Drivage-Concurrent Tunnel Seismic Prediction (TSP)

Results from Vereina North Tunnel Mega-Project and Piora Pilot Gallery

By Thomas Dickmann and Bernhard K. Sander

This paper describes TSP case history examples from two current rail tunnel construction sites in Switzerland – the Vereina North rail tunnel at Klosters and the Piora Pilot Gallery in the Ticino River valley for part of the proposed Gotthard Base Tunnel (Figure 1).

System summary

The TSP system is a unique underground reflection seismic package comprising measurement instrumentation and its own interpretation software (1,2). By employing the principle of echo sounding, it serves to predict changes in rock physical properties ahead of and around spatially very restricted underground excavations such as tunnel tubes (Figure 2).

In a typical survey, explosive charges are detonated individually in approximately thirty 1.5 m deep shot boreholes along a tunnel wall. A fraction of the outgoing energy of each shot is reflected back off physical boundaries in formation ahead, such that it can be recorded by the survey array in the tunnel.

Data from all shots are recorded and processed by well-established, routine oil industry seismic methods. They are then transformed and projected onto so-called diffraction stack plane images that represent space sectors ahead of the tunnel. These images display trains of red or yellow circles with different diameters that represent reflected events with different energy intensities (Figure 2). Red indicates positive signal polarity and a transition to softer rock (caution !), yellow negative signal polarity and a transition to harder rock. Geological boundaries usually show up as a series of sub-parallel red and yellow event trains.

