Predicting ahead of the face

Amberg Measuring Technique has patented a compact, versatile and easy-to-use measurement and evaluation system for moderate to hard rock tunnelling environments. Gerd Sattel, Bernhard Sander, Felix Amberg *and* Tadenobu Kashiwa *discuss experience gained from sites worldwide.*

Tunnelling sites are prone to sudden, often recurrent surprises resulting from changes in geotechnical conditions. In order to control costs, construction companies strive to maintain drivage at rates as rapid as conditions permit. Inadequate or poor geotechnical control often results in engineers' nightmares such as overbreak, caving and flooding.

A desirable solution is prevention by accurate prediction. If advance measures and safety nets such as pre-injection, rockbolting systems, steel arch supports, etc, can be put in place just before difficult rock is encountered, the far more costly tasks of problem solving and damage limitation can be avoided.

Several different prediction techniques are available, including pilot tunnels, exploratory drilling and non-destructive methods like seismics and geo-radar. However, most direct methods hold up drivage and so quickly become costly. On the other hand, conventional non-destructive geophysical techniques are prone to operational problems in the tunnelling environment and do not provide near instantaneous results.

Tunnel Seismic Prediction (TSP)

TSP is an underground reflection seismic technique specially developed for more effective and rapid geological and geotechnical prediction ahead of the face[1,2]. It fulfills both planning and monitoring tasks at underground sites such as tunnels, mines, caverns and repositories.

TSP employs the principle of echo sounding. Seismic (acoustic) waves are generated by small explosions at specific shotpoint locations and picked up by receivers. When a seismic wave hits a boundary marking a significant change in rock strength (e.g. changes in physical properties, rock type, fault zones and fracture zones), part of the incoming wave energy is reflected back at diffraction points (Fig 1, top). The travel time of the reflection signal is proportional to the distance to the boundary and so provides a direct measure.

Normally the measurement layout consists of approximately 24 shotpoints lined up along the right or left tunnel wall closest to expected geological boundaries. A receiver unit in each tunnel wall is used to investigate up to four 90° space sectors about the tunnel axis (TA) (Fig 1 bottom left). Each receiver system consists of groups of sensors (accelerometers) with components orientated along, and perpendicular to, the TA.

TSP meets several application-specific requirements. For example, the frequency range of seismic signals in most rocks (at 10-5000 Hz) is about ten times greater than that used in conventional seismic exploration, requiring special receiver units and recording equipment. TSP's versatility allows for different applications. Apart from periodic surveys at tunnel face positions (standard application), shooting in invest-

