Predicting rock conditions ahead of the face

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Seismic methods of predicting rock conditions ahead of the tunnel face have developed and improved significantly over recent times. As well as extending the prediction range up to 150m ahead of the face, three times that of probe drilling alone, comparisons with actual conditions when encountered are proving accurate and valuable to the tunnelling process. Dr Thomas Dickmann, of Amberg Technologies, assesses the performance of the company's Tunnel Seismic Prediction (TSP) technology on the long tunnel drives for the Pahang-Selangor water supply project through challenging mountain conditions in Malaysia.

Fig 1. Site location of the long water delivery tunnel

Three long and deep level TBM tunnels are central to the 44.6km long x 5.4m diameter Pahang Selangor Raw Water Transfer project through the granitic Main Range Mountains of the Malaysian Peninsular. Most of the tunnel is being excavated using three hard-rock TBMs.

The extent of site investigation carried out along the tunnel alignment from the surface was quite limited given the topography. As a result, there could be little or no warning of the need for applying preventative or remedial construction measures when meeting adverse geological features once into the tunnel drives. Serious problems including large breakouts, collapses, flooding and rush-ins could arise as a consequence. When using a TBM a continuous prediction of the rock mass is an important requirement for a smooth and efficient construction of the tunnel.

Exploratory drilling from the tunnel face is often used to detect lithologic heterogeneities ahead of the tunnel face but the maximum predictive range of this method is restricted to about 50m and causes significant delays to excavation. To overcome these drawbacks, the SNUI JV (Shimizu Corporation, Nishimatsu Construction, UEM Builders Bhd. and IJM Construction) added seismic measurements in all three TBM headings.

"We have had very good experience with our three-phase based risk assessment to get the geological uncertainties better under control," said Frank Pittard, Lead Geologist with the construction JV. This geological risk assessment comprises three methods.
The JV applied the Tunnel Seismic Prediction (TSP) method developed by Amberg Technologies AG of Switzerland when approaching suspected fault zones identified from surface topography and geological mapping. The actual testing on site takes about an hour, and data processing a further two to three hours. From this, it is possible to gather information about the mechanical properties of the ground such as compression and shear wave velocities, densities and elastic moduli. Even in rather complex geological hard rock conditions, prediction ranges of 150m ahead of the tunnel face can be achieved, a significantly longer distance than can be realized by probe drilling.
Once a geological risk zone is identified, the JV, in agreement with the Engineer, can verify the prevailing rock conditions in the suspected risk zone by then carrying out a probe drilling when the concerned zone is closer to the face. In addition, the JV's team of site geologists continually map the tunnel sidewalls to describe precisely the geological features encountered and to classify the rock mass for determination of the rock support.