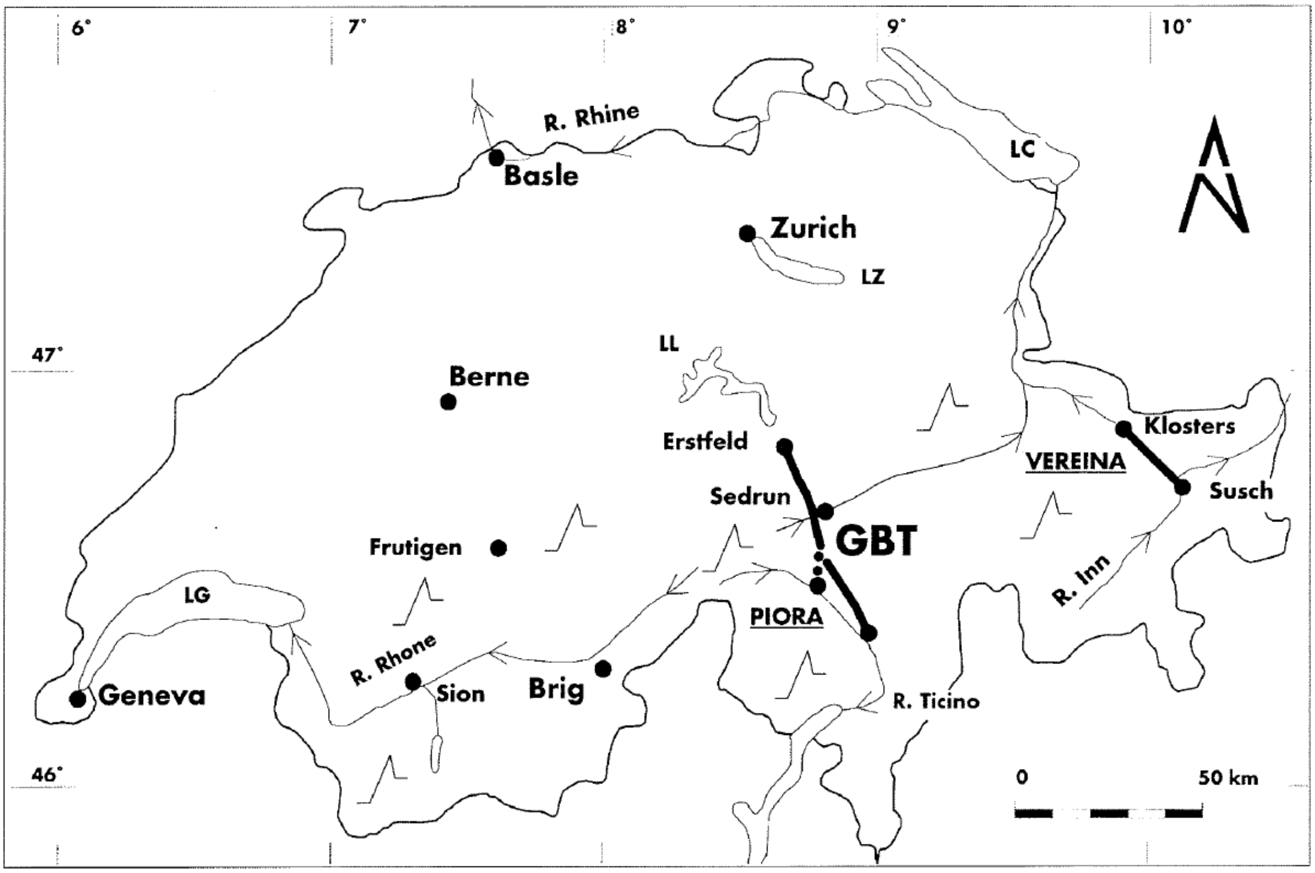

Figure 1 Locations of TSP case history surveys in Switzerland, GBT=Gotthard Base tunnel.

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Error margin vs investigation range of the TSP system.

Investigation range [m]	Error Margin in predicting distance ahead along tunnel access to intercept of an interpreted boundary
0 - 50	+/- 5%
50 - 200	+/- 10%
200 - 1000	at least +/- 20 %

Through an interactive event picking process in the software, the most significant reflection events can be selected and portions of their source boundaries can be imaged in space. In a final interactive projection process, the orientations of source boundary planes are defined relative to the tunnel axis and their intersection with the tunnel axis ahead of the face is estimated and plotted in the engineers summary. The engineers summary is a projection of significant boundary planes onto vertical and horizontal sections through the tunnel axis ahead of the tunnel face.

One should point out that this projection process is not a theoretically ideal solution. It is a good approximation dictated by the requirement to trade off short computation times against tolerable error margins. It has demonstrated its practical value in over 150 surveys that include some 20 TSP system sales worldwide (2).

Figure 3 summarizes a typical survey spread. Shothole charges are connected via a trigger box to a blasting machine and recording unit. The recording unit is normally connected to two 2.5 m long receiver rods, one in the left, the other in the right tunnel wall. The receiver rods fit tightly into steel casings cemented into the receiver boreholes at least 12 h earlier to achieve optimum formation coupling. Receiver sensors are a series of high frequency accelerometers oriented in two directions parallel and perpendicular to the tunnel axis.

The investigation range for a standard TSP survey in most rock conditions is 150 to 200 m ahead of the face with a maximum boundary localisation error of ±20 m at the far range. By increasing the length of the survey spread and shot charges, investigation ranges of up to 1 km can be achieved, albeit at the expense of greater error margins (Table). Also, boundaries intersecting the tunnel axis at low angles will display the largest predictive error margins, whereas those intersecting at high angles will display the least error margins.

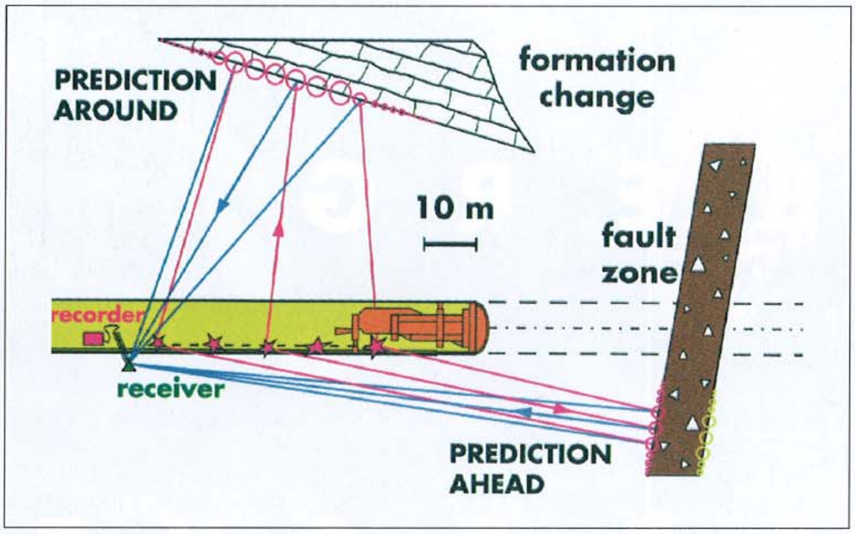

Figure 2 Principle of tunnel seismic prediction technique.

