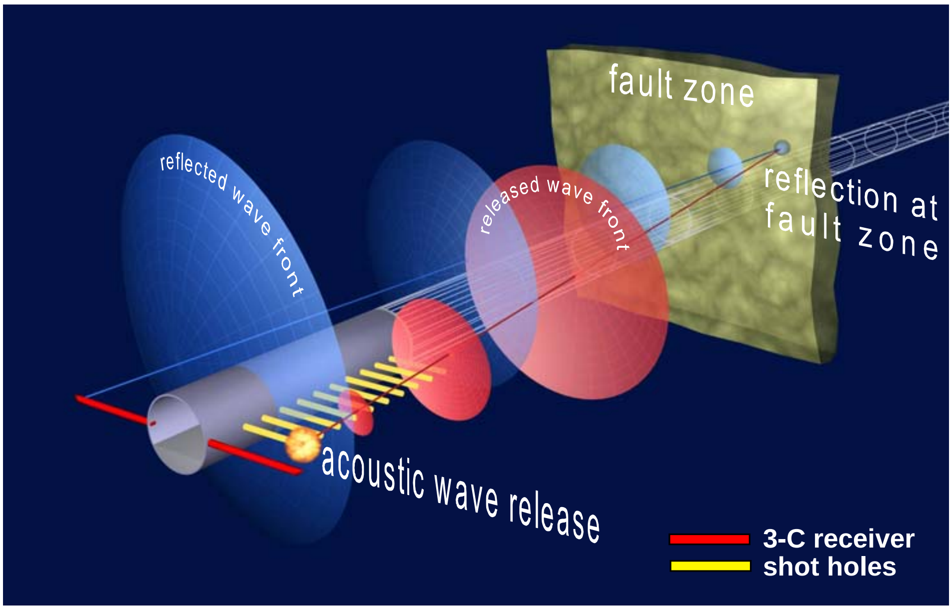


Figure 1

Principle of the Tunnel Seismic Prediction Method

After the measurement in the tunnel, which is taken in tunnelling production breaks of around one hour, the seismic data can immediately be processed on a Laptop PC at the construction site. The specially designed TSPwin software leads the user automatically through the sequence of processing. A subsequent evaluation routine presents the seismic events with reference to the chainage of the tunnel.

The result will provide a 2D- or 3D- overview of the event distribution within the predicted area and will characterise the transition of rock strength by charts of computed rock mechanical properties within the prediction area. Hence, the result of the seismic prediction can be compared directly with the geological profile (prognosis) and if necessary the prognosis can be completed on time.

3 THE SEISMIC RECEIVER UNIT

The receiver unit for picking up the seismic signals operates in a special steel casing, which will be firmly bond to the rock formation by cementing or using two-compound resin cartridges. It will be inserted into the steel casing before starting the survey. The external dimension of the receiver allows to set the receiver casing in a borehole with a nominal diameter of 42-43 mm and a total length of 2 m. With the use of resin cartridges the casings can be installed within a few minutes since the compound allows a reactions time of 5 minutes only. Hence, approx. 10 minutes after installation the steel casing is firmly bond to the rock mass and the receiver rod is ready for insertion and measurement (Fig. 2). Besides using hand-hold drilling machines the setting of the receiver casing can also be done by rocket boomers like the normal installation of rock bolts.