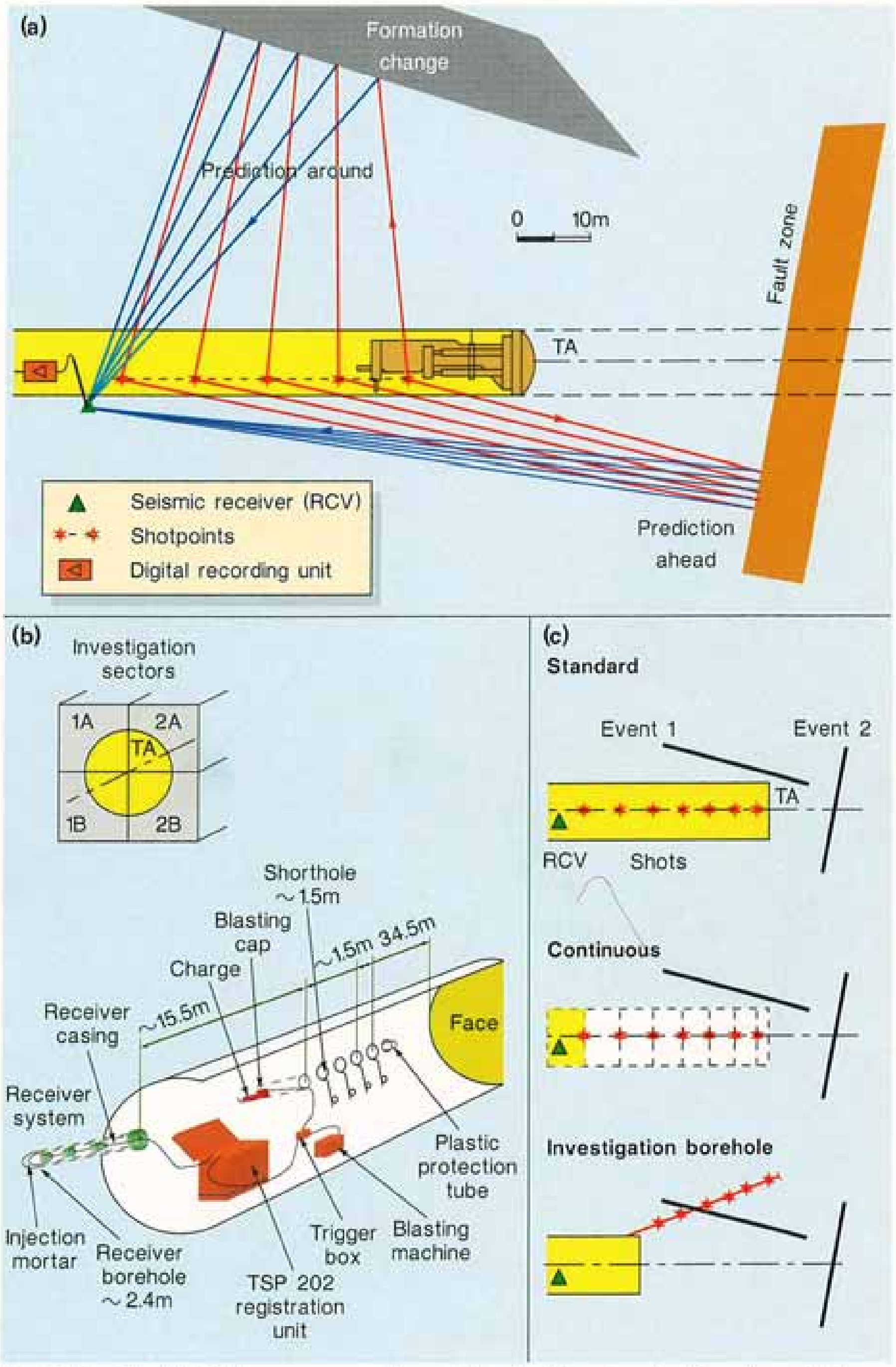


Fig 1. Principle of TSP (a); measurement layout (b) and different application schemes (c).

igation boreholes increases the investigation range and permits precise definition of geometries of boundaries intersected by the boreholes (Fig 1, bottom right).

TSP 202 equipment is very suitable for high resolution tunnel refraction seismic (microseismic) surveys to monitor zones of fracturing and reduced rock strength. It can also be used for high-resolution engineering seismic surveys on the surface. However, TSP's greatest value derives from its survey costs being sufficiently competitive to make it feasible for continuous monitoring during TBM or conventional drivage.

To economise on survey time, all preparatory work for a TSP measurement (drilling boreholes, cementing metal receiver casings) can be integrated into normal tunnelling operations. Setting up for measurement includes insertion of the receiver system, charging of shotholes and a functional test and takes approximately 1h. Seismic registration involves firing and recording each shot individually and takes approximately 45 minutes. Including equipment clear-up, the entire measurement cycle takes approximately 2h.

Data processing images reflect boundaries ahead of and around the face area in order that they can be located. The technique employs specially developed TSP 202 for a standard PC and follows a systematic sequence of steps.

First, an appropriate investigation sector is selected for evaluation. Then, wavefield processing serves to separate the direct and reflected wavefields (Fig 2, top left) and to transform the energy of the reflection signal on to an evaluation plane using the diffraction stack migration method (Fig 2, top right; Fig 6, bottom left). This plane, the diffraction stack plane (DFS), is defined by the axis of the shotpoints parallel to the TA and the diagonal through the relevant investigation sector.

Separate interactive interpretations are usually possible both for the primary compressional P-wave and for the secondary S-wave (shear wave), whose velocity is a valuable additional investigation parameter. S-wave interpretations can help improve discrimination of water bearing fault/fracture zones and of structural grain in rock masses. This interpretation cycle is repeated for other relevant investigation sectors.

The final product of all the separate space sector interpretations is the Engineer's summary. This is a synthesised vertical and horizontal section plot of the advancing tunnel and its coordinate system. It displays the anticipated entry and exit points of the most important reflecting boundaries ahead and the associated changes in rock strength (Fig 2, bottom right). Calculated velocities of the primary and secondary waves permit determination of important rock mechanical parameters such as Young's modulus and Poisson number. These parameters assist the tunnel engineer in planning construction measures and are a valuable rock mechanics monitoring tool during continuous TSP profiling.

The TSP 202 software allows a comparatively rapid, straightforward interpretation on site. Typically, a quick look interpretation is available after 2h. A comprehensive interpretation and report can be generated in 4h. Margins of error in TSP predictions ahead increase as the investigation ranges of survey are increased. Greater TSP survey range is achieved by increasing shotpoint and receiver separations using larger explosive charges, etc.

Experience from several hundred investigations reveals the following typical margins of error in distance predictions, assuming potential interpretational pitfalls (e.g. hidden fault offsets of rock boundaries, curved or irregular boundaries, etc) are recognized in advance (Table 1).

Major advantages of the TSP system compared to other methods for prediction ahead in tunnelling are its state-of-the-art sensitivity, ease of use and interpretation, relatively low cost, significant range, power of 3-D resolution, versatility and robustness. However, its overriding advantage is its unrivalled speed from measurement through to final interpretation.

Cost-benefit analysis

Financial planning for predictive surveys at tunnelling projects must consider two aspects concurrently: pure survey budgets and drivage interference budgets brought