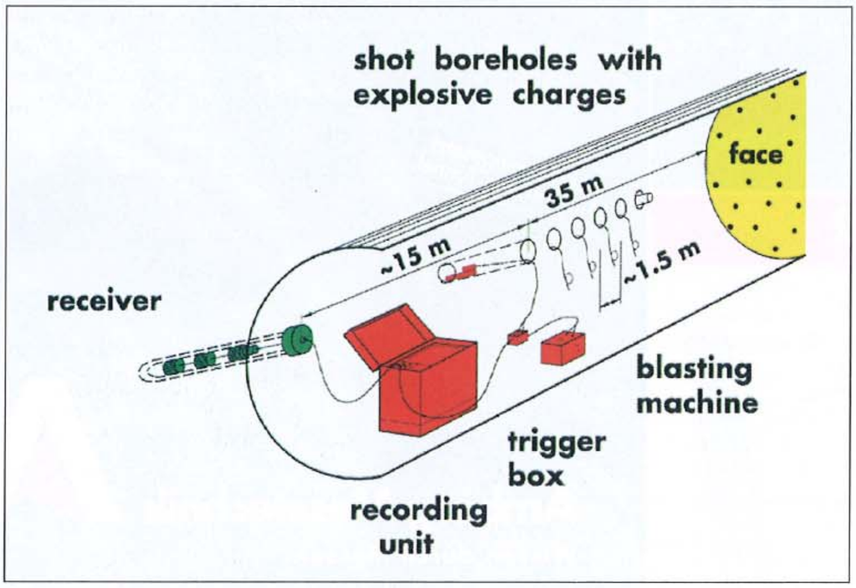

Figure 3 TSP survey spread.

Vereina North Rail Tunnel Example

Designed for improved access to the Inn valley and associated holiday resorts, the 21 km Vereina tunnel construction project is currently one of the largest single tube tunnel heading projects in Europe. It has an average diameter of 7.5 m and is being advanced simultaneously from the north portal by TBM (currently at approximately TM 9 000) and from the south portal by drill and blast heading (currently at approximately TM 7 000). Breakthrough is expected around spring 1997.

For TBM drivage, TSP was selected from the start as the fastest and lowest cost prediction technique. Drill probing ahead of the TBM was not feasible due to unacceptable risk of TBM damage.

We have performed some 40 TSP surveys to date at Vereina. The Vereina tunnel geology is a particularly challenging TSP and construction setting on account of its highly variable geology made up of structurally complex superimposed nappe structures (2).

Here just one example is presented – the special survey commissioned urgently at face TM 3618 days before the 1995 Christmas break shutdown. Considerable convergence was being experienced in brittle, caving schists. In the absence of an improvement in rock conditions, this im-