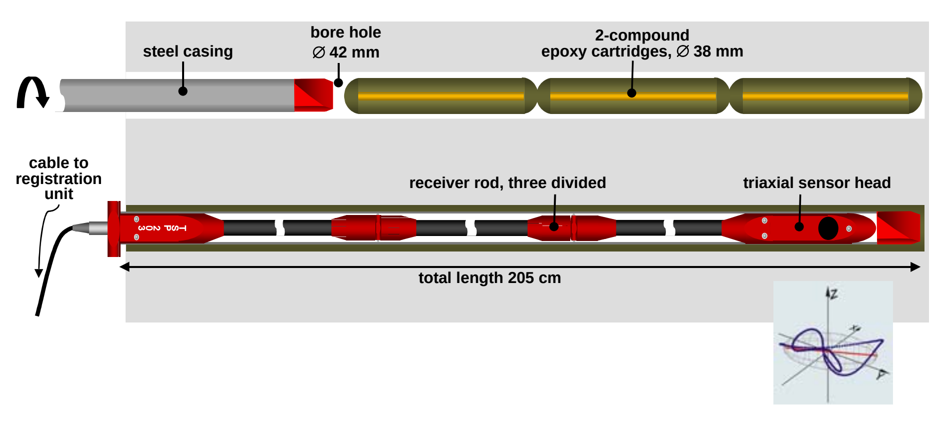


Figure 2

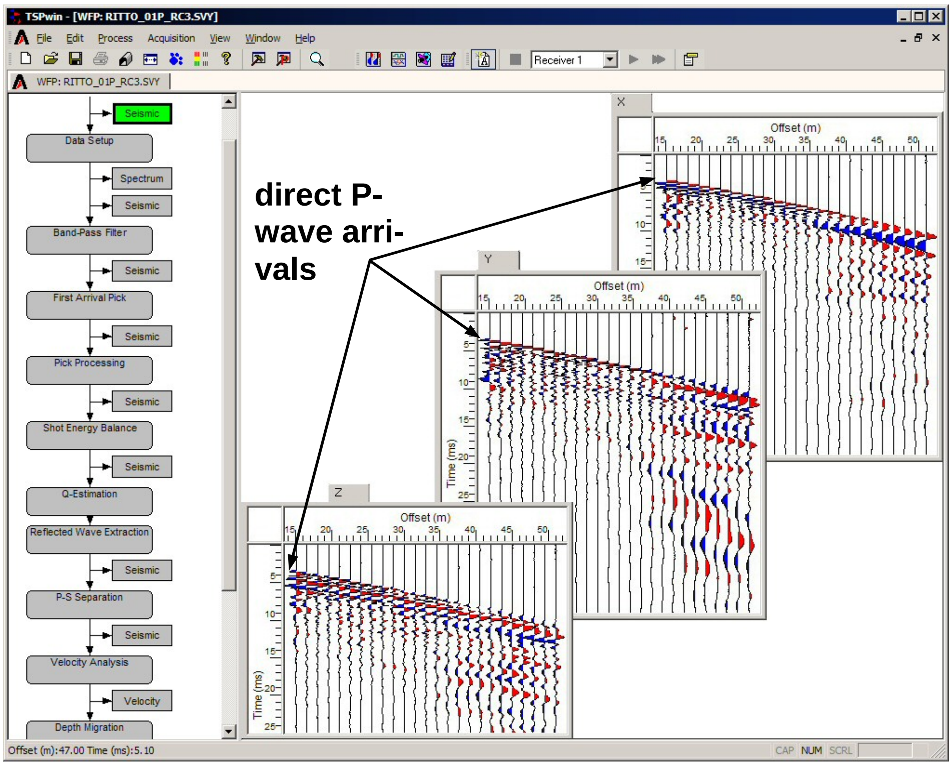
Setting of the receiver rod equipped with an ultra sensitive triaxial sensor head: (top) while turning the steel casing, its sharp blade is cutting the resin cartridges and the hardening process is starting. (bottom) After 10 minutes the receiver rod can be inserted into the casing that is already firmly bond to the rock mass. The hodograph in the lower right corner illustrates particle motion of the incoming seismic signals and the resulting wave field vector in a given time window.

The receiver unit consists of an ultra sensitive triaxial seismic accelerometer, which transforms the seismic signals (acoustic signals) into electrical voltage signals within a frequency band from approx. 10 to 5000 Hz covering the required dynamic range. It provides a coverage of all three directions (x-y-z-component) in space which guarantees a recording of the full wave field and hence, a discrimination of the different wave types as compressional (p-) and shear (s-) waves. Furthermore, the three component recordings which are aligned normal to each other enable the computation of the wave incidence's direction. Despite its total length of 2 meters divided into 3 parts the receiver rod enables a quick and easy installation.

4 THE PROCESSING AND EVALUATION CAPABILITY OF TSP 203 *PLUS*

The entire software package TSPwin is embedded in a modern Windows based architecture supporting a multi document interface. Data acquisition and processing is usually directly handled on a standard field laptop PC. An interactive process control flow provides a high user-friendliness while guiding the user straightforward and directly to the results (Fig. 3). All parameters for the given data processing modules are set automatically or semi-automatically. By analysing each single data set the program finds and already sets suitable parameters. Nevertheless, manual processing is still possible by inserting parameters via comfortable dialogue boxes.

Since the 3C-receiver rods record the entire incoming wave field in its three spatial directions, the program is able to separate and extract the wave field in its compressional (P-) and shear (S-) parts (Fig. 4) applying a polarisation analysis. Hence, both types P- and S-waves are being simultaneously processed by the following processes of velocity analysis and depth migration. The resulting velocity field for the area ahead of the face indicates wave velocity variations within the rock mass (Fig. 5). This information is put into the depth migration process where the reflection energy from geological discontinuities migrates to the right location in space. Furthermore in the process of reflector extraction, the most prominent reflections are automatically detected and set into a numerical format by the program (Fig. 6).



Offset (m):47.00 Time (ms):5.10

Figure 3
(left pane): The process control flow allows an easy handling while clicking on the processor and result boxes, respectively. (right pane): Seismic raw data view. 25 traces (shots) are shown in an order according to ascending offset (distance shot-receiver) for each component X, Y and Z. The dominant first arrival signals represent the direct compressional wave (p-wave).

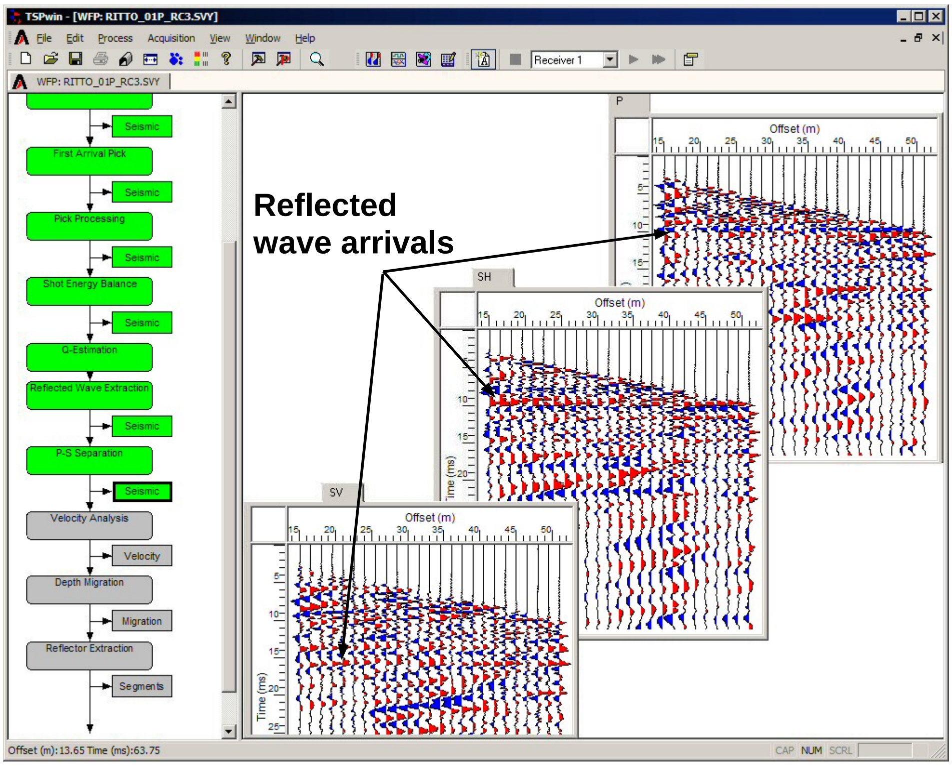


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Figure 4

(left pane): The process control indicates the already successful processed steps by green coloured boxes. (right pane): Seismic data view of the wave-type separated components P, SH and SV (s-waves). The dominant direct wave signals are suppressed while the reflected wavefield is enhanced.