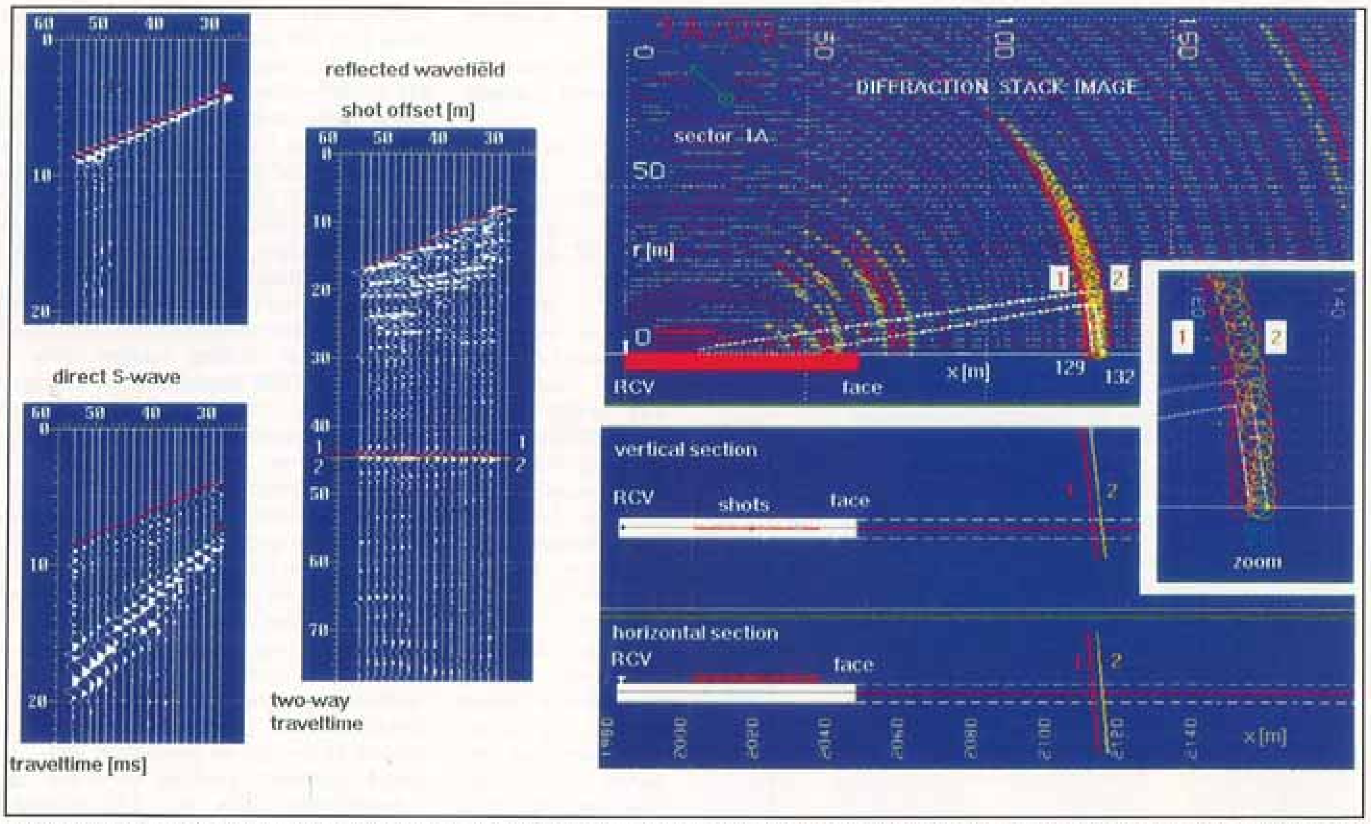


Fig 2. Plot examples from TSP 202 interpretation of data from Piora synform (Gotthard Base Tunnel), face at TM 2046: direct primary P-wave and shear S-wave arrivals (left); reflected wavefield (centre); investigation sector 1A (top right) with selected major events (red circles equal transition to weaker rocks, yellow circles equal transition to harder rocks) and engineer's summary - vertical, horizontal sections (bottom right).

Table 1. Vital statistics of tunnelling projects investigated by TSP case histories.

Tunnel project	Construction period	Approx. total constr. cost (US$ mill.)	Final length (km)	No.of TSP surveys to 10/95	Tunnel diameter meter (m)	Max. overburden (km)
SWITZERLAND						
Vereina rail	91-2000	420	21	35	7.6	1.2
Cleuson Dixence hydropower	94-98	900	15	2	5.6	0.8
Gotthard Base Tunnel (Piora)	93-99	70	5.5	12	5	1.8
JAPAN						
Miyagase hydropower	93-96	60	7.7	6	3.5	0.7
Gorlgamine bullet train	92-97	150	3	2	9.5	0.3
Karlsaka Highway	92-97	100	6.6	1	9.6	0.9
Kazunogawa hydropower	92-97	96	0.7	>3	5.6	-
S. KOREA						
Anmin Highway,	93-95	70	2 x 1.8	6	11.4	0.25
SWEDEN						
Hallandsas rail,	94-2003	110	2 x 8.5	4	9.1	0.15

Exchange rate employed: 1 US$=1.2 Swiss Francs

about by the surveys. The latter survey downtime budgets are additional budgets incurred as a consequence of having significantly to reduce or stop tunnelling advance in order to be able to carry out the predictive surveys. Survey downtime budgets normally significantly exceed pure survey budgets.

The unit measurement cost of a standard TSP 202 survey is approximately $15 000 and its unit measurement time is approximately 2h, assuming that trained staff and TSP equipment are routinely available at a project site.

In a recent feasibility study for construction of the Gotthard Base tunnel, Amberg Civil Engineers carried out a cost-benefit analysis to compare full tunnel construction costs by TBM without predictive investigation against tunnel construction costs including predictive investigations using exploration drilling, or TSP. The basic construction cost for a reference section of 500m of tunnel constructed in about 25 days amounted to approximately $7m (Fig 3, bottom). For this section, time and costs accruing for additional stabilisation measures immediately before entering zones of difficult ground and while traversing them are low relative to the basic construction budget. They have therefore already been included in the basic construction budget in each instance.