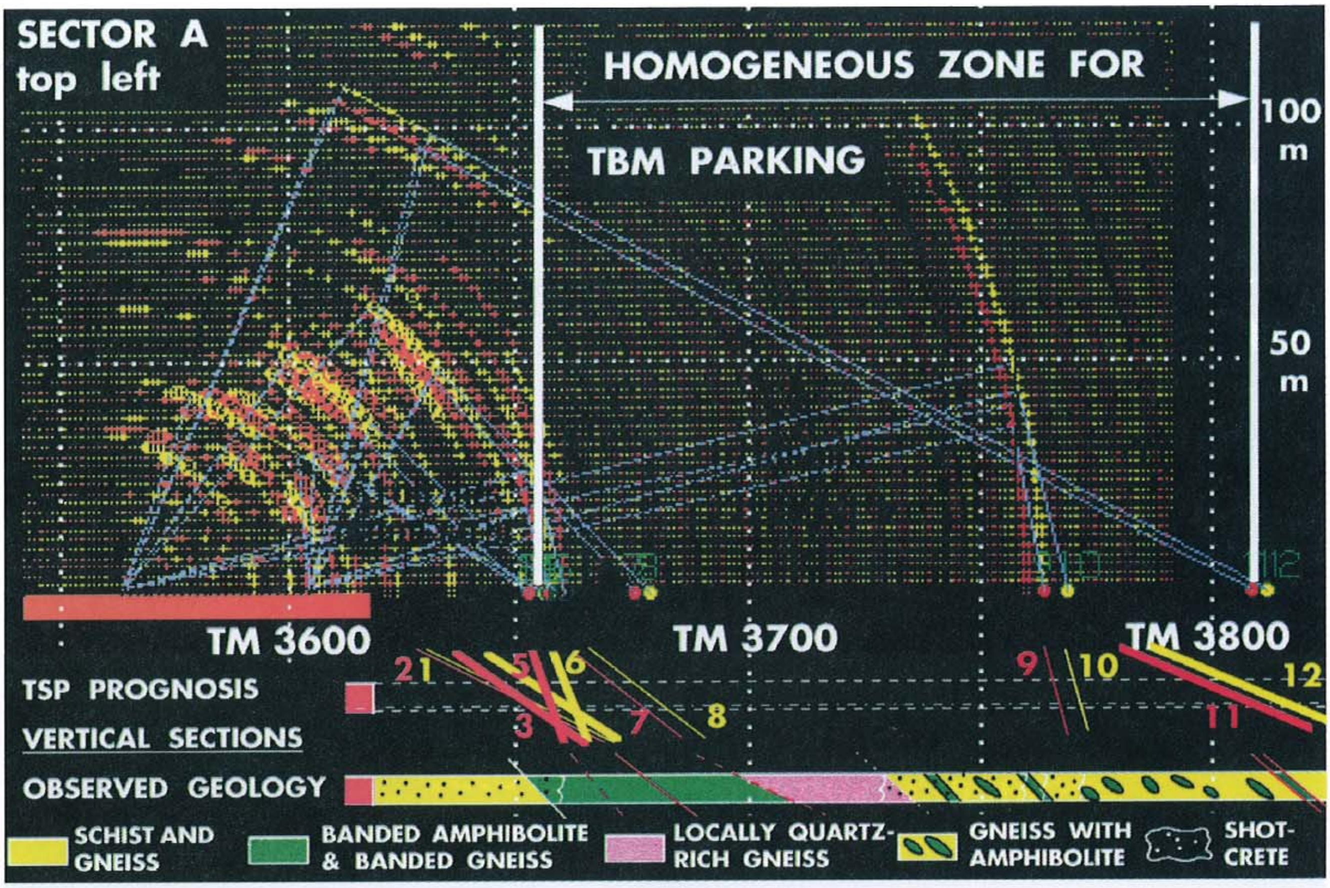

Figure 4 Representative result of TSP survey at face TM 3618, Vereina North rail tunnel near Klosters, Switzerland.
Top: Seismic Diffraction stack image, Below: TSP prognosis showing most significant recorded boundary planes ahead of tunnel face in vertical section, Bottom: Summary of tunnel geology in vertical long section as observed upon subsequent drivage.

plied TBM jamming upon halting the advance, with the threat of TBM damage and major downtimes later to manually widen the tunnel profile in order to set the TBM free again. The two alternatives were to stop and widen the tunnel profile manually by 20 to 30 cm in the area of the cutter wheel at considerable added expense in order to compensate for convergence during the Christmas break, or to make a dash for a zone of better ground ahead, if such a zone could be located by TSP.

Figure 4 (top) shows the characteristic diffraction stack plane image for the upper left search sector (1A) of the TSP survey conducted at face TM 3618. The red bar is a schematic of the vertical tunnel section showing receiver position at TM 3543 and the shotpoints extending up to the tunnel face. The interpretation range extends some 200 m ahead of the face. Ten to twelve major reflection events with variable orientations to the tunnel axis are recognized.

Plotted below this is the engineers summary (TSP prognosis) depicting the most important recognized boundary planes projected onto a vertical long section. All of the observed boundary planes were assumed to strike approximately perpendicular to the tunnel axis – hence the engineers summary in horizontal section is not shown here. A final vertical long section at the very bottom of Figure 4 is a schematic summary of the tunnel geology as mapped upon subsequent drivage. For summary purposes, the corresponding horizontal section has been excluded. Geological boundaries in plan section were observed to strike at high, but variable angles to the tunnel axis. This clearly introduces some unavoidable discrepancies between the TSP prognosis and geological reality.