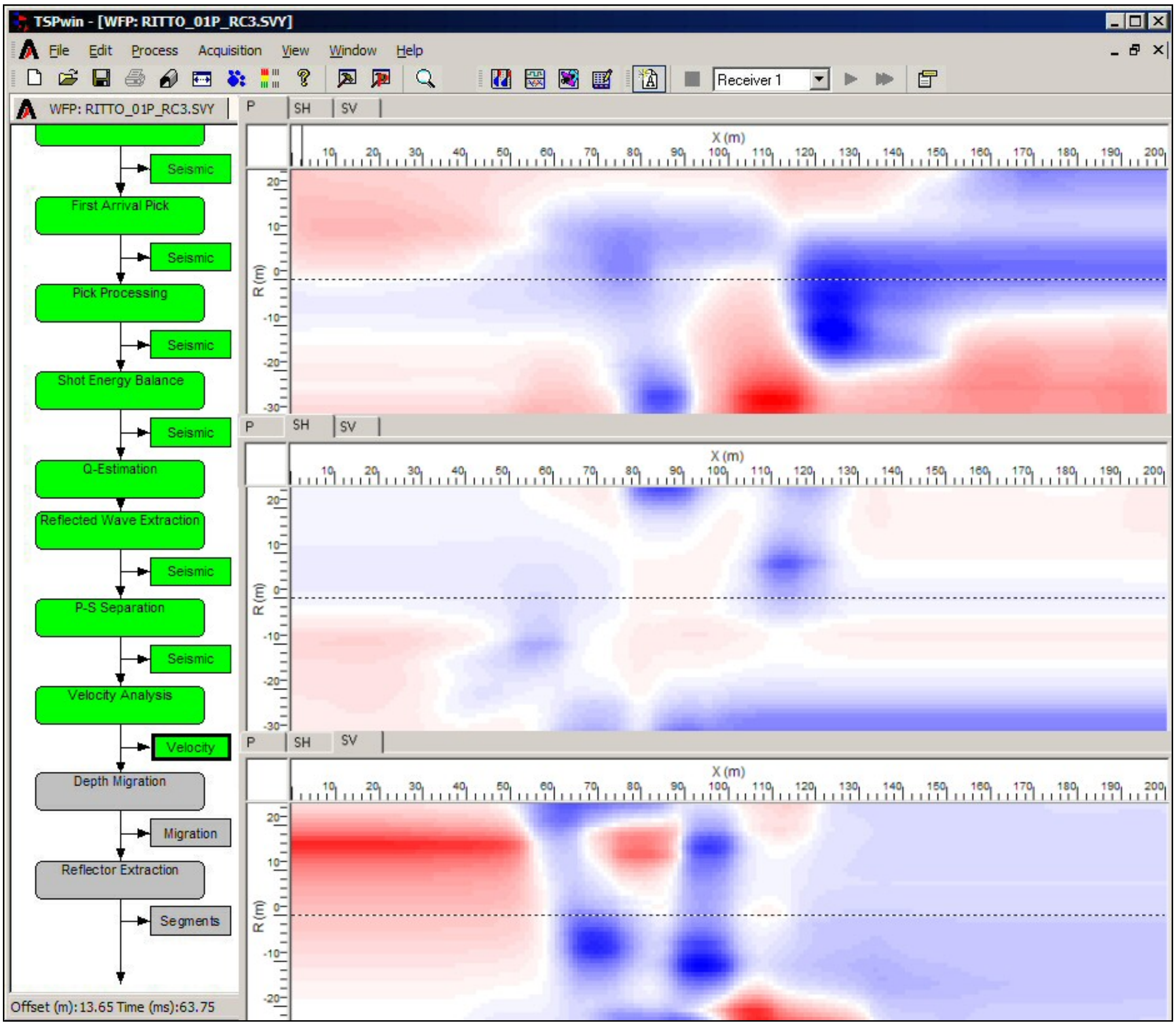
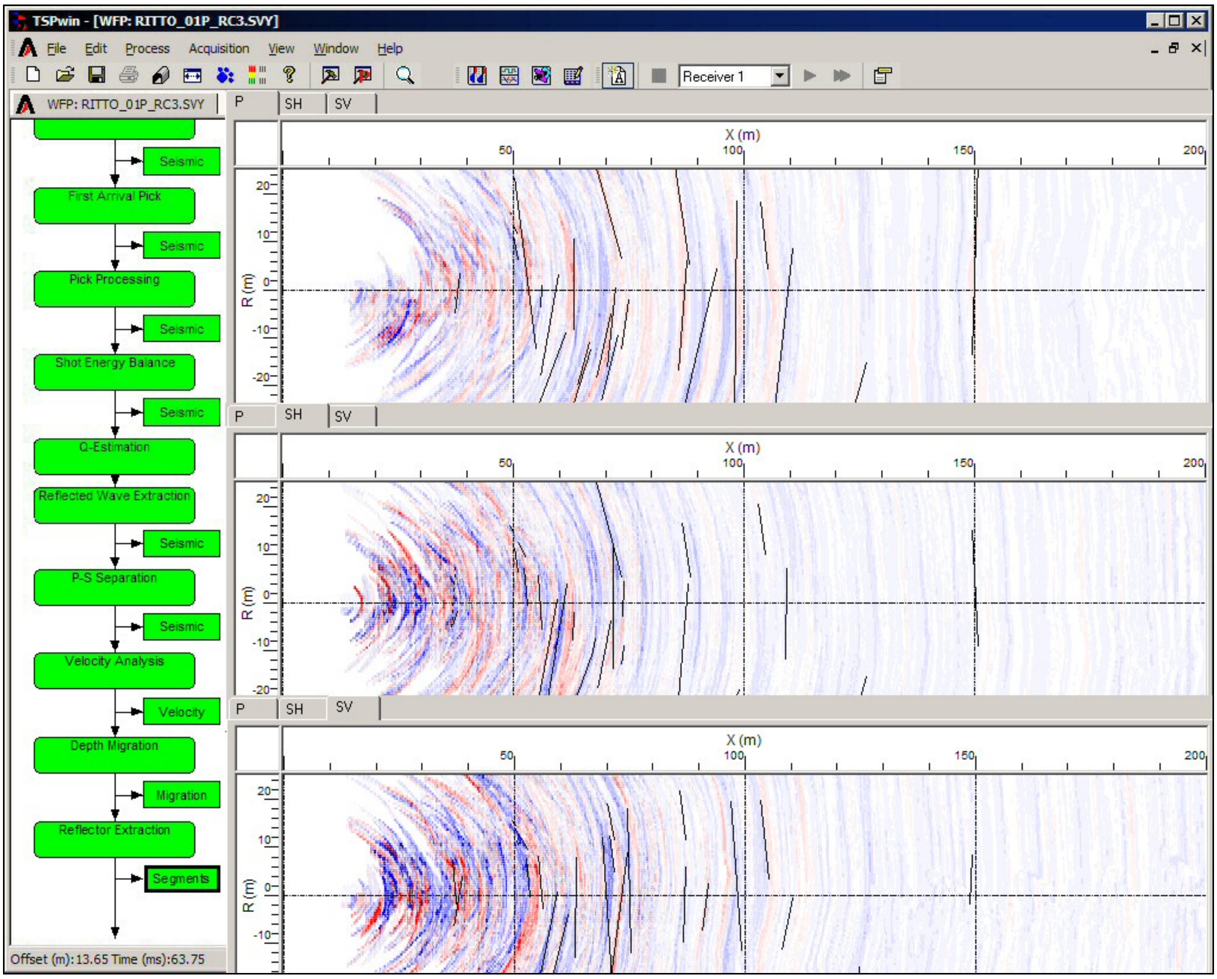