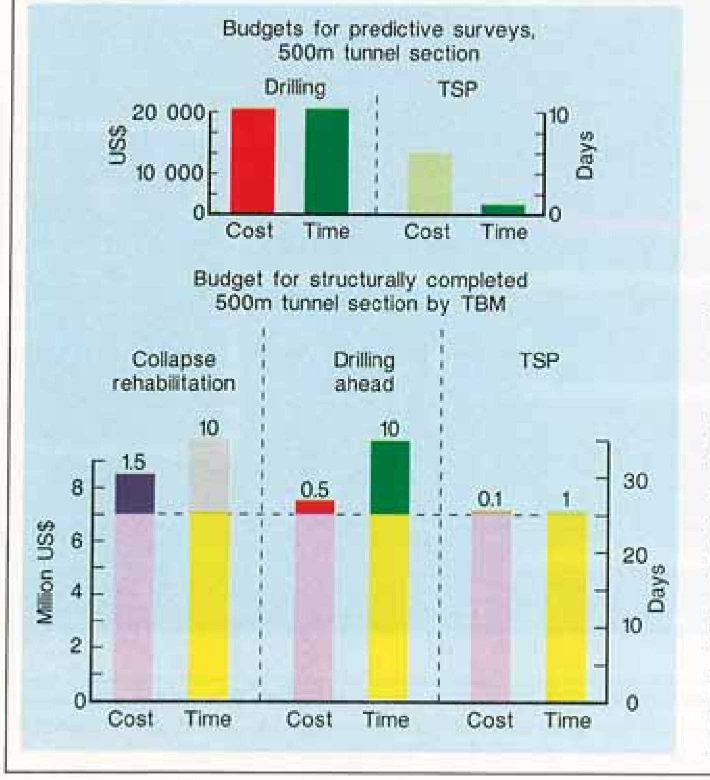


Fig 3. Cost benefit analysis for a structurally completed 500m long tunnel excavated section by TBM.

Lower histogram refers to additional incremental costs for drilling ahead and TSP which accrue from TBM downtimes necessary to carry out these surveys and which by far exceed pure survey costs quoted in the top histogram.

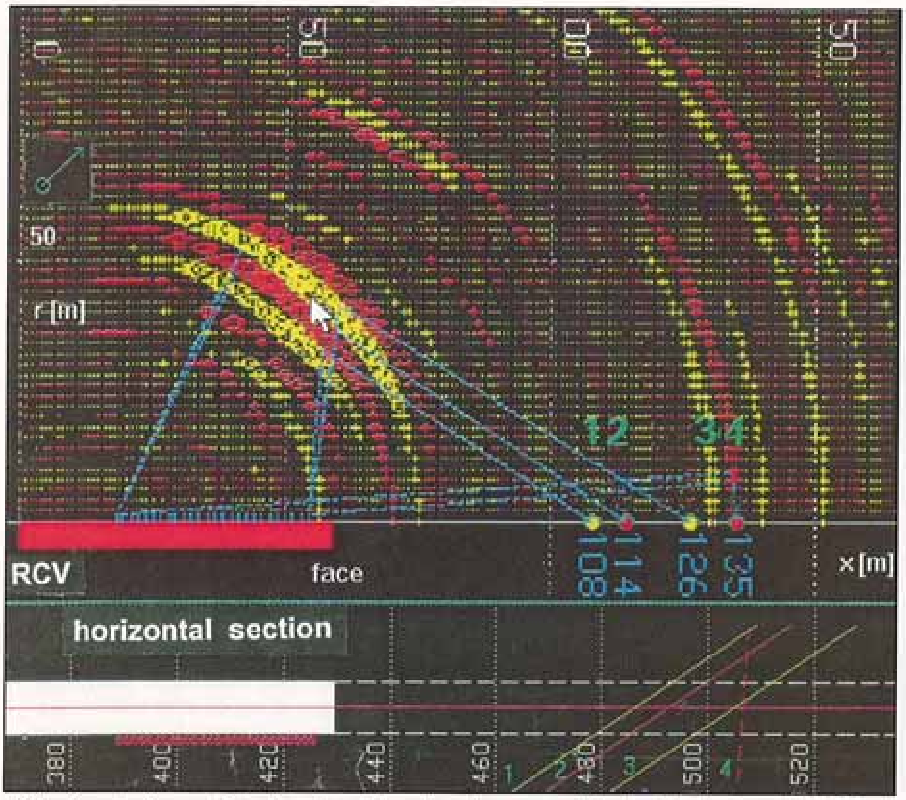
In the lower histogram, additional incremental collapse rehabilitation budgets (bottom left) accrue from downtime from minor tunnel overbreak due to no prediction ahead. (coutesy Amberg Civil Engineers).

For the scenario with no predictive investigations, it was assumed that one minor tunnel collapse occurred every 500m without injuries or fatalities to personnel. However, this resulted in downtime of ten days for tunnel rehabilitation (essential repairs, stabilisation measures, mucking out, etc) before full resumption of normal TBM drivage and construction. This translates to a downtime cost of approximately $1.5m (Fig 3, bottom). For options with prediction, successful prevention of tunnel collapse was due to advance warning of difficult conditions and implementation of additional tunnel support.

The construction option with exploratory core drilling allowed for drilling ahead of the face by 50-100m every 30m of advance at a unit drilling cost of $20/m. For the 500m of drivage under consideration, this takes approximately ten days and costs some $ 25 000 in its own right (Fig 3, top). The construction option with TSP allowed for a TSP survey every 50m of new advance. Thus total TSP cost for the 500m tunnel section is some $15 000 over 10h x 2h taken to add up to one full working day on site (Fig 3, top). Even if a reasonable amount of verification drilling is added to this TSP budget, TSP remains far more competitive than exploration drilling.