In the TSP results, a first seismically reflective rock zone extends from TM 3570 to sub-parallel events 5 (red) and 6 (yellow) projecting to intersect the tunnel axis at TM 3657 and TM 3660 respectively. This zone was interpreted as the continuation of the bad ground experienced at the face. Thereafter, yellow events 4 and 6 herald a transition to significantly harder rock and a change in structural orientations. Ignoring event pairs 7, 8 and 9, 10 that represent subordinate minor fault or fracture zones, a seismically very quiet zone extends from TM 3660 up to the next pair of low

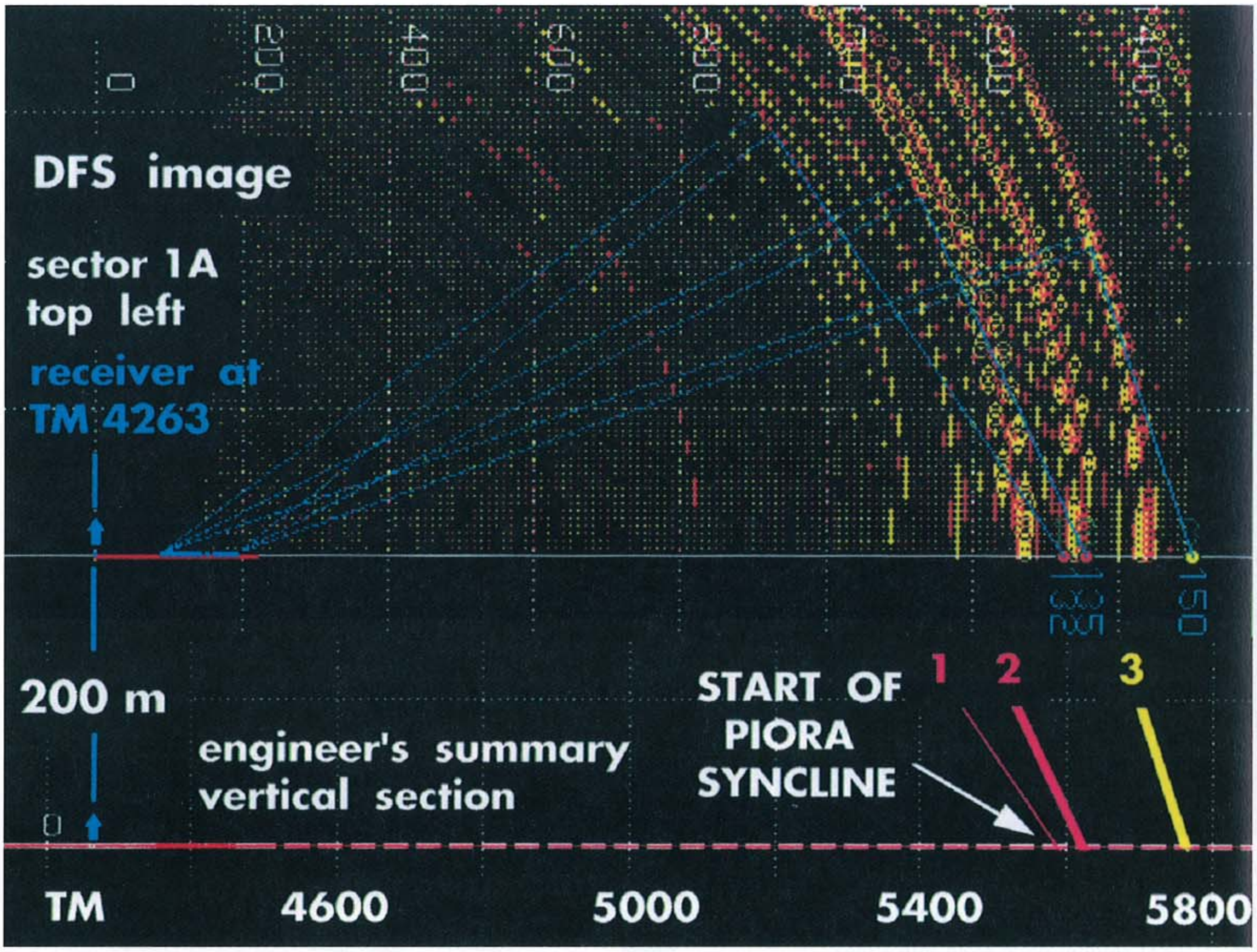

Figure 5 Representative results of long range TSP survey at face TM 4484, Piora Pilot gallery for future Gotthard Base rail tunnel, Switzerland. Diffraction stack image for primary P-wave (top) and engineers summary in vertical section (bottom). For engineers summary, strike of boundaries in plan section is assumed to be at right angles to tunnel axis.

angle event pairs 11 and 12 projecting to intersect the tunnel axis from 267 m (TM 3810) onwards. Given that this event pair and similar pairs projecting to the tunnel axis beyond them have similar orientations to events 1 to 4, they were interpreted to herald a return to the earlier, less favourable rock structure conditions.