Figure 5 (right pane): Velocity distribution view of the wave-type separated components P, SH and SV.

P: Min=4450m/s, Max=5450m/s
SH: Min=2780m/s, Max=3380m/s
SV: Min=2830m/s, Max=3430m/s

A further outstanding feature is the 3-D and 2-D result display. The interactive 3-D display allows geological discontinuities to be visualised in any perspective (Fig. 7 & 9). The 2-D display presenting the geological targets in horizontal and vertical cross sections with reference to the tunnel axis additionally shows rock mechanical parameters in charts derived from the velocity field of the velocity analysis (Fig. 8). Finally, as a further impressive benefit of the software the results can be made directly available on-site within a few hours.



Offset (m):13.65 Time (ms):63.75

Figure 6 (right pane): Kirchhoff Depth Migration images of the wave-type separated components P, SH and SV along 200m ahead of the receiver positions. Black lines indicate the automatically extracted most dominant reflector elements.

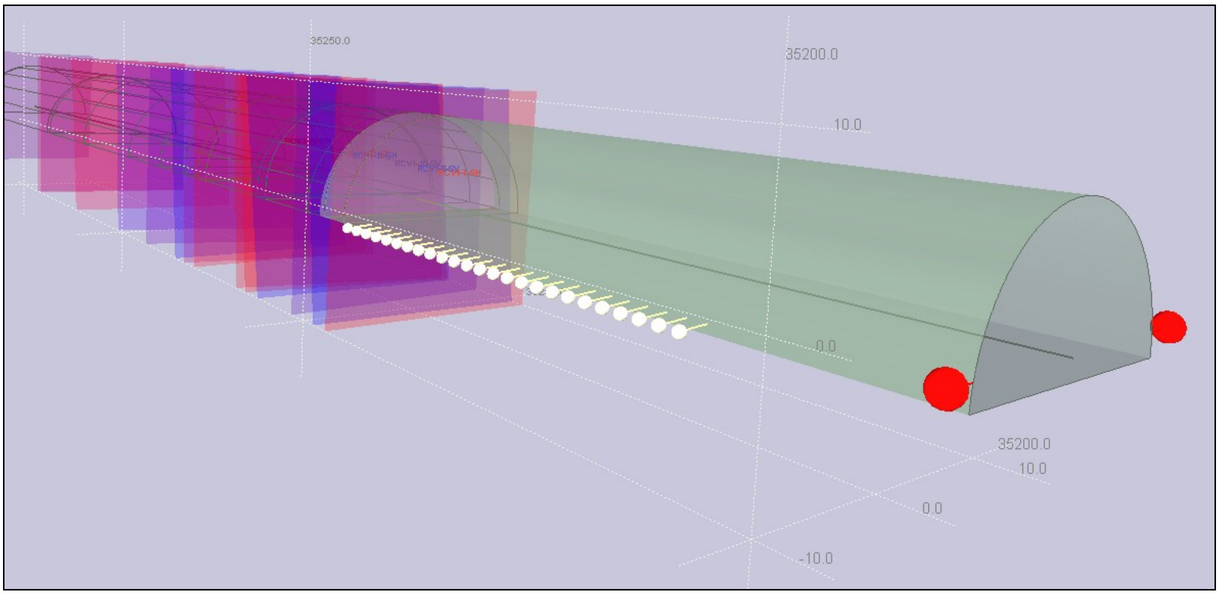
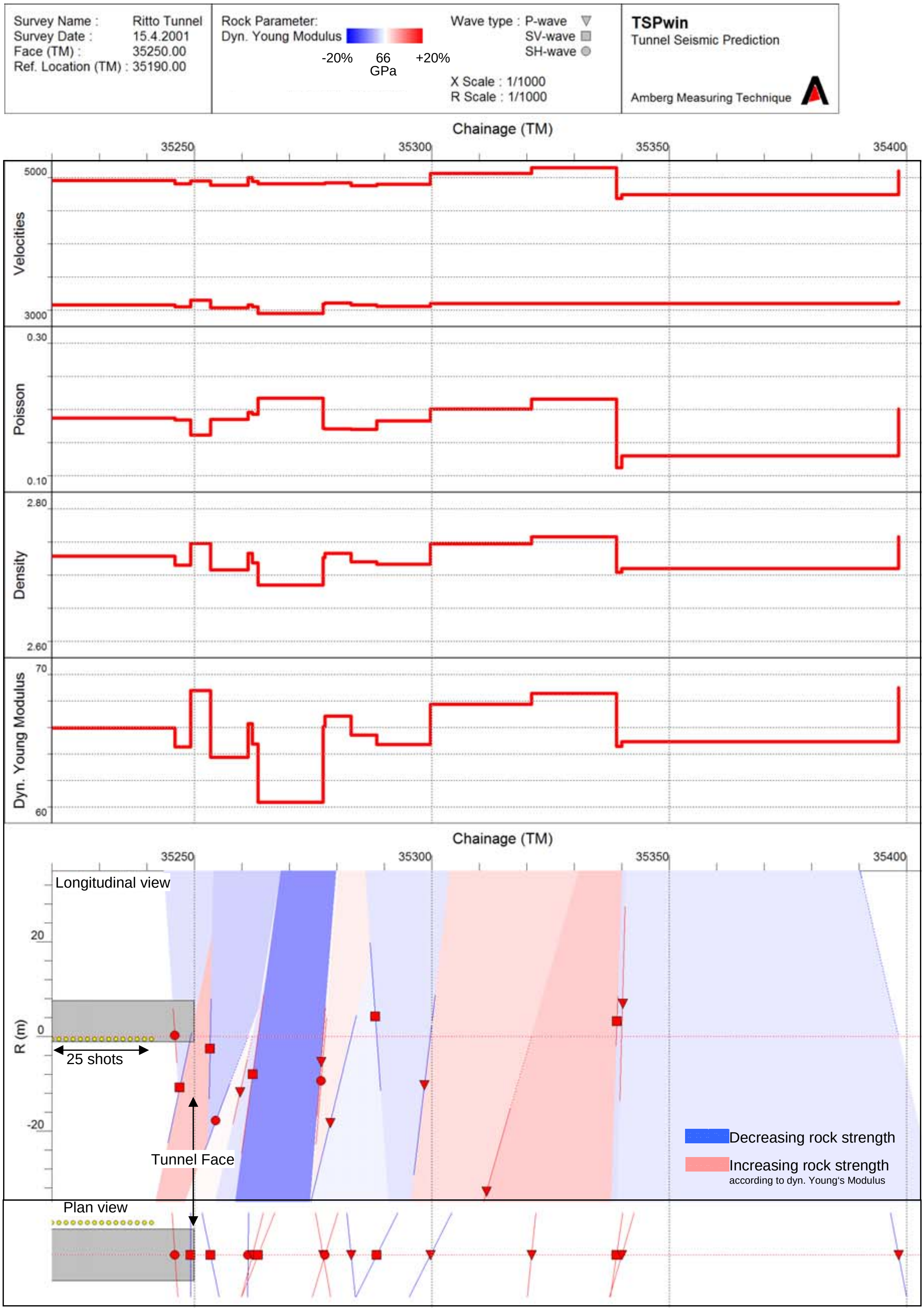