In the overall context, major additional TBM downtime penalties have to be added to exploratory drilling budgets (Fig 3, bottom). If TBM downtime cost averages at least $50 000/day, the ten days of exploratory drilling add on at least $0.5m to overall tunnel construction costs.

Overall additional TBM downtime due to ten TSP surveys — at most one day amounting to an extra cost of $50 000-$100 000 — represents less than 1.5 per cent of the overall unit construction cost of $7m (Fig 3, bottom). This is considered a conservative maximum estimate. If at all, it is usually logistical constraints relating to shifts that impose TSP related downtime. Relative to the overall unit construction cost of $8.5m for no prediction with one minor collapse, resulting in a ten day rehabilitation delay, the TSP inclusive overall unit construction cost of approximately $7.1m represents a potential cost saving of some 15 per cent or more.



Diffraction stack event intensity plot with engineer's summary, Vereina North, face TM 1430.

This large saving easily covers the cost of a TSP system several times. Even if a more pessimistic scenario is assumed where additional necessary tunnel support measures are put in place in time for only one of every two instances of TSP predictions of major problem zones, the potential cost saving of approximately 7.5 per cent remains very significant.

For lengths of modern large tunnels, computations of potential cost and time savings with TSP prediction become even more impressive as they can increase by several orders of magnitude more! Consider, for example, a more typical tunnel 5km long with an approximate basic construction cost of $70m. In summary, a modest budgetary addition for TSP surveys seems a tenable investment to achieve a significant reduction in tunnelling risk.

Case histories

Vital tunnelling statistics of the ensuing case histories are summarised in Table 1. The reference point (zero point) of every TSP survey is the position of its receiver (s). This defines the origin of the TA coordinate system. Alignments of diffraction points on diffraction stack plots are referred to as seismic events.

Vereina rail tunnel

The Vereina construction project in the High Alps is one of the largest single tube tunnel heading projects in Europe[3,4] and is an important precursor for acquiring engineering expertise for imminent construction of the 57km Gotthard Base tunnel and the 42km Lötschberg Base rail tunnels in Switzerland[5,6].

The 19km Vereina Tunnel and the completed 2.1km Zugwald Tunnel make up the engineering project. Vereina is being advanced from the northern Klosters portal by TBM (Vereina North section, current face approximately 3.5km from portal) and from the southern portal by blasting. TSP has been routinely used as the main predictive method at the Vereina North project from the start and some 35 surveys have been carried out so far.

With the tunnel face at Tunnel Metres (TM) 1430 in the Vereina North section, results of a TSP survey were eagerly anticipated. Progress had slowed dramatically to 1-3m/day after passing into highly sheared, incompetent serpentine requiring major stabilisation. An accurate prediction of the end of this difficult zone was vital to budget for an additional stock of stabilisation material and to prepare for a greatly increased advance and major adjustments to construction logistics upon passing back into harder formation.

The strongest signals were observed in investigation sector 2A (Fig 4), where events 1-4 with greater reflection energies than all events in previous surveys were dominated by events 1 and 3 (yellow), signalling a transition to considerably harder rock. Events 1 and 3 were interpreted to intersect the TA near 108m (TM 1479) and 126m (TM 1497) ahead of the reference point, with initial entry expected in the right tunnel roof at low intersection angles to the TA. The multiple, clustered form of the events also indicates some form of structural duplication at the boundary. Subsequently, a complex sheared contact from serpentine to gneiss along an imbricate structure was excavated at the predicted distance.

TSP surveys have now been conducted at more than 35 tunnel project sites in Japan. Construction companies Sato Kogyo and Nishimatsu performed pioneering TSP surveys at many sites and were instrumental in promoting widespread acceptance of TSP as a standard predictive technique in Japanese tunnelling.

Gorigamine bullet train tunnel

The 127km long Takasaki-Nagano bullet train line is due for completion for the 1998 Nagano Winter Olympics. It will help reduce travel time from Tokyo to Nagano to 1½h. Gorigamine is the major tunnel project along the new section and the fourth largest tunnel in Japan's bullet train system. Sato Kogyo is engaged in construction of the south portal section. NATM advance passes through a Tertiary mountain range comprising a dacite dome fringed by dacite tuff overlain by black shale and soft sediments with variably orientated geological contacts.

A TSP test survey was located in a completed section of tunnel in dacite with a receiver reference location at 89.4km. It predicted that five sub-parallel events with relatively high inclination angles to the TA would be encountered successively in the right tunnel floor in a relatively uniformly layered rock sequence with good contrasts in strength (Fig 5). Event 3 (red), predicted to intersect 85m ahead of the reference point, has the strongest negative intensity and coincided with the observed contact from dacite to weaker tuff. Events 1 and 2 related to an associated fracture zone.