Based on this interpretation and previous TSP experience, the rock mass from TM 3660 to TM 3810 was interpreted to be a tectonic wedge, imbricate structure, or lens of harder, more massive rock well suited for TBM parking.

Construction management instructed the TBM contractor to make a dash for this rock zone. On December 15, 1995 the TBM intersected harder banded amphibolites. By December 18, 1995 the advance had reached TM 3690 in competent banded amphibolites and fine-grained gneiss with little convergence and the TBM could be parked safely without misgivings.

It was most unfortunate that TSP events 1 to 6 could not be reconciled with observed geological boundary planes since a major increase in water seepage – up to 22 litres per second – over a large tunnel surface area between TM 3640 and TM 3658 dictated immediate shotcreting before a geological inspection was possible. However, these documented conditions were considered to provide sufficient indirect evidence in their own right for the presence of a composite fault and fracture zone from events 1 to 6 at TM 3653 to TM 3660. After start-up in the new year, the TBM crossed 2 fault zones at TM 3797 and TM 3815. These reintroduced poor quality schists and gneisses.

An earlier worst case scenario projection for manual tunnel widening to prevent TBM squeezing indicated that an extra semi-cylindrical roof section 8 m long and 30 cm thick would need to be stopped out above the cutter head. This would take five days. The cost for this work and for penalties incurred as a result of lower yields of excavation aggregate would come to at least CHF 125 000. Possible additional penalty costs relating to the five days of TBM downtime could supersede this basic cost by several orders of magnitude, confirming the great cost-saving potential of TSP.

Piora Pilot Gallery Examples

Tunnel statistics are: 6 km final length, TBM diameter 5 m, geology gneisses, 15 TSP surveys. Main problem: unknown depth extent of 300 m wide Piora syncline hosting sugary dolomite exposed on surface 1.2 km above tunnel axis.

In May 1995, a first long-range TSP survey was commissioned at face TM 4484 to search for possible evidence for the Piora syncline near the gallery level. The survey revealed a seismically quiet zone – continuation of massive,