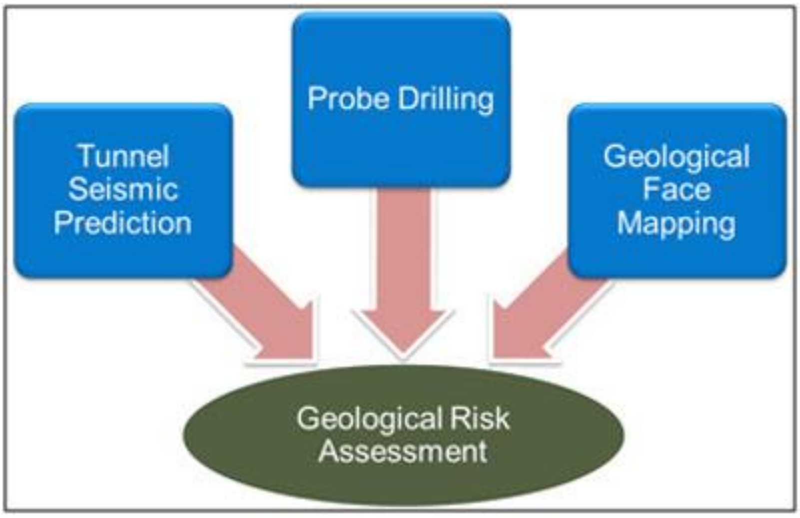

Fig 2. Three phases of geological risk assessment

Seismic prediction during tunnelling
The Tunnel Seismic Prediction (TSP) method needs to be robust and reliable and must avoid disrupting the tunnelling process while yielding results quickly and at moderate cost. It is the most effective prediction method because of its large prediction range, high resolution and ease of application on the tunnel construction site. It is based on evaluating elastic body waves excited by explosive charges providing the best signal to noise ratio. Body waves travel as compression or shear waves through the ground and are reflected at interfaces of different properties, including density or elasticity (Fig 3).

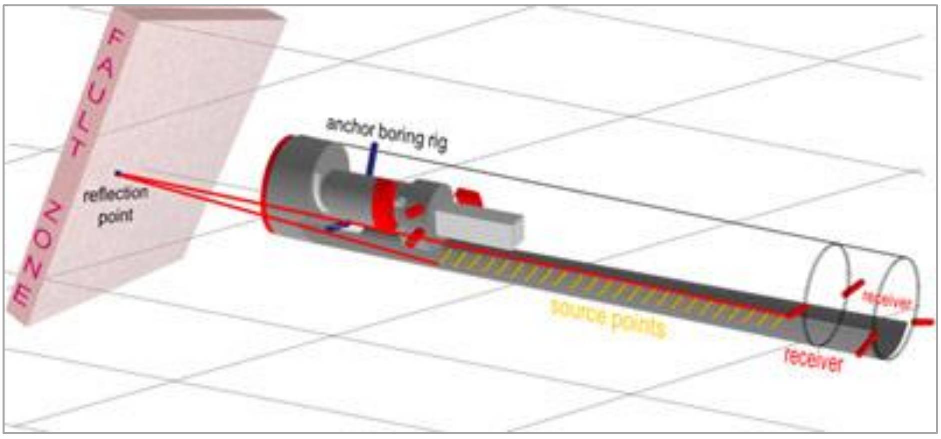

Fig 3. Standard TSP layout in a TBM heading. Acoustic waves are reflected from a geological discontinuity and picked up by receivers

The test cycle begins with boreholes to house explosive charges and receivers being drilled into the side of the tunnel behind the TBM. These are installed routinely by the JV tunnelling crews using ordinary handheld rock drills and without causing disruption to the excavation schedule. Installing seismic receivers and loading and detonating 30g explosive charges takes about one hour and can be scheduled during maintenance intervals or short excavation breaks. The fast installation procedure and functionality of all the system components ensures that there are no complications or delays during the survey cycle.
The TSP system equipment is handy and easy to transport. The SNUI JV is operating two systems that enable teams to perform measurements in the TBM drives and in the project's conventional NATM headings.

TSP system on TBM site Site geologist at TSP work TSP receiver set 2m deep

Processing and evaluation

After each TSP measurement the site geologists use the TSP integrated software that provides a set of semi-automated processing steps for analysing the heterogeneity in different datasets obtained in differing geologic conditions (Fig 4). Using these steps the geologist is guided to the final, well-presented and comprehensive result. The seismic event display shows all seismic discontinuities as indicated by lines of varying length and inclination (Fig 5). These lines represent reflectors, i.e. interfaces, where seismic waves are reflected. In addition, the areas between the reflectors are presented in different colours. These colours are based on the various rock properties, for example the dynamic Young's modulus, whose occurrence along the projected tunnel axis is illustrated in the upper graph of the result display (Fig 5). The Young's modulus is determined by calculating the seismic velocity distribution of measured P- and S-waves and the resulting densities.