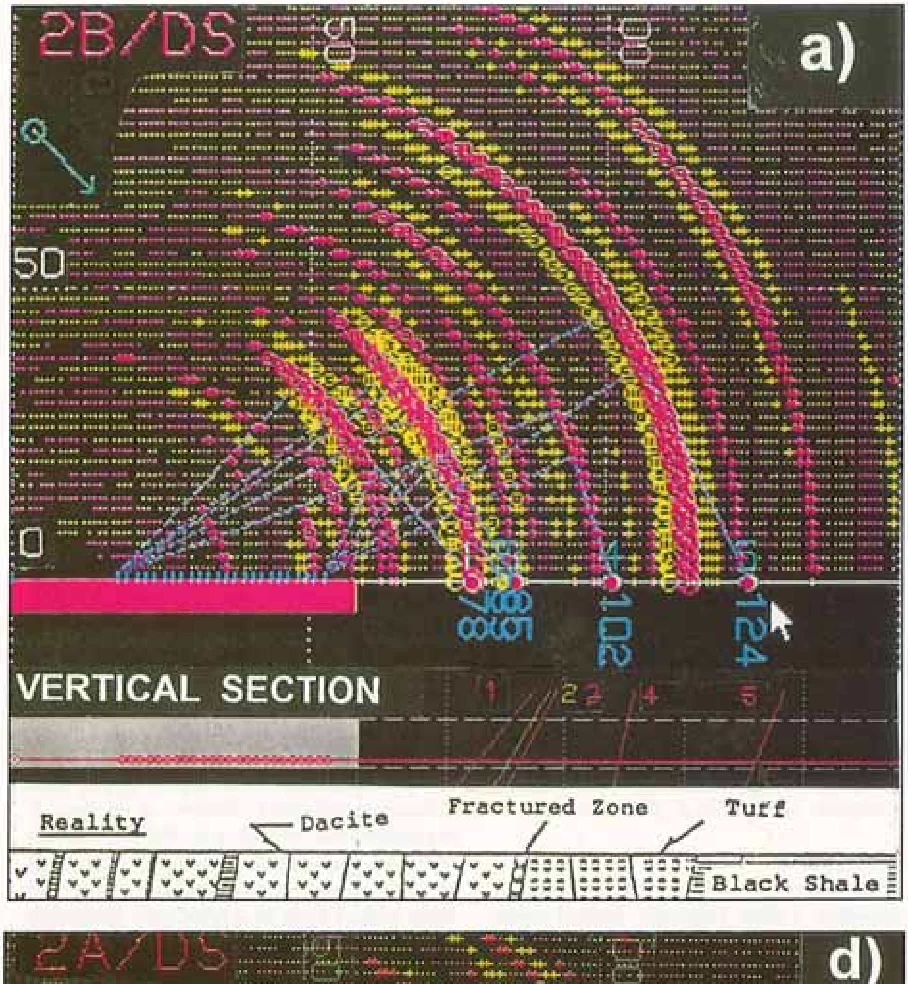
Event 4 (red) signalled a transition to slightly softer tuff. Event 5 (red) predicted another transition to weaker rock near 124m ahead of the reference point and coincided with the known contact from tuff to black shale. In subsequent TSP surveys at the advancing face, the successful recognition of similar changes in rock strength enabled advance implementation of more rigid tunnel support construction measures and maintenance of maximum advance rates in zones of competent rock.

At Sato Kogyo's Miyagase Dam hydroelectric project, a TSP interpretation located a major 14m wide fault zone in a headrace tunnel in layered volcanic rocks[7].

Kazunogawa Hydro

This new project for Tokyo Electric Power, northeast of Mount Fuji, derives its power from two dams connected by a tunnel network to the central underground Kazunogowa turbine plant. Host rocks are alternating hard mudstones and sandstone in synformal structures. The most prominent of three differently orientated fracture trends can host significant water and can reach tens of metres in width.

A TSP survey was performed in October



TSP interpretations, Japan, with diffraction stack event intensity plot, engineer's summary profile and geology/structure profile: (top) Gorigamine bullet train at tunnel km 89.428 (by courtesy Sato Kogyo Co) and (below) Kazunogawa hydro, face near TM 450 (by coutesy Nishimatsu Co).

'94 in mudstones of a NATM driven diversion channel tunnel with the tunnel face near TM 450. Its interpretation yielded several zones of events intersecting the TA at high angles and entering from the right roof. Only three individual events were considered to be of sufficient intensity to merit close attention (Fig 5). Event 1 (red) signals a change to weaker rock strength, intersecting the TA near 111m ahead of the reference point. Only 5m further ahead, event 2 (yellow), of stronger relative intensity, is interpreted to intersect the TA, signalling a return to harder rock.

From prior tunnelling experience, a possible fracture zone was predicted. A 14m wide fracture zone was subsequently encountered, beginning at 112m, with a spring of clear water (Fig 5, bottom log). Event 3 (red) predicts an abrupt transition to weaker rock from approximately 136m ahead. Beyond this, at least five more low-intensity negative amplitude red events can be recognised for at least 35m further ahead along the TA, suggesting persistence of moderately weak ground.

Subsequent excavation encountered another broad zone of water ingress from 136m to 198m ahead. Here, TSP enabled implementation of advance construction measures to control water inflow and support weak fracture zones.

In another Nishimatsu project, the Karisaka Highway 140 Tunnel, TSP interpretation of a series of up to 10m wide water-bearing fracture swarms in hornfels enabled tunnel support and drainage measures to be implemented ahead of the fracture swarms.

Anmin Highway tunnel, S. Korea

The 1.9km long Anmin Tunnel forms part of a new highway linking the cities of Changwon and Jengyu. It is being driven by SUNKYONG Engineering and Construction in an NATM advance through a ridge of granite and andesite. At the portal sections, the granite is intensely weathered to a crumbly, incompetent sandy soil, calling for special support during tunnel construction. It is therefore particularly important to gain advance knowledge of the expected extent of such poor quality rock sections and accurately to define transitions to fresher, more competent rock ahead of drivage.