Figure 7 TSPwin view presenting detected boundaries in an area of 150m ahead of the tunnel face. The interactive 3-D functionality presents boundaries of rock strength changes in any perspective. Red dots indicate receiver position and white dots the alignment of 25 shot points.



Survey Name : Ritto Tunnel
Survey Date : 15.4.2001
Face (TM) : 35250.00
Ref. Location (TM) : 35190.00

Rock Parameter: Dyn. Young Modulus

Wave type : P-wave
SV-wave
SH-wave

X Scale : 1/1000
R Scale : 1/1000

Figure 8 TSPwin result printout showing longitudinal and plan view and selected rock mechanical property charts. In the range of 150 meters ahead of the face one significant rock zone of decreasing rock strength and of approx. 14 meters length has been detected. Minor fracture zones are indicated in front and behind this zone

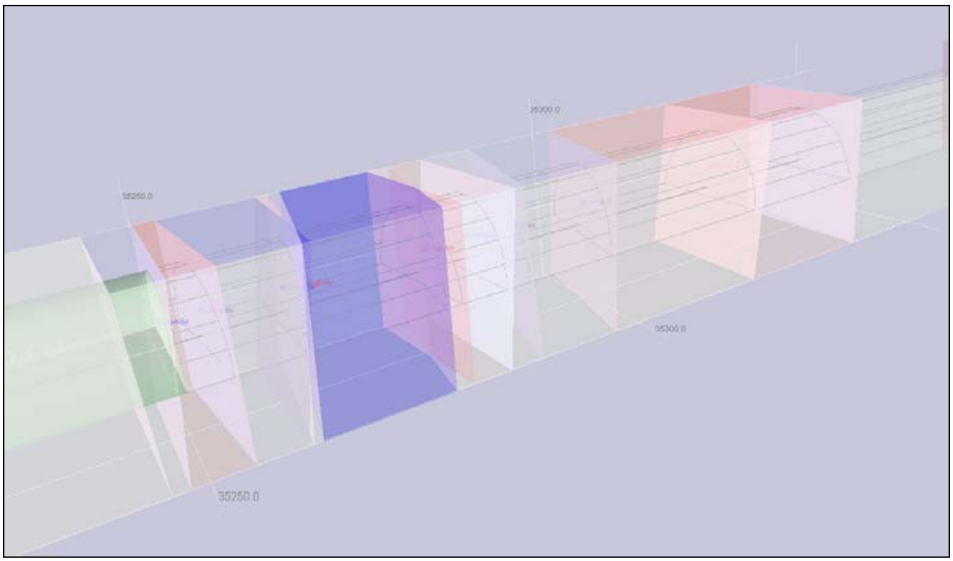


Figure 9 TSPwin view presenting detected boundaries in an area of 150m ahead of the tunnel face. The interactive 3-D functionality presents rock zones by shaded volumes according to Young’s Modulus changes. The dark blue zone indicates a 20% decrease of this Elasticity Modulus compared to the value of the already excavated tunnel section. Notice also the graphical transfer of computed dip and strike angles of the boundaries.