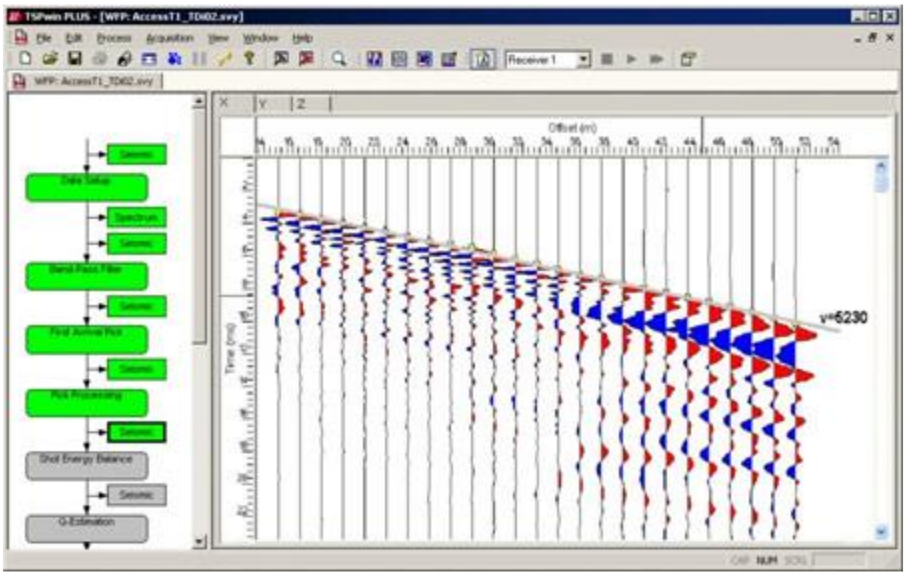

Fig 4. Interactive processing flow chart with seismic displays

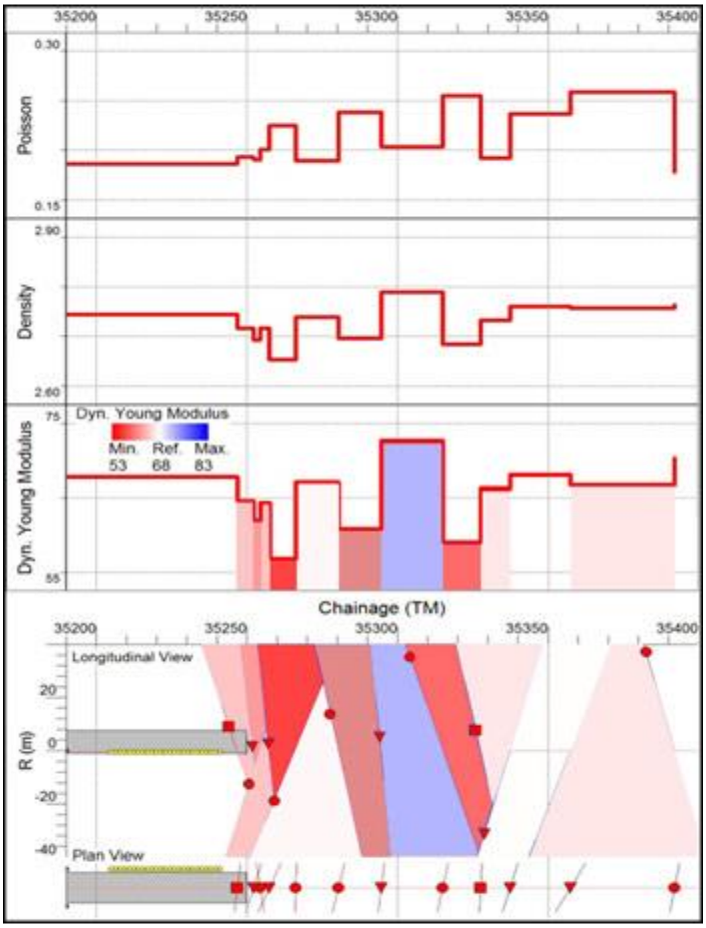

Fig 5. Seismic event display ahead of the face

Data interpretation

The SNUI JV is logging continuously machine performance data via different sensors on the TBMs. It is desirable that the seismic predictions are directly related to TBM advance parameters, including penetration rate or TBM thrust forces. In this way, rock class grade points and support types can be related directly to seismic velocities and hence, they may become predictable once all data involved are adjusted. Exploring such correlations however, is ambiguous and can be misleading in some cases since geologic features affecting seismic velocities do not affect TBM performance to the same degree.