A TSP survey was performed in March '95 in the south portal section in intensely weathered granite with the face at TM 90. Due to the strong dissipation of seismic energy in this poor rock, the TSP investigation range was restricted to about 100m ahead of the face. The diffraction stack image reveals discontinuous and truncated seismic events, suggesting some form of structural control (Fig. 6).

Three distinct, high intensity events are clearly defined and can be expected to enter the tunnel with moderate to low angles to the TA from the right tunnel floor/wall. Event 3 (yellow) displays the greatest intensity for a clear transition to stronger rock and is interpreted to intersect TA some 153m ahead of the reference point. This is in approximate agreement with the transition to fresher granite as predicted from exploration borehole TB5 (Fig 6) and the results of geoelectrical profiles conducted at surface. However,

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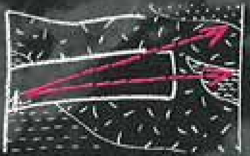

High drivage rates in tunnelling depend upon insider knowledge, ahead of the face.

The TSP 202 system uses a completely new type of "**T**unnel **S**eismic **P**rediction". It facilitates reliable and accurate data on changing ground conditions ahead of and in the vicinity of the face and provides rock-mechanical properties of the ground in the excavation zone. Easy to handle and economical - resulting in measurable cost savings.

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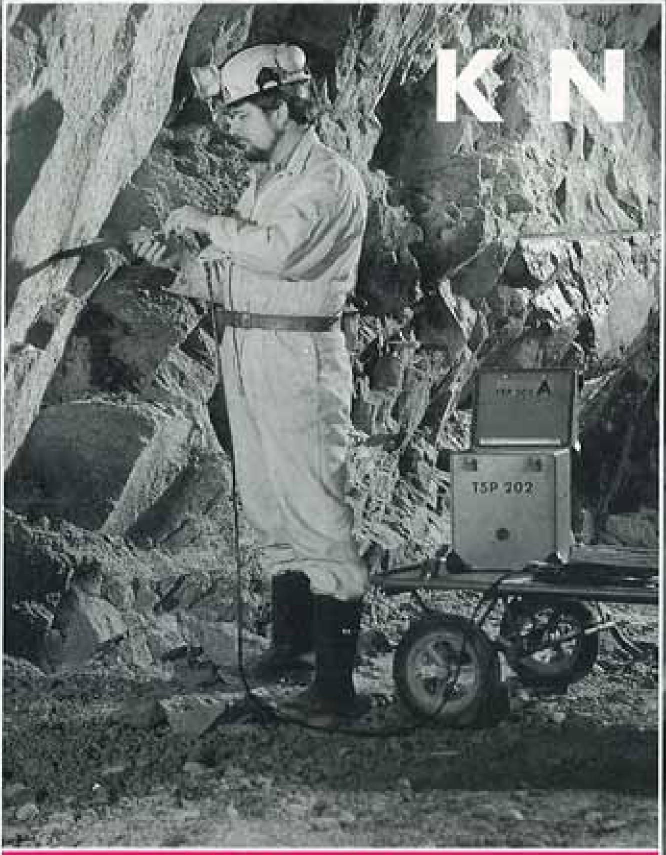
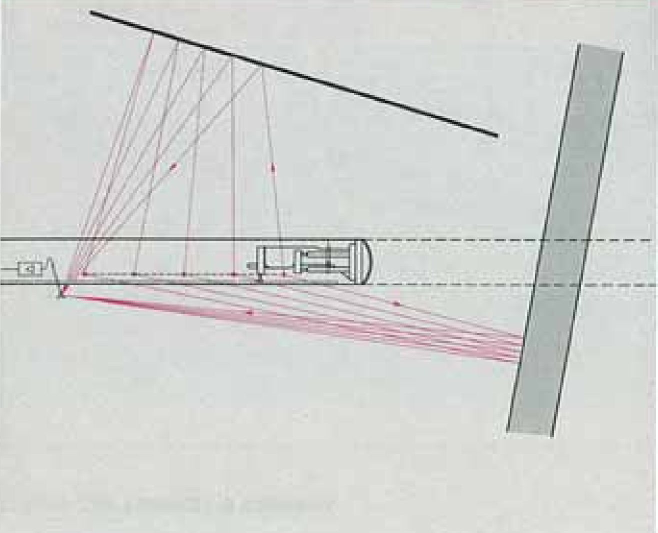


Actually in use at the Vereina Tunnel.

TSP 202



Amberg Measuring Technique

Knowledge by Measuring

Amberg Measuring Technique Ltd.
Trockenloostrasse 21
CH-8105 Regensdorf-Watt
Switzerland

For further information please contact:
Phone (+411) 8 70 92 22
Fax (+411) 8 70 06 18

Write 12 on information card

according to the TSP interpretation, the slope of this contact is considerably more gentle than that of the geological prognosis. This discrepancy is solved by the TSP interpretation for mixed phase events 1 (red) and 2 (yellow). The events intersect the TA near 85m and 90m respectively ahead of the reference point and, importantly, at a higher angle than all other adjacent seismic events.

Their close proximity, parallelism and good event continuity suggest that they define a normal fault that offsets the more gently dipping weathered granite — fresh granite contact in a step-like fashion, thus accounting for the apparent steeper dip of this contact (in the geological prognosis).