5 TSP-PROJECT EXAMPLE: ZUCKERBERG GALLERY, GERMANY

In the framework of modernisation measures to the existing sewage plants the city of Stuttgart invested in the building of a second sewer under the Zuckerberg mountain in order to convey mixed water through this 2747 meter long tunnel, with the old sewer being used for dirty water. The Zuckerberg sewer II has an average diameter of 3.4m and was being advanced from the north portal by open faced TBM.
The sewer crosses a ridge of Triassic hard rock superimposed by thin young soft soil. The limestone of the Upper Muschelkalk of 80 m thickness is crossed by two almost vertically dipping faults. Besides minor phenomena of corrosion along single fracture planes no indication of karst phenomena inside the limestone sequence had been given from previous investigations. The sewer entirely runs through this limestone (Fig. 10).

The TBM heading encountered unforeseen problems due to some karst zones and zones of tectonic disruption, which abruptly came in without any previous notice. The length of the fracture zones passed ranged between 10m and 30m, where boulders were torn from the rock mass by the turning cutter wheel due to poor formation strength.

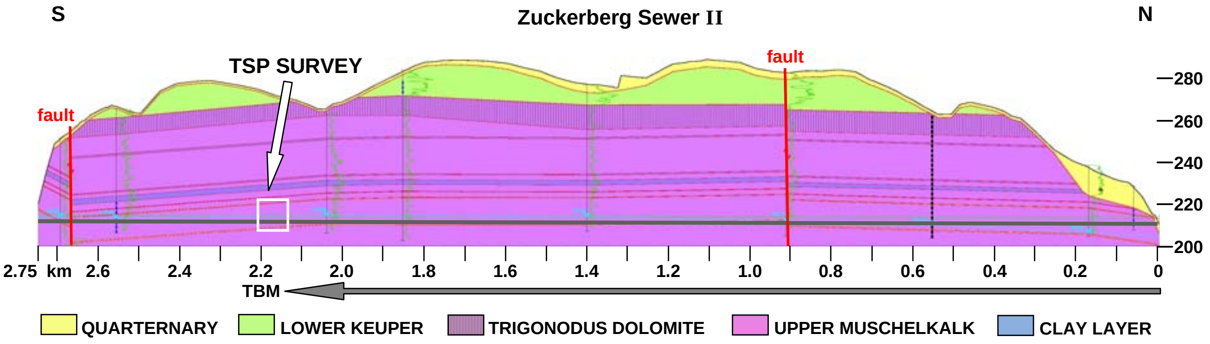


Figure 10 Longitudinal section of the Zuckerberg geology (prognosis).

These enormous overbreaks resulted at the tunnel face forced the site personnel to cut loose boulders manually in various cases. At tunnel face station TM 2134 because of considerable overbreak a core drilling had been ordered, which required large-scale conversion work of the TBM.

In conclusion, the 38m long horizontal borehole and two further vertical boreholes from the surface could not give any evidence of possible fracture zones.

The contractor decided to apply a TSP survey in order to predict a possible end of the current karst zone. The figure shows the longitudinal section image of the TSP survey conducted at face TM 2154.