The success of the SNUI JV's approach to using all available parameters to support the TBM drives and mitigate geological risks, can be assessed by comparing the forecast result of a TSP measurement taken in the TBM-3 drive in February 2012 and the later experience of geological conditions actually encountered. These are presented in Fig 6, which is divided into four sections.

The upper section shows two graphs, which reflect the predicted curve progression of the P-wave velocity and Bulk Modulus along the tunnel axis. The top graph of the P-wave velocity is also colour shaded below its line. The same colouring is found again in the middle part of Fig 6. As explained, a colour change takes place at a reflector according to the geotechnical parameter selected. For the Fig 6 example it is the seismic P-wave velocity.

At the time of measurement, the tunnel face was at about 6,230m from the portal and about 40m from the TSP charge and receiver installation layout; slightly farther than the usual 30m. The measured velocity of the direct P-waves in the area of the TSP layout was 5,090m/s, corresponding to moderately jointed and slightly weathered granite. Beyond the 6,230m tunnel face location, the values of the mentioned parameters begin to decline. There are indications of a higher jointing. Just ahead of the tunnel face at 6,230m, the analyzed P-wave velocity falls down to 4,580m/s. A stronger weathering of the granite and primary fracture zones are likely. The situation may stay worse for about 12m. About 45m further ahead, at about tunnel distance 6,275m, the P-wave velocity drops again, to 4,670m/s indicating another fracture zone forecasted for the area.

The lower section of Fig 6 consists of four graphs, which include the description of the geological findings in the geological tunnel plan at the lowest part of the graph. Here, significant changes of geology are mapped and described in detail. Since TBM operating parameters can be regarded as a continuous measure of rock mass properties, they can be used to validate the results of seismic exploration data obtained before excavation, which depend also on elastic properties of the rock mass.

But unlike TBM performance, during which rock behaviour is measured continuously along the tunnel axis, seismic exploration data are only sensitive to sharp changes in rock mass properties. Despite this restriction, a significant correlation of seismic data and TBM drive data can be found.