Just beyond the investigation range of this TSP measurement, boreholes TB3 and TB4 drilled from surface intersect the tunnel axis (Fig 6). Their logs can be reinterpreted in terms of a gentle granite contact as predicted by TSP, offset by a second, sub-parallel normal fault. Thus, the contact between bedrock and weathered overburden along the hill slope below, at and above the south portal, appears to be affected by a series of step-like normal faults, a common feature at many tunnel portals in different rock types.

Every tunnelling project poses unique challenges. Project experience highlights the dangers of taking for granted simplified, general geological prognoses. While these prognoses are impressive on paper they rarely conform to geological reality because they are almost inevitably based on insufficient support. TSP seeks to address this shortcoming as an independent, scientifically rigorous technique for predicting ahead into 3-D space.

TSP 202 is a service package made up of the proprietary technique, equipment and special PC software for data processing and interpretation. It was developed and commissioned by Amberg Measuring Technique (AMT) between 1991 and 1993. Some 15 such systems have been sold and several hundred commercial investigations performed in most rock types.

Case histories bear witness to TSP's applicability in moderate to hard rock environments. With good geological control and interpretation experience from one to two initial surveys on an individual project basis, TSP's capabilities are at the brink of full commercial exploitation.

Outlook

TSP's dependence on the physical properties of rock as a function of wave velocity (600 per cent variation range) and rock density (50 per cent variation range) makes it a powerful interpretation technique. Its full potential still remains to be fully exploited by means of the advanced algorithms and computing technology available today. AMT is actively pursuing this goal for its clients. ■

Acknowledgements

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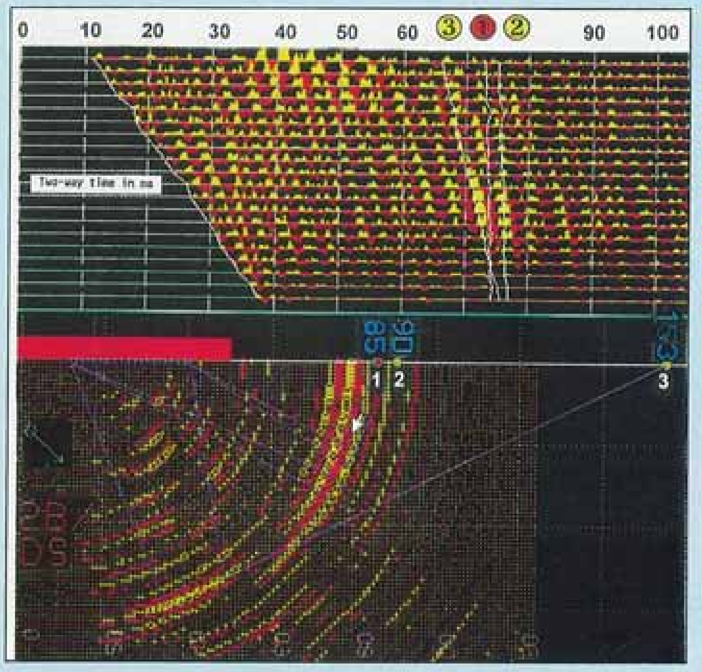

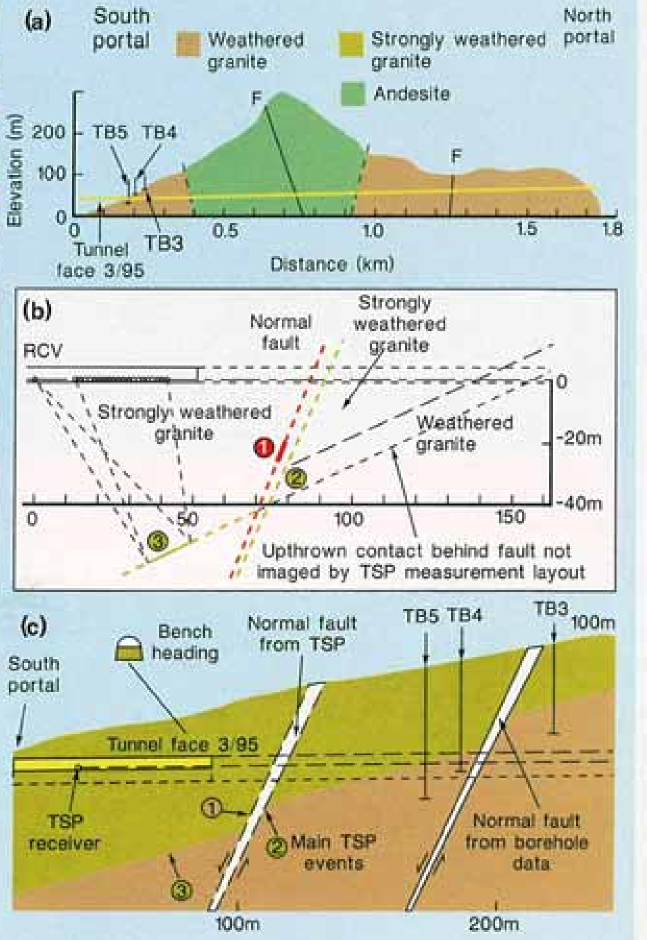

Fig 6. ***Right (a):*** *geological section of 1.9km long Anmin Highway tunnel, S. Korea.*
(b): *longitudinal section, Engineer's summary.*
(c): *combined interpretation, south portal section.*
Above: *TSP diffraction stack image taken in intensely weathered granite reveals discontinuous and truncated seismic events.*