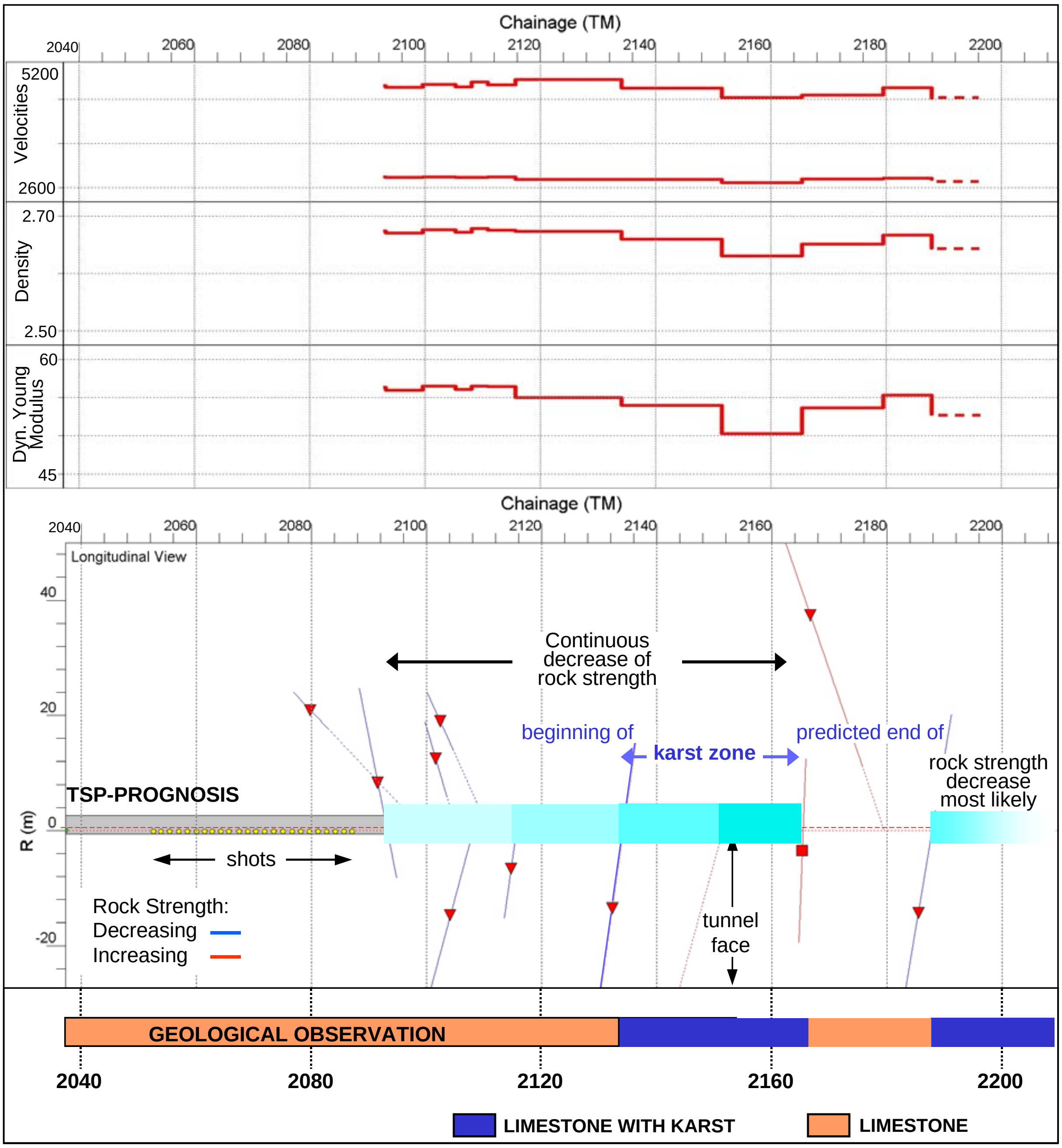


Figure 11 Longitudinal 2D section in combination with selected rock mechanical parameters. The continuous drop down of the Young's Modulus characterises the Karst zone. A further raise up is obvious when the Karst zone ends. In comparison with the observations the TSP prognosis fully confirmed the end of the Karst zone.

Because of the unplanned TSP operation and lack of working space in the TBM backup area the receivers were located at TM 2037, 60m behind the ideal position. With 117m between receiver and tunnel face the interpretation range still extends some 70m ahead of the face.

The TSP results firstly confirmed the front of the karst zone at TM 2134 and revealed the corresponding end at TM 2165, 11m ahead of the face.

Moreover, it predicted a further decrease of rock strength from TM 2188. Due to the caved zones, poor geology conditions and the related high signal absorption no further seismic signal energy was possible to evaluate. After start-up from the shutdown, the TBM left the karst zone at TM 2166 and encountered poor rock quality again at 2190.

Because the TSP survey predicted a shorter range of karstic fracture zone the contractor decided to slowly continue the heading instead of planning and excavating an expensive bypass through the karst zone. Moreover, he was pre-warned for a further decreased rock strength that enabled him to take appropriate logistic measures for the necessary reinforced rock support. Consequently, the contractor saved several days of TBM downtime and related extra costs.

6 TSP-PROJECT: CHESHMEH-LANGAN WATER SUPPLY, IRAN

The Cheshmeh Langan Water Supply Tunnel project consists of a 13.8 km long tunnel that is designed for transfer and diverting water of the rivers Dez and Karaun and their branch rivers Sardab, Sibak and Cheshmeh Langan to the Zayandeh River valley routing to the city of Esfahan.

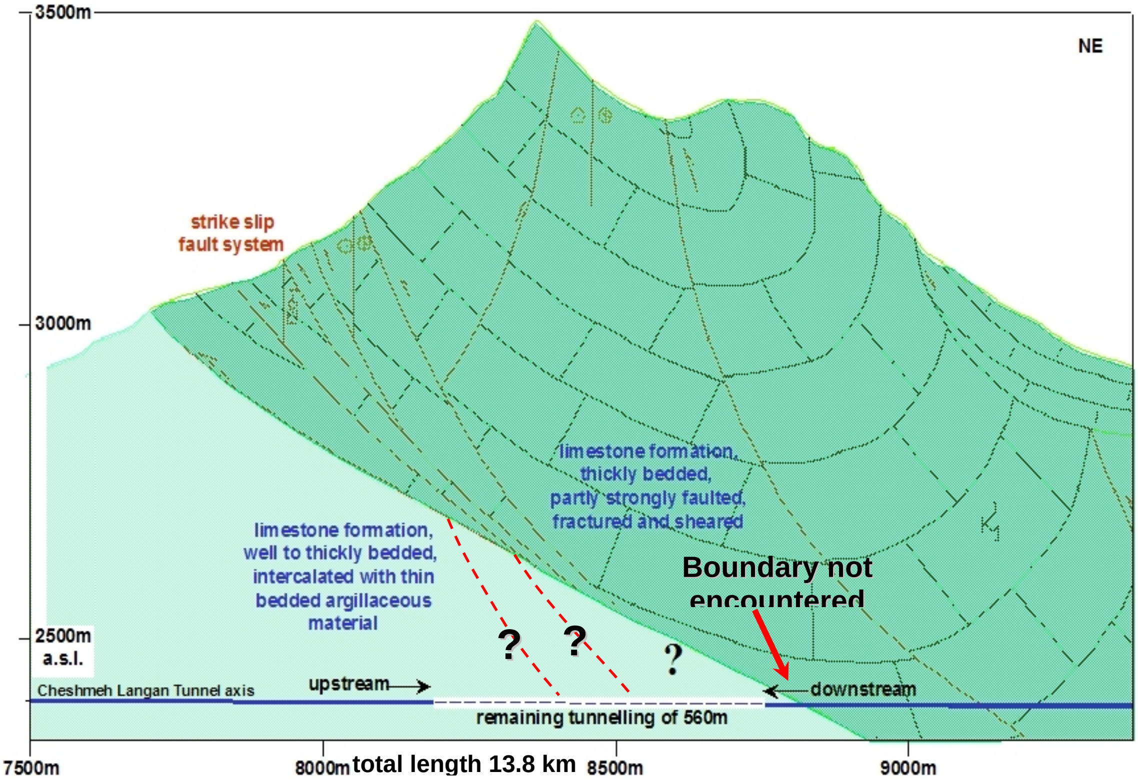


Figure 12 Longitudinal section of geological prognosis for remaining tunnelling stretch of 560 m at the time of TSP measurements. Limestone formation, partly strongly fractured. Target of forecast: high water inrush is supposedly related to wanted interface and would cause risky undertaking for upstream heading.