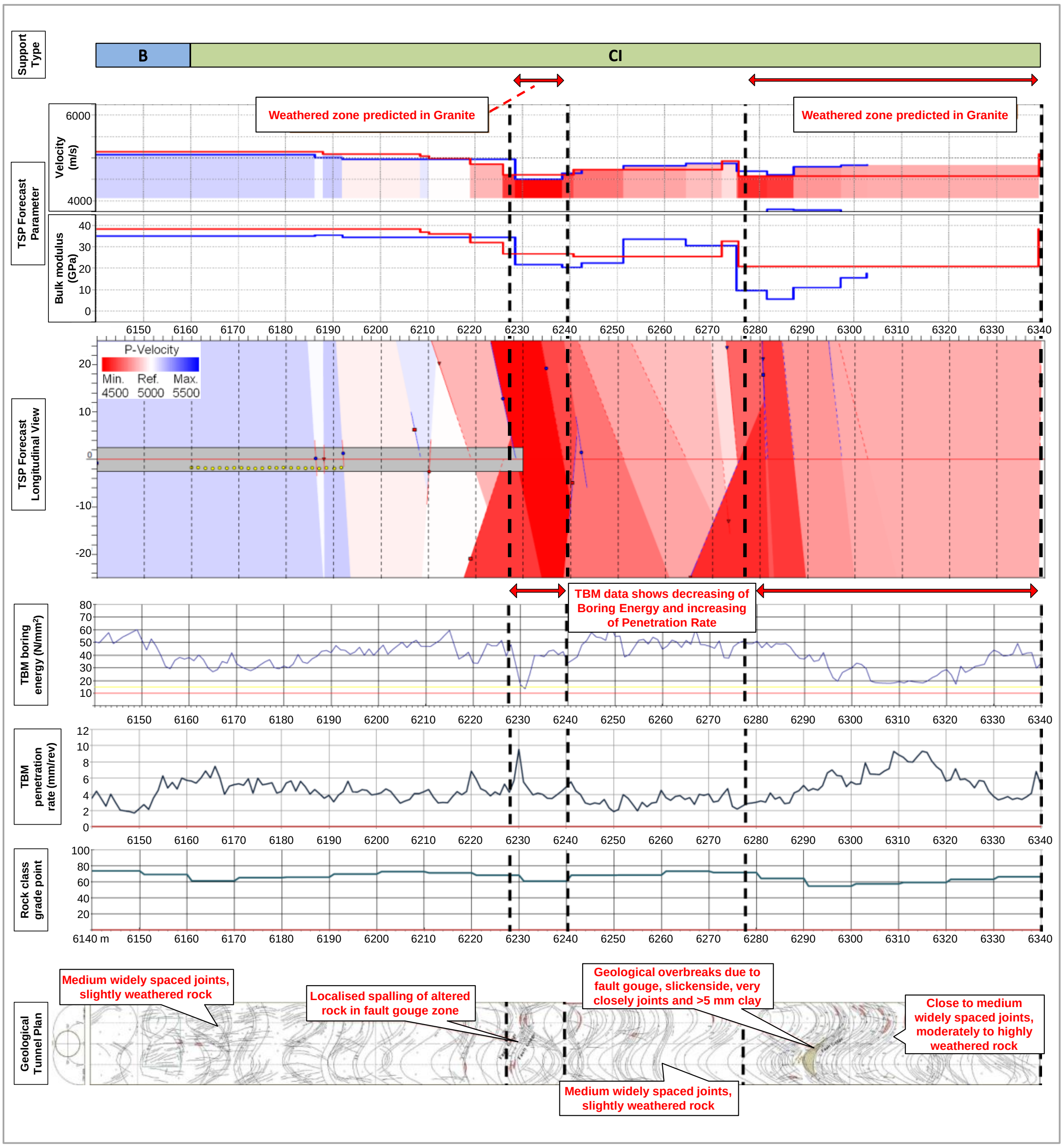

Fig 6. TSP forecast, TBM data and compared geological findings

The graphs of Fig 6 outline the developing of the TBM power consumption and its penetration rate. There is satisfactory correlation between the two parameters and the parameters derived from the seismic exploration data. However, a direct comparison of seismic exploration data with TBM data is limited by the circumstance that velocity changes are represented as step functions, whereas TBM data show also gradual changes. Gradual changes are almost impossible to image by seismic methods since a defined acoustic impedance contrast is necessary to record seismic reflection data.

"The prognosis of TSP correlates well with actual geological conditions," said Naufal Bakhudin, geologist with SNUI JV and one of the TSP operators. The first fault gouge zone, found at tunnel heading 6,226-6,240m is indicated by changes

in the TBM data as well. It was successfully detected by TSP as a drop in seismic velocity.
After several metres of excavation beyond this zone, the operator was advised to control the TBM carefully due to the next weathered zone predicted by TSP from tunnel heading 6,276m to 6,340m. A fault gouge zone was encountered at this point with geological overbreaks, slickenside jointing, very closely spaced jointing and more than 5mm clay filling. Again the TSP system provided good prediction data.
The rock class declined by 10 grade points in the described zones and the SNUI JV decided to maintain the support type CI, a systematic application of fibre mortar, to prevent any continuous geological overbreak or tunnel deformation.