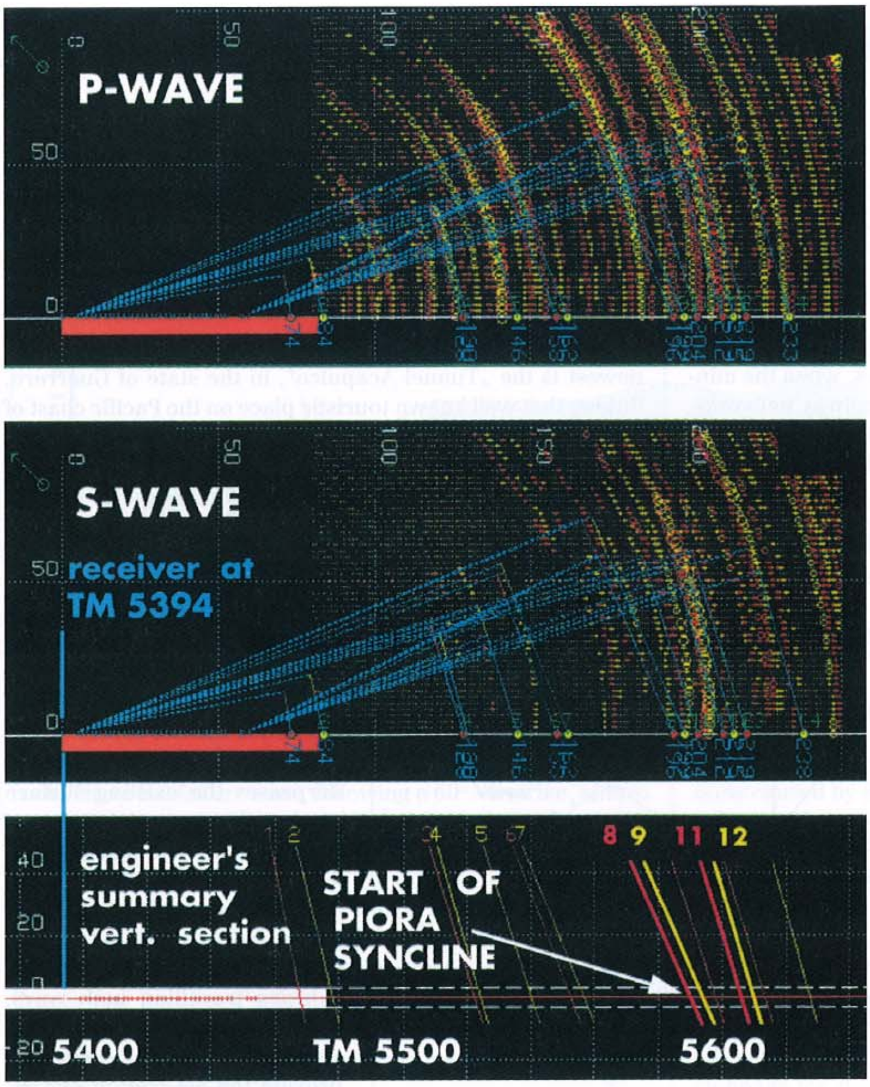

Figure 6 Representative results of standard TSP survey at face TM 5476, Piora Pilot gallery for future Gotthard Base rail tunnel, Switzerland.
Survey conducted as a more detailed follow-up to approximate long range survey in Fig. 5. Diffraction stack images (top) and engineers summary in vertical section (bottom). For engineers summary, strike of boundaries in plan section is assumed to be at right angles to tunnel axis. Shear wave data pinpoint beginning of Piora syncline better than primary wave data that also show up preceding subordinate fracture zones.

homogeneous gneiss – extending for some 1.1 km ahead of the face (Figure 5). The onset of a seismically reflective zone is recorded by red events 1 and 2 that project to intersect the tunnel axis from approx. TM 5600. This was interpreted as a possible candidate for the beginning of the Piora syncline at pilot gallery level.

By the beginning of March 1996, TBM drivage had progressed 1 km and an additional standard TSP survey was commissioned at face TM 5476 to define more precisely the results of the earlier long range survey. P-wave reflection data were supported by independent shear wave reflection data (Figure 6). Events marking the candidate structure for the start of the Piora syncline could be located more precisely as event pair 8 and 9. Their initial intersection with the tunnel axis was interpreted at approximately TM 5595.

TBM drivage was stopped at TM 5553 and a horizontal exploration borehole was initiated. At TM 5588, the borehole intersected the start of a water-bearing fault zone. At TM 5595, there was a major inrush of pressurized sugary dolomite mud into the borehole resulting in partial flooding of the gallery as documented by the press.

The possible end of the Piora structure could not be located from the TSP data due to very strong signal energy loss at the onset of the very inhomogeneous Piora rock mass.

Summary and Outlook

At both advancing faces of the Vereina rail tunnel, a final campaign of six TSP surveys is underway to accurately ascertain rock conditions leading up to breakthrough and to locate the most optimal competent rock zone for safe widening of a section of the tunnel into a cavern to facilitate dismantling of the TBM.

Significant geological boundaries that cut the tunnel axis at high angles cause the most serious problems and risks during tunnel advance because they are intersected very suddenly. Thus, where no forms of prediction ahead are carried out, there is little or no warning and time to put in place preventative and remedial construction measures. It is precisely these structures that TSP can and does locate most effectively. Geological events that cut the tunnel axis at low angles are more difficult to pinpoint accurately by the TSP method due to the limited spatial aperture of the TSP survey spread. However, these structures also tend to be less serious from a tunnel construction viewpoint, since their much more gradual entry into or exit from the tunnel profile generates longer, generally adequate advance warning timeframes for activating suitable construction measures.

Thus, TSP can achieve considerable cost savings during tunnel construction. With some 20 systems sold worldwide and over 150 survey experiences in most rock types, TSP is a proven commercial system beyond the development stage.

TSP is not our only seismic prediction system. We are also developing and testing a TBM-housed continuous monitoring system for soft rock tunnelling. This is called SSP for sonic soft ground probing system and is expected to achieve ranges of up to 50 m ahead of the face.

References

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