The client is the Esfahan Regional Water Board, who pursues an annual water transport's capacity of 218 million m^3 in the future. The tunnel having a slope of 2‰ was being under excavation from both portals using TBMs of 3.9 m diameter.

Two measurements had been carried out in the Cheshmeh Langan Tunnel, one of each in the upstream and the downstream heading. The tunnel is located in a general stabile rock mass of differing limestone formations, well to thickly bedded, one formation partly strongly faulted, fractured and sheared, another intercalated with thin bedded argillaceous material. Almost in the middle of the tunnel route, where the two headings are supposed to meet each other, the coverage reaches up to 1000 m above the already 2400 m a.s.l. located tunnel route (Fig. 12).

The target of the measurements was to identify the zone between the above-described differing rock masses of the remaining tunnelling stretch of 562 m. At this zone heavy inrush of water was expected and it was vital that this zone was intersected by the downstream of the two 3.9 meter open faced TBMs.

It was shown that the area between the two TBM's was not homogenous. TSP predicted 4 rock zones in the range between the two headings where rock strength was decreasing and possible water bearing could have been expected. Predicted areas of those weaker rock zones are marked with a shaded background in figure 13. One of the zones - between TM 8654 and TM 8689 - was regarded as the expected transition zone describing a 35m wide rock mass fracturing. At a later date, the downstream excavation encountered the expected transition within this predicted fracture zone that was connected with minor water inrush.

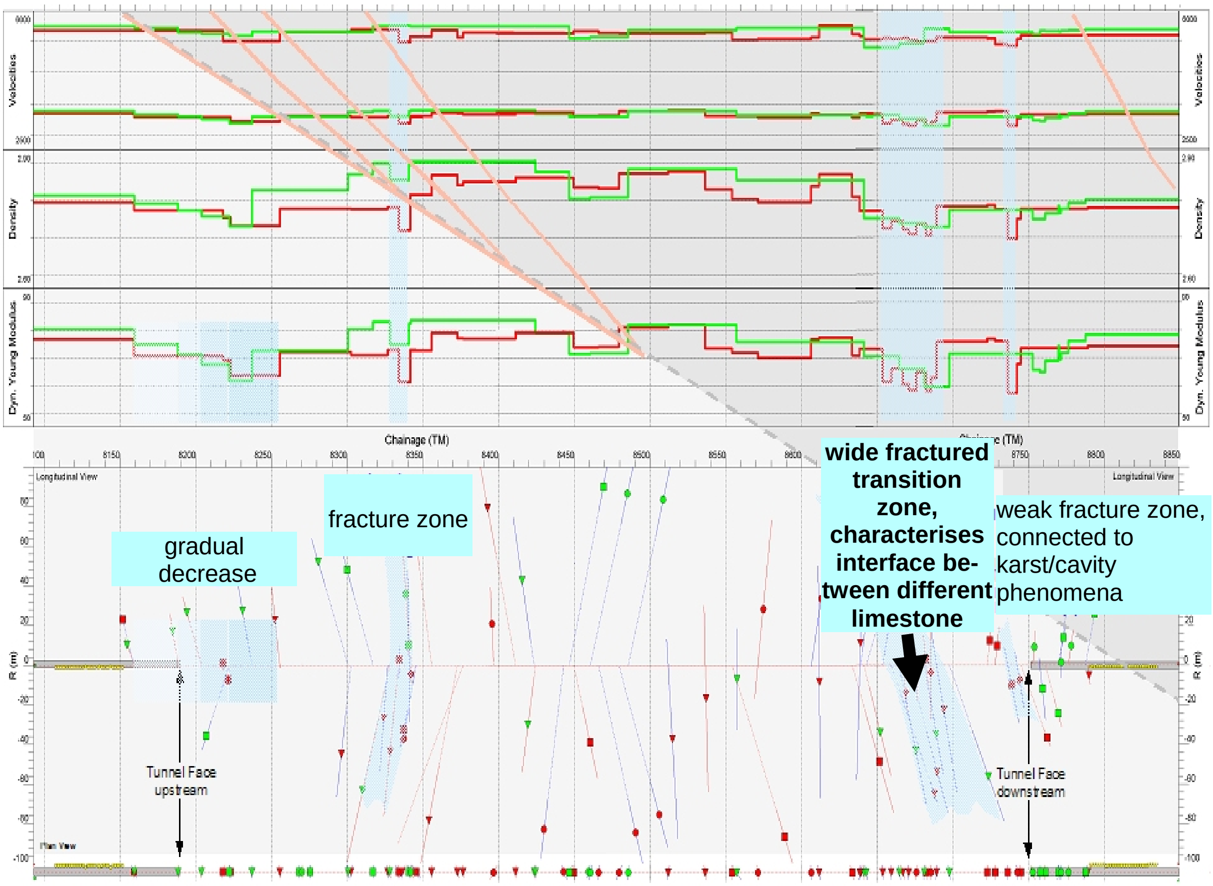


Figure 13 2D result presentation with longitudinal and plan view and selected rock property charts at up- and downstream.

7 CONCLUSION

Significant geological boundaries that cut the tunnel axis at high angles cause the most serious problems and risks during tunnel advance because they intersect very suddenly. Thus, where no forms of prediction ahead are carried out, there is little or no warning and time to put preventative and remedial construction measures into place. Nowadays, geophysical methods become more and more an essential part of modern and mechanised tunnelling.

They can be applied throughout both design and construction stages and enable continuous risk assessment and management during construction. Especially during tunnel construction, TSP can furthermore achieve considerable cost and time savings and helps the contractor in logistical planning on possible construction measures.

TSP is a valuable method to get additional important information on the conditions of rock to be excavated and a further characterisation due to the evaluation of rock mechanical properties. Data acquisition does actually not delay or effect the tunnelling operation itself and can be performed continuously or as needed. For an appropriate efficient tunnelling advance predictive information gained by TSP investigation can be used to guide appropriate measures in tunnel construction.

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